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Implementation of sustainable refrigeration technology with phase-change material storage at rural communities in Kampung Labang, Bintulu Sarawak, Malaysia: A case study

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Abstract

Solar-powered refrigeration is a promising solution for ensuring sustainable access to cooling in areas with weak or off-grid electricity supply. However, conventional solar-powered fridges rely heavily on high-cost electrical battery storage and photovoltaic (PV) panels, which limit their economic feasibility in many rural settings. To address these challenges and reduce reliance on electrical storage, phase-change materials (PCMs) have been introduced as a viable thermal energy storage solution. A PCM system can be more energy-efficient than conventional solar-powered fridges because it stores excess cooling during the day and releases it during night-time or cloudy conditions. This leads to reduced dependence on electrical batteries, which are typically a major cost driver in solar refrigeration systems. Experimental validation demonstrated that PCM packs maintained an average temperature of 6.73°C in the chiller and −5°C in the freezer during low or zero solar irradiance, outperforming conventional solar-powered fridges with the same electrical battery and PV panel arrangement. The integration of PCM reduced the levelized cost of cooling to 27 cents USD/kWh, or 70% lower than conventional solar-powered fridges. In addition, this study uniquely combines technical advancements with social engagement by involving end-users through pre-installation analysis and semi-structured interviews, ensuring the system's relevance, practicality, and acceptance. These findings highlight the importance of integrating both technical and social perspectives to accelerate the adoption and implementation of sustainable cooling technologies in off/weak-grid areas.

Keywords: Rural refrigeration; Solar PV; PCM storage; Low-cost PCM; Real case study

1. Introduction

Food security in rural areas is often associated with the unavailability of sufficient cold storage due to weak/off-grid power supply. Access to sustainable cooling, including access to freezers and refrigeration, is seen as a promising approach to the solve these challenges, since reports have shown that lack of access directly results in 526 million tons of food production losses every year.[1] However, conventional refrigeration systems are designed for stable grid conditions – which means intermittent and unreliable power supply have become the main barriers for related industries in rural area to have access to this technology.[2] As a result, postharvest, food, and medicine storage issues in rural areas are known to be due primarily to weak/off grid power supply. This is in line with research[3] reporting that the conventional cold-storage solutions have not taken off at the smallholder level, mainly due to a lack of availability and access to reliable grid electricity. This explains postharvest lost due to food spoilage among farmers in rural areas. From a report identifying issues related to vaccine storage in rural areas[4] in several Southeast Asian (SEA) countries, the Philippines, Timor-Leste and Lao People's Democratic Republic experience continuous logistics challenges in accessing rural or remote areas due to poor infrastructures. Meanwhile, in the Philippines and particularly Myanmar, which have the lowest electrification rate in the SEA region, a lack of electricity supply leads to poor utilization of refrigerators in healthcare facilities. From the report, storing vaccines through solar-powered or battery-powered refrigerators is seen as a promising approach. In South Sudan for instance, as one of the least electrified country in the world, solar-powered fridges has been proven to be reliable in vaccine storage. Solar-powered refrigerators have contributed to a 50% increase in child vaccination rates in some of the most impoverished rural provinces of Congo. Furthermore, a 2015 pilot project in remote areas of Indonesia demonstrated the effectiveness of solar-powered refrigeration, receiving positive feedback. This approach holds potential for broader implementation across Southeast Asia and other remote regions with limited access to reliable electrification and infrastructure.[3]

However, expensive battery storage is a key limitation. To ensure 24 h of cooling supply, electrical battery storage is required. Refrigeration with thermal energy storage using phase-change materials (PCM) at a controlled temperature range powered by solar photovoltaic (PV) panels has been reported by researchers[5,6] as a promising approach to providing sustainable cooling in rural areas. The use of the PCM extend the operational time of the refrigeration by storing excess cooling during the day and release the cooling at night-time or time with low to zero solar irradiance.

As presented in Table 1, many researchers have proposed the use of refrigeration systems with PCM storage powered

Table 1. The summary of research that has been conducted on solar-powered refrigeration system with and without PCM storage

Description of research	Type of research	Research gap
Investigation of solar-powered refrigerator design and performance analysis[7]	Testing battery performance and load for 2 h with temperature control at 16°C.	Further testing on long-term battery durability and system portability need to be investigated.
Evaluation of PV-powered variable-speed DC compressor with PCM storage for off-grid areas[5]	Lab and field tests, including transient power consumption and temperature stabilization using PCM.	The effects of PCM placement in the refrigerator and additional cooling time during power outages were not explored.
Design and analysis of a solar-powered refrigeration system for scorpion antivenom storage[8]	Testing saltwater PCM in varying quantities to optimize temperature for scorpion antivenom storage.	Investigating alternative PCM compositions for even better temperature retention.
Performance analysis of a household refrigerator with PCM-integrated heat exchanger[9]	Experimental setup with 2D simulations to study the effect of PCM emplacement.	The research does not explore PCM performance in real-world variable conditions, nor the long-term stability of PCM in household refrigerators. More studies are needed on dynamic environmental conditions.
Testing of vapor compression refrigeration system performance using various PCMs. [10]	Tested with no PCM, with PCM in different configurations (freezer, fridge, and condenser).	The long-term durability of PCMs in different configurations (freezer, fridge, and condenser) and their impact on refrigerant flow are not deeply analyzed. Investigation into the effects of PCM degradation over time is needed.
Assessment of low-temperature PCMs with nanoparticle additives in VCC systems. [11]	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.
Examination of PCM thickness and frost effects on refrigeration efficiency[12]	Theoretical and experimental tests on a conventional refrigerator with PCM and frost effects.	More research is needed on frost mitigation techniques in PCM-enhanced refrigerators. The impact of frost on PCM performance needs in-depth investigation across various climates.

(Cont'd...)

