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REVIEW ARTICLE

Role of Phase Change Material in Implementing Renewable Energy for Small Scale Residential Cooling Appliances

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ABSTRACT – One of the main solutions to energy and environmental problems is to offer cooling using renewable energy sources (RES). However, in the utilization of RES, appropriate energy storage systems are required to overcome the intermittency issues of RES. Phase change materials (PCMs) play a vital role in implementing RES in low-temperature cooling applications, and several studies have reported their advantages and limitations. This review article aims to provide a comprehensive evaluation of current studies on PCM selection, applications, advantages, and the scope of further research to effectively utilize RES for cooling applications. We reviewed recent articles related to theoretical, numerical, and experimental studies on PCM-based solar cooling systems, including transport refrigeration, food outlet chilling, and commercial building cooling. A rigorous examination and summarization of the literature provides a comprehensive overview of the PCM's involvement in enhancing the performance of refrigeration systems. Compared to conventional systems, the inclusion of PCH enhances off-time temperature maintenance by more than six times, reduces pulldown time by up to 78%, and results in energy savings of up to 18.5%. Furthermore, PCM allows the refrigerators to work at the required temperature even after sunshine hours with 8–15% less energy consumption and without battery storage. However, further studies using the recently developed PCMs can determine the performance of system components and their potential application in various sectors of the refrigeration industry in the coming years.

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1. INTRODUCTION

Since energy is a necessity for humans and practically all industrial activity comes to a halt without it, finding an unending source of energy will always rank among the most significant objectives in human life[1]. However, the energy produced by fossil fuels has a serious impact on the environment. Therefore, using renewable energy sources (RES) is an attractive option to reduce emissions of global warming gases [2], [3]. The sources of "renewable energy" are natural resources, which are infinitely renewable. Renewable sources include wave, solar, geothermal, wind, biomass, hydropower, and tidal power [4]. People prefer solar energy to other RES because it has economically viable energy content and low environmental impact [5], [6]. Most countries now acknowledge solar energy as having significant promise due to its cleanliness, low cost, and universal availability. Solar power plants are among the commercial applications. Sweden has had a solar power facility in operation since 2001 [7]. The demand for cooling systems in recent times has led to a steep increase in energy demand in numerous countries [8]. In underdeveloped nations, there is not enough electrical energy or storage to support cooling needs. As a result, solar cooling solutions have attracted attention on a global scale.

The global energy landscape has created an opportunity for solar energy to handle peak electrical demand as well as cooling difficulties [9]. Since solar energy is dependent on weather-related natural phenomena, it is challenging to manage the supply. Storing solar energy not only reduces the need for fossil fuels but also gradually lowers the cost of system upkeep, ultimately eliminating energy waste. There are many different types of energy systems [10]. Figure 1 illustrates the various energy storage methods. Thermal energy storage (TES) is the most efficient technology [11]. Thermal applications can receive solar energy for the entire day through TES. We can utilize systems like batteries or phase change materials (PCMs) to store energy. Researchers and customers are opting for PCMs as an alternative due to the severe limitations of batteries' energy storage capacity (kWh) [12]. The PCM stores and releases energy during the phase transformation. The latent heat of fusion occurs more frequently in PCMs [13]. The PCM should have high latent heat, high thermal conductivity, and an appropriate melting point [14].

The primary benefits of PCMs include a decrease in temperature fluctuations and an enhancement in system performance. Therefore, the use of PCMs in low-temperature operations has increased significantly in recent years [15], [16]. Several studies propose innovative methods to regulate the temperature fluctuations of food in refrigerated trucks, including the application of latent heat thermal energy storage (LHTES) materials, such as low-temperature PCMs [17]. The food industry is increasingly using PCM to save energy, boost productivity, and enhance thermal performance. Food preservation and transportation chilling are the two primary uses of PCM in the food business. Changes in temperature,

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particularly in non-refrigerated systems, can have a negative impact on the quality of food. To safeguard and preserve the quality of food, the storage and transportation of temperature-sensitive commodities require precise thermal control. Using the appropriate PCMs during the cooling, shipping, and packaging processes can help with thermal control [18].