Table 1. *(Continued)*

Description of research	Type of research	Research gap
Development of a PCM-enhanced domestic refrigerator with a miniature DC compressor for off-grid use[5,6]	Lab and field tests in the UK and Ghana, analyzing power consumption and PCM's impact on performance.	Further research is 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.
Evaluation of refrigerator evaporator integrated with eutectic PCMs[13]	Experimental tests to measure power consumption and internal temperature fluctuations.	Research should expand to test PCM performance in other climatic conditions, such as tropical and subtropical environments. Effects of humidity on PCM behavior are not fully explored.
Review of PCM applications in evaporators, condensers, and refrigeration compartments[14]	Various studies examined the use of PCMs in evaporators, condensers, and compartments.	Further research is needed on applying PCM in condensers and optimizing thermal conductivity.
Study of PCM-enhanced refrigeration in transport vehicles under varying conditions[15]	Experimental study on the integration of PCM in refrigerated vehicles under various temperature conditions.	Further exploration is needed for PCM application under extreme conditions during transport.
Analysis of PCM types and designs for improving refrigerator and freezer performance[16]	Experimental analysis of different PCM types and container designs in refrigeration systems.	Further research is needed on enhancing thermal conductivity and reducing costs of PCM systems.
Assessment of PCM performance in domestic refrigerators under off-peak modes[17]	Tested under off-peak refrigeration mode with PCM and conventional refrigeration systems.	PCM placement optimization is needed for better energy savings and thermal performance.
Testing of PCM materials and placements in refrigerated display cabinets[18]	Experimental tests on different PCM materials and placements in refrigerated cabinets.	Research is needed on retrofitting existing cabinets with PCM and commercial viability.

Abbreviations: DC: Direct current; LSHX: Suction-line heat exchanger; PCM: Phase-change materials; PV: Photovoltaic; VCC: Vapor compression cycle.

by solar panels or alternative energy sources. However, our research standouts by addressing both the social and technical aspects, which have often been overlooked. To ensure the feasibility and suitability of the proposed technology, semi-structured interviews were conducted before installation, engaging end-users to evaluate the system's appropriateness and practicality for real-case implementation. This user-focused approach has facilitated a more tailored and relevant demonstration of the system. In addition, after installation, a preliminary impact study was performed to assess the initial effects of the system in rural areas. This study has utilized a combination of semi-structured interviews and photographic evidence to comprehensively document and evaluate implementation outcomes.

From a technical perspective, this paper discusses the application of a solar-powered refrigerator using PCM storage, focusing on minimizing reliance on costly electrical battery storage to reduce overall installation costs, including material and logistics requirements. Furthermore, the innovative use of locally-sourced PCM materials enhances the system's affordability and sustainability, making it practical in remote and rural settings. These contributions collectively underscore the importance of integrating social engagement with technical innovation to advance sustainable cooling solutions.

2. Methodology

This research is a combination of both technical and social investigations aiming to implement a standalone PCM refrigeration system that is fully powered by solar energy. The study considers not only technical factors but also social motivations. The following method, as illustrated in the methodology framework in Figure 1, was implemented in this study.

2.1. PCMs selection

In the selection of PCMs, different types of materials were investigated for the freezer and the chiller compartments, which require different temperature ranges. Specifically, we experimented with various mixtures of glycerol, water, and alcohol for the freezer compartment. In this setup, a mixture of glycerine, alcohol, and water was selected for their freeze-resistant properties. These materials enable the ice packs to stay flexible at low temperatures while maximizing thermal storage. Different ratios of glycerine to alcohol to water were tested to determine the best balance of thermal retention and structural stability. As shown in Table 2, we synthesized six PCM samples with glycerine concentrations ranging from 10% to 30% and alcohol from 5% to 10%, with the remaining volume as water. These variations allowed us to analyze the melting temperatures of different PCM blends and how they influence cooling performance. The solutions, as shown in Figure 2, were sealed in bubble wrap, which provided insulation and structural integrity to prevent leakage during temperature fluctuations. These bubble-wrapped packs, as illustrated in Figure 2, were then frozen, with subsequent testing focusing on freezing points, thaw rates, and overall thermal endurance.

Table 2. The mixture of the PCMs

	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

Abbreviation: PCM: Phase-change material.

2.2. Experimental design setup and testing

The preliminary investigation of the solar-powered fridge system with the selected PCMs energy storage, as discussed in section 2.1, encompasses the complete design and setup of the system under real environmental conditions. The design framework incorporates critical parameters including total electrical load, working hours of the DC fridge, electrical battery storage capacity, PCM thermal energy storage, solar PV panel sizing, and the balance of system (BOS) components, including the solar charge controller. The following step-by-step design process was

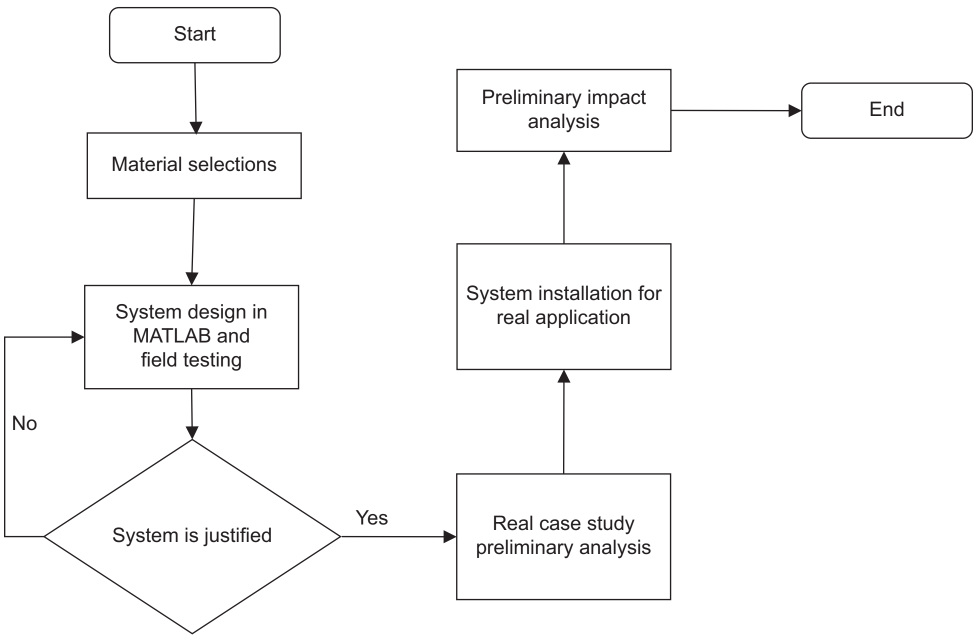

Figure 1. The flowchart on research framework used in this study

Figure 2. The synthesized phase-change materials packed in bubble wrap

employed to ensure accurate sizing and integration of all system components.

First step: Determining total load

$$\sum Q_{load} = \sum (Power\ rating \times hours\ of\ usage)$$

Second step: Sizing of the electrical battery storage

$$E_{batt} = \frac{\sum Q_{load} \times D_{no\_sun}}{\eta_{batt} \times V_{system} \times DoD}$$

where $\sum Q_{load}$ is the total load, D_{no_sun} is the days without the sun, V_{system} is the battery charge voltage of the system (*i.e.*, 12 V, 24 V, or 48 V system), η_{batt} is the battery efficiency, and DoD is the depth of discharge of the battery.

Third step: Sizing of the PV panel S_{PV}

$$S_{PV} = \frac{\sum Q_{load}}{h_{sun} \times \eta_{pv}}$$

Where h_{sun} is the sunshine hours, and η_{pv} is the efficiency of the PV panel taking into consideration various correction factors.

Fourth step: Determining the voltage and current rating of the charge controller (manages charging of the battery and directs power flow)

$$Voltage\ rating = N_{series} \times V_{OC_{PV}Panel} \times T_{factor}$$

$$Current\ Rating = \frac{P_{\max\_PV}}{V_{system}}$$

Where $V_{ocPVpanel}$ is the open circuit voltage for a single panel, T_{factor} is the temperature correction factor, P_{max_PV} is the total maximum power from the PV panel.

The following parameters were considered in the experimental design:

(i) *Load and operational hours.* The total daily energy load was calculated to be 1.02 kWh based on the power rating of the fridge (85 W) and its operational hours (12 h/day). The operational hours were selected to reduce the reliance on electrical battery storage, which has been replaced by thermal energy storage.

(ii) *Battery storage sizing.* The electrical battery storage capacity was determined considering the system voltage (24 V) and depth of discharge (DoD), resulting in a parallel configuration of two 12 V, 100 Ah batteries.

(iii) *PCM thermal energy storage.* For the fridge compartment, PCM packs with a melting temperature of 4°C, provided by PCM Products Ltd. (UK), were selected to maintain consistent cooling. For the freezer compartment, a low-cost PCM ice gel with a melting temperature suitable for the freezer compartment was synthesized at the lab which was utilized to enhance thermal storage efficiency

(iv) *PV panel sizing.* The PV panel capacity was sized to meet the system load based on available sunshine hours and panel efficiency, resulting in the selection of two 200 W panels

(v) *BOS.* BOS components, including the solar charge controller, cables, connectors, and earthing system, were carefully sized to ensure system safety, reliability, and efficiency.

The step-by-step system design process was developed in MATLAB. Using weather data for the specified locations, the average performance of the PV panels was simulated to design the system. Meanwhile, Table 3 summarizes the system design for the development of the Proof of Concept (PoC) prototype. The prototype, as shown in Figure 3, was installed at the Solar Energy Research Institute, Universiti Kebangsaan Malaysia, located at 2.9398° N, 101.7876° E.

PCM packs with melting point temperatures of 4°C, manufactured by PCM Products Limited, were selected for the fridge compartment. Meanwhile, a low-cost PCM pack featuring a melting temperature of −12.7°C was employed in the freezer compartment. These materials were chosen

Table 3. Specifications of the solar-powered fridge system components

Component	Specification
Total daily load	85 W×12 h=1.02 kWh
Electrical battery size	2×12 V, 100 Ah (parallel configuration)
Solar DC fridge	90 L (chiller), 80 L (freezer), 85 W capacity, COPR~1.3
System voltage	24 V
PV panels	2×200 W
PCM ice packs	Melting temperature: 4°C (fridge)×16 packs
PCM ice gel	Melting temperature: −12.7°C (freezer)×3 kg
Battery	2 units of 12 V×100 Ah
Solar charge controller	Tracer 6210AN, Voc range 100 V
Solar DC cable	4 mm², double-insulated, UV-resistant
Battery DC cable	10 mm² DC cable
MC connector	MC4 Connector
Earthing system	LV DC earthing with <10 ohm resistance

Abbreviations: COPR: Coefficient of performance for refrigerator; DC: Direct current; LV: Low voltage; MC: Multi-contact; PCM: Phase-change material; PV: Photovoltaic; Voc: Open-circuit voltage.

Figure 3. Proof of concept prototype installed at the test house at Solar Energy Research Institute Malaysia: (left) The installed solar PV panels, (middle) the solar DC fridge with the BOS and battery storage, and (right) PCM packs in the fridge.
Abbreviations: DC: Direct current; PCM: Phase-change material; PV: Photovoltaic.

to enhance the thermal energy storage performance of the system under real operating conditions. The temperatures in the fridge and freezer compartments were measured using Type-K thermocouples with sensitivity values of ±2.2°C. The thermocouples were placed at three different locations in the fridge and freezer compartments. The average temperature was calculated based on the collected data of the sensors located at three different locations in the fridge. The temperatures were measured and collected using a data logger at 1-min data interval. Meanwhile, the weather data (solar radiation and ambient temperature) were measured using those from the Vantage Pro2 weather station set at 1-min data intervals.