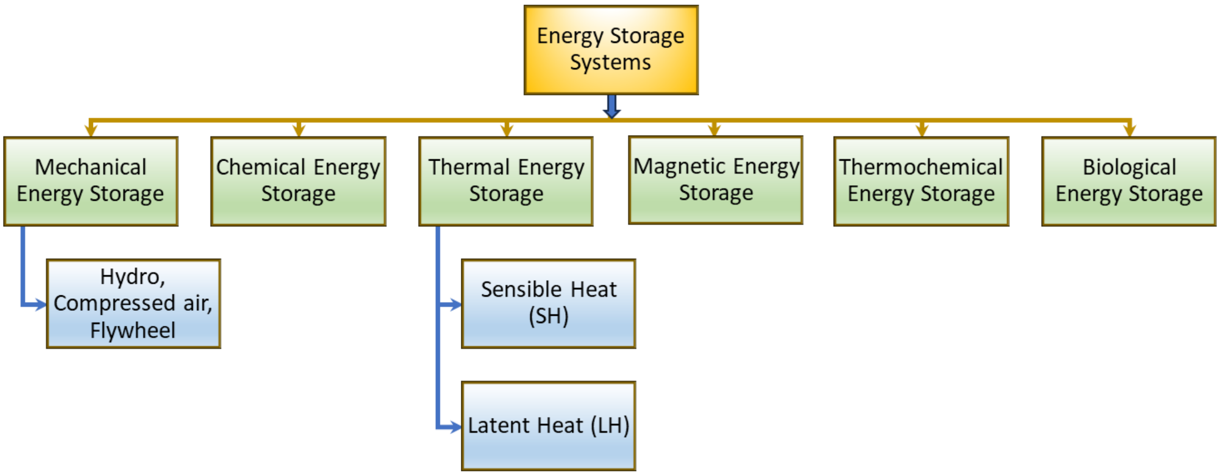

Figure 1. Schematic representation of various energy storage systems

PCMs work in cold chains to efficiently implement renewable power, emissions reduction, green energy use, and economic transport. The PCM's ability to sustain the conditioned space temperature for longer durations contributes to improving the efficiency of the cold chain logistics system [19]. The technologies used in the encapsulation of PCMs and their orientations play a key role in the performance of refrigerators. PCMs in cascade cladding have a positive impact on the performance of household refrigerators [20]. Solar refrigerators need PCM to overcome the issues related to batteries and the non-stable supply of energy from renewable sources [16]. An appropriate method of PCM cladding can maintain a solar refrigerator's stable working temperature even after sunset [21]. Several experimental and simulation studies on small-scale refrigeration systems demonstrate the promising opportunity to clad PCMs in various components of household refrigerators, coolers, and air conditioners [22]. Placing PCM cladding between the wall insulation and cooling coil in the freezing cabinet enhances the system's coefficient of performance (COP). Furthermore, an appropriate use of PCM reduces the total equivalent warming impact (TEWI) of refrigeration systems [23]. To overcome the power issues and high investment and operating costs of solar refrigerators in remote places, PCM cladding is a promising strategy [24]. Researchers have looked at the properties of PCM, including water, organic and inorganic substances [25], and nanomaterials [26], to improve the performance of refrigerators by covering them on the side that has the evaporator and condenser.

The salient features of PCMs make their implementation a promising strategy for expanding the use of renewable energy sources in refrigeration, air conditioning, and food supply chain technologies. Even though several studies have analyzed the prospects of PCMs in various applications, this technology still requires maturity for effective implementation. This paper offers a comprehensive examination of phase change materials as a feasible energy-saving option and the application of renewable energy in cold storage equipment, such as freezers, refrigerators, refrigerated truck trailers, food refrigerated display cabinets, and other refrigeration devices used in food preservation. This review article focuses on four major areas to identify the research gaps and prospects of PCMs in renewable energy-based cooling systems. These areas include the current trends of various technologies used to implement renewable energy in cooling appliances, the current trends of PCMs for medium and low temperature applications, the effects of PCM on refrigeration system components, and the role of PCM in solar energy utilization. With suitable tables and figures, this article evaluated the merits and challenges encountered by the researchers. Furthermore, each section of this article highlights potential solutions and future directions. The overall observations and scope for future studies discussed in Section 6 provide possible directions for further research in this area.

2. CURRENT TRENDS OF VARIOUS TECHNOLOGIES TO IMPLEMENT RENEWABLE ENERGY IN COOLING APPLIANCES

Solar refrigeration technology refers to the use of solar power for cooling purposes [27]. There are two main ways to cool anything down. The first method focuses on cooling systems working with electrical power from solar photovoltaic collectors [28]. The second method employs a solar thermal refrigeration system, which uses a vapor absorption technique to cool the system rather than using electrically operated vapor compressors [9]. We assess the refrigeration system performance using these systems' energy indicators, as outlined below.

$$COP = \frac{E_u}{E_c} \tag{1}$$

where, Eu = Refrigerating usable energy (Refrigerating Effect) in kW

E_c= Energy consumed by system (Energy input to the system) in kW

The energy efficiency ratio (EER) in British thermal units per Watt-hours (Btu/Wh) is also defined by:

$$EER = 3.413COP \tag{2}$$

However, since a thermal solar collector in this review study directly converts light into heat, our main attention is on thermal solar cooling systems. For instance, Otanicar et al. [29] introduced the thermal systems. We must store thermal energy in a specific way for future use. This helps to shift the load to off-peak times and reduce the imbalance between supply and demand [30]. At a constant temperature, latent heat storage (LHS) works by storing and releasing heat during a substance's phase change. Solid-to-liquid phase transitions are typical. The melting process releases heat as the material transitions from a solid to a liquid phase. The term "phase change material" refers to materials that possess this property. The following formula [31] calculated the amount of heat stored:

$$Q = \int_{T_i}^{T_m} mC_p dT + mL_f + \int_{T_m}^{T_f} m\,C_p dT \tag{3}$$

where, m = Mass (kg), Cp = Specific heat (kJ/kg K), L = Latent heat (kJ/kg), T_i, T_f and T_m are initial, final, and melting temperatures (K)