2.3. Preliminary and post-installation semi-structured interview with the locals

Following the lab testing, the system was tested for three different sites representing rural areas with differing requirements. On selecting the location, semi-structured interviews were conducted to ensure that the locations are justified. Bintulu, located in Sarawak, Malaysia, was selected as the location for installation with the following case study examples:

(i) Sekolah Kebangsaan Labang: For chilled water and food storage for school children
(ii) A grocery shop: Addressing limited freezer space and unreliable electricity for villagers
(iii) A rural farm: Supporting fish storage in an off-grid setting.

Semi-structured interviews with local users were conducted before and after installation to assess user needs, challenges, and feedback.

2.3.1. First case study location: Sekolah Kebangsaan Labang, Kampung Labang, Bintulu, Sarawak

Four teachers from Sekolah Kebangsaan Labang, a primary school in the region, were interviewed. The semi-structured interview questions are as follows:

(i) How is the electricity supply at the school?
(ii) Are there any issues with the electricity supply?
(iii) Is there any urgent need for an additional fridge system powered by solar panels?
(iv) Are there any issues with heat stress?
(v) Are there any issues with food storage or spoilage during blackouts?

The interviews with the school teachers and head teacher revealed that while the electricity supply had improved significantly over the past 2 – 3 years, irregular blackouts still occurred due to the school's remote location. Previously, the school relied entirely on a generator set, but grid access has now provided a more stable supply. However, power outages remain a concern. The teachers further noted that blackouts are often caused by adverse weather conditions, such as heavy rain, floods, or fallen trees, which disrupt the already vulnerable power infrastructure in the area.

Given the limited and unstable nature of the electricity supply in deep rural regions, it is essential to carefully monitor and manage the electrical load, particularly for energy-intensive appliances like refrigeration systems, to prevent overstressing the grid. In addition, there are currently no educational programs at the school aimed at introducing solar energy or clean energy practices to students and the local community. The teachers highlighted that incorporating such educational initiatives would benefit the community, by raising awareness and encouraging sustainable energy adoption. Finally, the hot and humid climate poses health risks for students, particularly during outdoor activities. To address this, the teachers emphasized the need for a chiller for drinking water, which would provide much-needed relief. However, it is essential to ensure that such a solution does not place additional stress on the already-fragile electrical supply. The teachers believe that a solar-powered water chiller would be an ideal solution, as this could provide chilled drinking water while maintaining energy efficiency and reliability.

2.3.2. Second case study location: A grocery shop at Kampung Labang, Bintulu, Sarawak

The semi-structured interview questions posed to the grocery shop owner, per Figure 4, are as follows:

(i) How often do you experience blackouts or power outages?
(ii) Why are there so many freezers in the grocery shop?
(iii) How often do the locals store their meat and perishable food at your shop?
(iv) Do you think a solar fridge would be useful for your shop?

Findings from the interview are summarized as follows. We found that the grocery shop plays a critical role in addressing the food storage needs of the local community, due to limited freezer capacity and unreliable electricity at the villagers' homes. This dependence ensures the preservation of perishable food but highlights the challenges associated with inconsistent refrigeration access. In addition, high transportation costs make frequent trips to the city to purchase fresh food financially burdensome and impractical, further increasing reliance on the shop for local storage solutions. Villagers from neighboring areas, who stay close to the school during weekdays to care for their children, also store their perishable goods at the shop, benefiting from the owner's generosity, as he provides this service at no cost. However, the grocery shop faces frequent power outages, which are typically caused by an overloaded electrical supply from running multiple freezers. These disruptions pose a risk of food spoilage and operational challenges. Recognizing these issues, the shop owner expressed strong support for a solar-powered freezer system, emphasizing its potential to reduce the electrical load, provide reliable food preservation, and sustainably meet the community's needs.

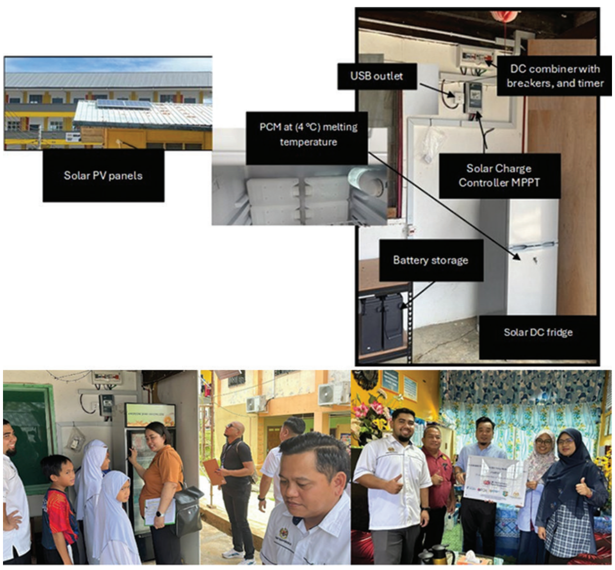

Figure 4. Photos of the installed system and photos during the briefing of the solar-powered fridge system with PCM storage for the school community.
Source: Photos are reproduced with permission.
Abbreviations: DC: Direct current; PCM: Phase-change material; PV: Photovoltaic.

2.3.3. Third case study location: A rural farm at Bintulu, Sarawak

The semi-structured interview questions posed to the farm owner were as follows:

(i) Do you have any difficulties managing your farm?
(ii) Do you think solar fridges will be useful for your farm?

The interviews with the farm owner revealed significant challenges arising from a lack of access to electricity, as the farm is located in a sparsely populated area, making it economically unfeasible to extend the electrical grid. Furthermore, the farm is situated on private land, where receiving public utility services is a challenge, further intensifying the lack of infrastructure. Operating as a small-scale farm, the owner faces constraints in financial and technical resources, limiting the ability to adopt advanced energy solutions. Furthermore, the absence of electricity poses critical challenges for essential farm operations, including irrigation, lighting, and the preservation of perishable products such as harvested fish, thereby reducing productivity and income potential. The farmer emphasized the urgent need for a reliable electricity source to address these issues. A solar-powered fridge system has been identified as a highly beneficial solution, providing a reliable method for storing fish and other perishable goods while maintaining freshness until they can be transported or sold. In addition, solar energy could support basic farm operations, such as powering lighting systems and water pumps, enhancing overall productivity and working conditions on the farm.

3. Results and discussion

3.1. Material selection

3.1.1. For the freezer compartment

Figure 5 presents a comparative analysis of the melting temperatures for the synthesized PCM ice packs, namely, PCM 1 – 6. The graph explains 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.

By systematically varying the proportions of glycerine and alcohol in these PCM formulations, we synthesized PCM ice packs with a range of melting points. This diversity has allowed for the selection of a PCM with a melting point tailored to specific temperature regulation requirements.

Based on the thermal analysis and melting point investigations, we chose to utilize the PCM ice gel with a melting point of −12.7°C as the PCM for our refrigeration system's freezer compartment. This particular PCM formulation was selected due to its ability to maintain temperatures that are congruent with the refrigeration requirements for extended periods, which is especially beneficial for thermal management.

3.1.2. For the chiller compartment

Meanwhile, for the chiller compartment, PCM A4 ice packs from PCM Products Limited.[19] were selected. The PCM A4,

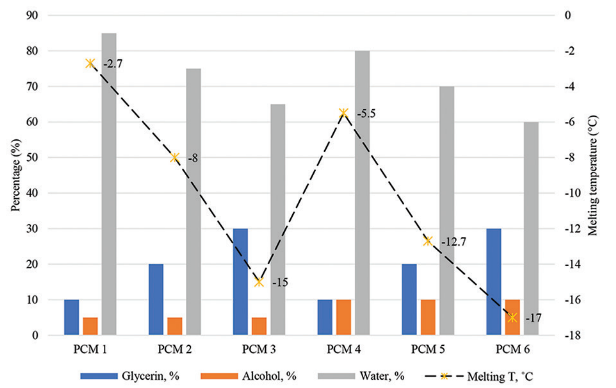

Figure 5. Melting temperature comparison among six phase-change material ice packs. Note: Melting T indicates Melting temperature

in a small size as shown in Figure 6, was encapsulated in a 150 mm × 80 mm container, with a cooling capacity of 15 Wh per pack. The phase change temperature was recorded at 4°C. PCM A4 was selected as it aligns with the average temperature requirements of the chiller compartment, meeting both food and medicine storage standards, by which chilled food should be stored at or below 5°C, and any food above 8°C should be rejected.[20] Meanwhile, a similar range of temperature between 2°C and 8°C must be met as these are the guideline for medicine storage.[21]

3.2. Preliminary field testing analysis

Figure 7 and Table 4 show comparative analyses of the solar-powered fridge with and without PCM thermal storage when operated entirely by solar panels. The experiments, conducted under real conditions, have demonstrated that the integration of PCM significantly improved the thermal stability of the system. In the chiller compartment, the average temperature was maintained at 6.37°C, attributed to the latent heat properties of PCM pack A4, which underwent phase change at 4°C, ensuring consistent cooling and minimizing fluctuations. In the freezer compartment, the system with PCM limited the maximum temperature to −5°C during periods of low to zero solar irradiance, while without PCM, the temperature rose to 3.02°C, failing to maintain freezing conditions.

The system was evaluated based on three key parameters: average peak temperature, rate of temperature increase, and thermal performance under intermittent solar power. To reduce reliance on electrical battery storage, a 12-h operational period was chosen, replacing part of the battery storage with thermal energy storage using PCM packs. The system's performance was then compared with

Figure 6. Examples of PCM A4, also known as IcePACKS, in different sizes by PCM Products Limited[19]
Abbreviation: PCM: Phase-change material.

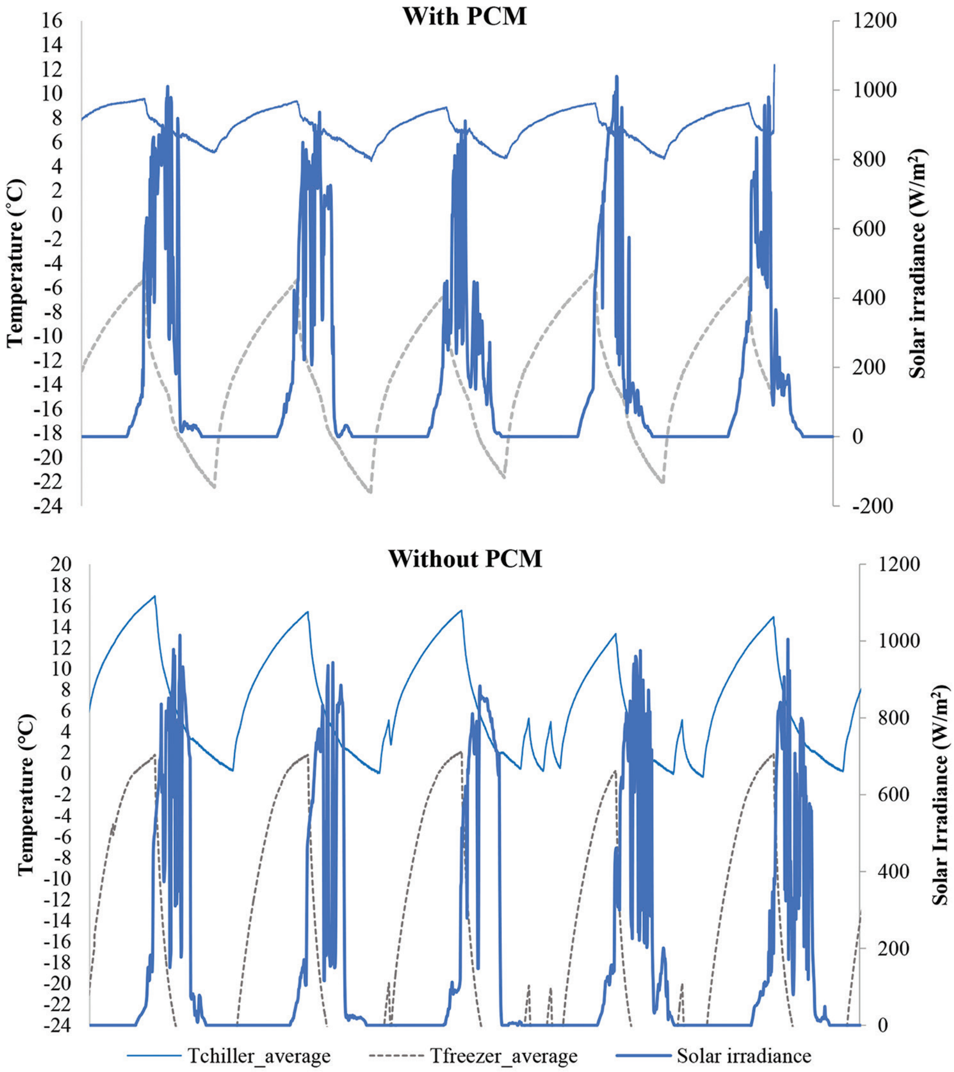

Figure 7. Preliminary findings from the solar-powered fridge with (top) and without (bottom) integrated phase-change material packs

Table 4. Comparison between the fridge with and without PCM thermal batteries

Parameter	With PCM pack A4 in the fridge and PCM pack (−12.7°C)	Without PCM thermal energy storage
Average peak temperature in the fridge section	6.73°C	14.09°C
Average peak temperature in the freeze section	−5.0°C	3.02°C
The rate of temperature increase	0.33°C/h	1.21°C/h

and without PCM. The results showed that in accordance with the first law of thermodynamics, the PCM packs effectively prevented overcooling during power availability and mitigated sharp temperature increases during power interruptions, while maintaining a similar coefficient of performance of the fridge (~1.3).

It is important to highlight that the chiller compartment without PCM experienced overcooling during periods of power availability, followed by a rapid temperature increase when the compressor was off during power outages. In contrast, the solar-powered fridge system with PCM avoided these issues, by storing excess cooling in the PCM packs. This design prevented unnecessary overcooling and stabilized temperatures during periods of low or zero solar power. The PCM-enabled fridge system demonstrated superior temperature performance. The chiller compartment with PCM achieved an average peak temperature of 6.73°C, compared to 14.09°C without PCM, while the freezer section maintained a peak temperature of −5.0°C, outperforming the non-PCM configuration. In addition, the rate of temperature increase was significantly lower with PCM at 0.33°C/h, compared to 1.21°C/h without PCM.

These findings highlight the effectiveness of PCM thermal energy storage in maintaining stable temperatures, reducing temperature fluctuations, and mitigating the adverse effects of power interruptions, particularly during periods of low or zero solar irradiance. The integration of PCM not only enhances the system's reliability but also ensures more consistent cooling performance under varying solar power conditions.

3.3. Real case study system design and installation

As discussed in section 2.4, the selection of locations for the real-case study installations has been justified. Three different systems were designed, representing a solar-powered fridge for a 300 L freezer, a 200 L chiller, and a 50 L chiller, intended for a grocery shop, a school, and a farm, respectively. During the preparation for system installation, available data for Bintulu, Sarawak, were used in MATLAB to predict the performance of the PV panels and ensure sufficient power supply for the system. A summary of the designed system's analysis is presented in Table 5. Each system, both with and without PCMs, was analyzed and compared to highlight the advantages of the solar-powered fridge system with PCMs. It is important to emphasize that incorporating PCM storage significantly reduces costs by lowering the reliance on solar PV panels, set in this study at a capacity of 350 watts, and by greatly reducing the need for electrical battery storage. This highlights the significant advantage of the solar-powered fridge PCM system, since electrical batteries have a significantly shorter lifetime than the PCM storage lifetime, cost 80% more, and are less environmentally friendly. The economic perspective will be further elaborated on in section 3.5.4.

3.4. Preliminary impact assessment

A simple impact assessment involving qualitative outcomes was conducted to identify and predict the initial impact of the installed solar refrigeration cooling systems. Semi-structured interviews were conducted with relevant stakeholders.

3.4.1. First case study location: Sekolah Kebangsaan Labang, Bintulu, Sarawak

After the installation of the solar-powered fridge system with PCM storage, the following activities were conducted at the school, namely, (i) system introduction and briefing for the teachers and students; and (ii) semi-structured interviews post-installation.

For the semi-structured interviews, teachers were asked the following questions:

(i) How do you think the installation of the solar-powered fridge with PCM storage influences the overall awareness of renewable energy technology within the school community?
(ii) How much will the chiller impact the well-being of the school children with the element of sustainability, considering that the chiller will not run out of power?
(iii) Will the school serve as a model school for other deep rural schools in Sarawak?

The school greatly appreciates the initiative, as it offers the school community use of the solar fridge. The

Table 5. The sizing of the solar-powered cooling system with and without PCM

Type of cooling storage	200 L chiller of 100 Watt[a]		300 L freezer of 85 Watt		50 L fridge of 50 Watt	
	PCM	No PCM (Conventional solar-powered fridge)	PCM	No PCM (Conventional solar-powered freezer)	PCM	No PCM (Conventional solar-powered fridge)
Solar PV panel (Pmax=350 Watt, Voc=45 V)	3 units	6 units	3 units	5 units	2 units	3 units
Solar charge controller	24 V 100 A	24 V 60 A	24V 50A	24V 80A	24V 30A	24V 50 A
Electrical battery storage	2 units of 12V 200 Ah battery in parallel.	4 units of 12V 200 Ah battery storage arrange in parallel and series	2 units of 12V 100Ah battery in parallel	4 units of 12V 200 Ah battery storage arrange in parallel and series	2 units of 12V 100 Ah in parallel	4 units of 12V 100 Ah battery storage arrange in parallel and series
Balance of system	1 unit (Lump sum)					
PCM storage materials	14 PCM packs of A4	0	3 kg of PCM 5 (at melting point temperature of–12.7°C)	0	7 PCM packs of A4	0

Note: [a]The door is transparent, thus heat loss is higher.
Abbreviations: PCM: Phase-change material; Pmax: Maximum power produced; PV: Photovoltaic; Voc: Open-circuit voltage.

introduction of the solar-powered fridge system with PCM storage has been well received, providing an opportunity for the school community to learn about sustainable energy solutions and the benefits of using a solar fridge. This exposure is significant in promoting environmental awareness and encouraging the practical application of renewable energy technologies.

In addition, the students now have chilled water readily available during outdoor activities. This immediate benefit is particularly valuable in the hot and humid climate, helping keep students hydrated and healthy. The school has also become a model school in the region. Teachers have become more aware of solar fridges and PCM storage packs. This increased knowledge has improved their teaching and sparked further interest in sustainable technologies.

During the briefing session, students were exposed to the solar fridge system and solar energy concepts, including the practical use of ice packs. According to the survey, most of the students, who come from rural areas and stay in the school hostel, expressed inspiration to share this knowledge with their families in the even more remote areas. Furthermore, as reported by the head teacher, the school has positioned itself as a model for other deep rural areas. The successful adoption of innovative solar technology demonstrates how such solutions can effectively improve living conditions and promote sustainability in remote regions.

Quantitatively, it is estimated that the model can be replicated in over 50 similar schools in the region, benefiting a large number of rural communities. In addition, the likelihood of students experiencing dehydration during outdoor activities has significantly decreased, with all students expected to have access to chilled water. In addition, the system contributes to energy and electricity savings, with an estimated reduction of approximately 10 kWh of energy consumption per year.

3.4.2. Second case study location: A grocery shop at Kampung Labang, Bintulu, Sarawak

As mentioned earlier, it is too early to measure the full impact of the solar-powered fridge system with PCM storage, as the post-installation phase remains in an early stage. A simple impact analysis was conducted through a semi-structured interview with the grocery owner to identify the immediate impact of the fridge.

The following interview questions were asked:

(i) Do you think the solar fridge is useful?
(ii) What are your expectations?
(iii) Will you store food from local people in your freezer?
(iv) Do you think this system will help to reduce your overall energy consumption?

From the interviews, valuable qualitative and quantitative insights were gathered. Initially, the grocery owner expressed some skepticism about the freezer's ability to retain its freezing temperature using solar power and PCM packs. Consequently, they had not yet stored meats or other perishable items. However, after a second visit and detailed briefing, the owner became more confident, as the PCM packs were observed to remain frozen even during the day, demonstrating the system's reliability. The owner confirmed that all food brought by the local community would now be placed in the solar freezer, highlighting the fridge's role in supporting local needs. In addition, the local community showed a keen interest in the solar freezer system, with many requesting contact details for the local solar supplier and installer, indicating growing awareness of and potential demand for this technology.

From a quantitative perspective, initial calculations revealed that operating the freezer for 24 h resulted in an energy saving of approximately 900 Wh daily, translating to a monthly saving of MYR 266.60 at the average cost of per kWh in Malaysia. This demonstrates significant energy cost reductions for the grocery owner, showing the system's potential to reduce overall energy consumption and operational expenses.

3.4.3. Third case study location: A rural farm at Bintulu, Sarawak

To identify both qualitative and quantitative impact analysis, a semi-structured interview was conducted with Mr. Morshidi, the owner of the rural farm we surveyed. The following questions were asked:

(i) How has the solar-powered fridge system with PCM storage helped you manage and store perishable items such as harvested fish?
(ii) How has the availability of reliable electricity changed your work activities on the farm, such as the time you spend here and the tasks you can complete?
(iii) Have you noticed any reduction in food spoilage or improvements in productivity since using the system?
(iv) Do you think this system would benefit other farms in the area, and what would you share with them about your experience so far?

From the interview, the farm owner provided qualitative insights into the changes observed after the installation. He highlighted that before the system's installation, their activities were restricted due to a lack of reliable electricity, limiting their ability to store perishable food and manage farm operations effectively. Since the installation of the solar-powered fridge system with PCM storage, the farm owner and his team can now extend their time on the farm to 2 – 3 days a week, compared to shorter visits previously. This extended working time has allowed them to plan their activities better and carry out more tasks efficiently.

Furthermore, the system has enabled them to store harvested fish and perishable food items, ensuring they remain fresh for longer periods. Mr. Morshidi emphasized that the reduction in food spoilage was a key challenge in their operations. In addition, the solar PV system supports other essential appliances, such as lighting and water pumps, which are critical to fish harvesting and overall farm management. The increased reliability of power has positively impacted their daily operations and productivity, with a strong indication that the system could support more sustainable farming practices.

From a quantitative perspective, initial observations and estimates have revealed tangible improvements. The farm team now spends 2 – 3 days per week on-site, compared to shorter, constrained visits before the system's installation, allowing for more efficient farm management. While exact figures are not yet available, the farm owner observed a noticeable reduction in food spoilage, particularly with harvested fish, due to the ability to keep perishable items fresh for longer periods. The solar-powered system ensures reliable energy access, enabling continuous operation of the fridge and supporting essential appliances such as lighting and water pumps, which are critical for fish harvesting and overall farm activities. Furthermore, he believes that the system has strong potential for scaling, and could benefit other farms facing similar challenges. This shows promise for replication and widespread adoption in rural settings.

3.4.4. Economic viability and sustainability

In this study, we have implemented the levelized cost of cooling (LCOC) (the cost of cooling per kWh cooling), a crucial parameter for economic evaluation, to compare between the solar-powered fridge with PCM storage and the conventional solar-powered fridge system. The LCOC was computed using Equation I:[22]

$$LCOC = \frac{I_o + \sum_{j=1}^{n} \frac{M_j + F_j}{(1+d)^j}}{\sum_{j=1}^{n} \frac{Q_{cooling}}{(1+d)^j}} \quad \text{(I)}$$

Where I_o, M_j, and F_j is the initial investment, maintenance, and fuel costs in the j th year, respectively. The discounted rate d in this study is taken as 8%.

Table 6 summarizes the costs associated with the calculation of the LCOC. Note that to provide an overview of the economic benefits of the solar-powered fridge system with PCM, the items involved in the calculation for the initial investment cost and the operation and management costs for a 200 L cooling system were included (assuming the same cost for the fridge and freezer integrated with PCM storage packs). A detailed analysis is not possible due to the current maturity level of the installed system. However, the implications of installing the solar-powered fridge with PCM can be projected using the LCOC over a 15-year lifetime.

The analysis shows that the cost of cooling for solar-powered fridge with PCM storage is only 27 cents USD/kWh, which is almost 70% lower than that of a conventional solar fridge system. This significant cost reduction is primarily due to the decreased need for extensive electrical battery storage, which mostly has now been replaced by the PCM ice packs. These ice packs are much cheaper and do not degrade as rapidly as electrical batteries, as can be clearly seen from the annual maintenance and capital cost of the systems.

For instance, a typical low-cost lead-acid battery with a DoD of 50% generally has a lifespan of only 1.5 – 2 years. In contrast, PCM ice packs offer a more durable and cost-effective solution, as they do not suffer from rapid degradation and require less frequent replacement. This durability contributes significantly to the lower operational costs of solar-powered fridge with PCM storage. In addition, the simple payback period analysis shows that solar-powered fridge with PCM storage outperforms conventional solar-powered fridge systems with payback period of only 6 years, which is 4 years lower than conventional solar-powered fridge. The shorter payback period indicates that solar-powered fridge with PCM storage is both more economical in terms of energy consumption and also more financially viable in the long run. This makes it an excellent choice for remote or rural

Table 6. Costs associated with total initial investment, operation, and management

Item	Estimated cost (USD)
Solar PV panel system (charge controller, DC cabling) without PCM	2,000
Solar PV panel system (charge controller, DC cabling) with PCM	1,200
Electrical battery storage (for the system without PCM)	1,200
Electrical battery storage (for the system with PCM)	600
PCM ice packs (for PCM-integrated system)	400
Annual maintenance cost without PCM	374.15
Annual maintenance cost with PCM	98.60

Abbreviations: DC: Direct current; PCM: Phase-change material; PV: Photovoltaic.

areas, where maintenance and replacement of battery storage systems can be challenging and costly.

4. Conclusion

The present study was conducted to explore both the social and technical aspects of using solar-powered refrigerators with PCM storage in rural areas, where reliable and sustainable cooling is essential due to limited electricity availability and logistical constraints. To achieve this aim, the study included experimental investigations focusing on material selection and lab-scale testing under real conditions to validate the system design, which was developed using computer programming software. These efforts were undertaken to ensure that the system's sizing and performance would be sufficient for installation in rural locations.

From a technical perspective, the study validated the system design and performance through experimental testing under real-world conditions. Key technical outcomes include:

(i) *Material selection*. PCM ice packs with a melting temperature of −12.7°C were used for the freezer compartment, while PCM A4 ice packs with a melting temperature of 4°C were selected for the chiller compartment. The customized PCM materials effectively maintained stable temperatures, with the freezer achieving a peak temperature of −5.0°C and the chiller maintaining an average temperature of 6.37°C.

(ii) *Thermal performance*. The integration of PCM storage significantly reduced temperature fluctuations, with the rate of temperature increase measured at just 0.33°C/h, compared to 1.21°C/h without PCM. This highlights the effectiveness of PCM in ensuring consistent cooling, even during periods of low or zero solar irradiance.

(iii) *Efficiency*. The system demonstrated energy savings of approximately 900 Wh/day in real-world conditions, translating into reduced operational costs and environmental impact. The calculated LCOC for the system with PCM was 27 cents USD/kWh, which is nearly 70% lower than that of the conventional solar-powered fridge systems reliant on battery storage.

The need for the installed system has been clearly emphasized through pre- and post-installation semi-structured interviews. The findings clearly highlight the relevance and significance of solar-powered refrigerators with PCM storage:

(i) The use of locally available materials for PCM storage provides valuable insights into their potential as a cost-effective and sustainable solution for cooling applications in remote areas.

(ii) The system was tailored to meet the diverse needs of rural communities, including grocery shop owners, farm owners, and schools, effectively addressing the unique challenges faced by these groups.

(iii) The integration of PCM storage with solar-powered refrigeration ensures reliable cooling while reducing dependency on costly and environmentally unfriendly battery storage. Initial skepticism from end-users was overcome, and the system gained their confidence, encouraging the prospect of further expansion.

In economic terms, the integration of PCM storage significantly reduced dependency on expensive and less sustainable battery storage. The system's payback period was calculated at 6 years, which is 4 years shorter than that of the conventional solar-powered fridge systems. This makes the technology not only more affordable but also more accessible for rural communities.

The findings of this research justify the technological need for solar-powered refrigeration systems with PCM storage and demonstrate the preliminary impacts of their installation under real-world conditions. Furthermore, this study also addresses a practical methodological gap, which has been identified as a barrier to the widespread implementation of this technology, thereby contributing to its accelerated adoption and broader application in rural settings. Future research should be conducted focusing on the quantitative analysis from the post implementation of the proposed solar-powered refrigeration technology with PCM storage.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

For this study, which was conducted in rural villages in Malaysia, the participants were fully informed of the study's purpose, and consent was obtained before their involvement. In addition, no personal identification data such as national ID and names were collected during the survey and the questionnaire has been assessed by the funder.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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