Increasing a solid or liquid substance's temperature in order to store heat is known as Sensible Heat Storage(SHS) [32]. The following formula can be used to calculate sensible heat:

$$Q = mC_p(T_f - T_i) \tag{4}$$

One benefit of LHS is its high storage density at an almost constant phase change temperature. In comparison to SHS, LHS uses less volume and material for a given amount of energy. For example, organic PCMs such as LHS require 5300 kg of mass to store 106 kJ of energy, while water such as SHS material requires 16000 kg [32].

2.1 Thermal Solar Cooling Systems

The direct conversion of solar radiation to heat favors solar thermal refrigeration (STR) over PV-based cooling techniques. Otanicar et al. [29] proposed a thermal system that can absorb over 95% of the sun's incident radiation, depending on the type of heat transfer medium. Figure 2 presents a schematic representation of STR. A STR system consists of four components: a heat exchanger, a sorption cooling system, a thermal storage tank, and a solar collecting array. After absorbing solar light energy, the thermal collector heats up, which causes the heat transfer fluid (HTF) inside its evacuated tubes to warm up via heat convection. The thermal air conditioner runs on vapor adsorption or vapor absorption units, which take heat from the thermal storage tank. Heat exchangers are necessary to transfer heat between different temperature compartments, including generators and evaporators [27].

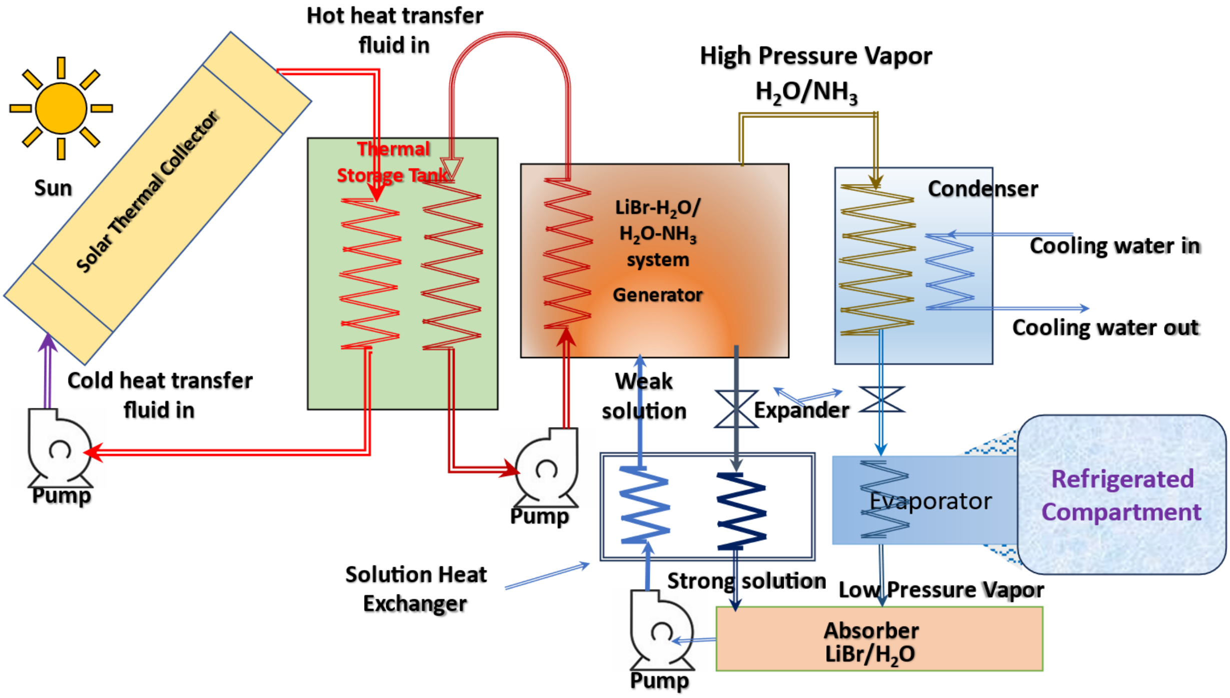

Figure 2. Solar thermal cooling system's schematic diagram

Thermal cooling methods make use of sorption technology. The sorbent and refrigerant interact chemically or physically to provide a cooling effect. There are two basic types of sorption technologies: open sorption systems and closed sorption systems. Open sorption systems typically employ one of three desiccant technologies: liquid desiccant systems, solid desiccant systems, or desiccant solar cooling systems. Absorption refrigeration and absorption refrigeration are the two main strategies for closed sorption systems. In solar thermal absorption refrigeration, the tank attached to the solar collector serves as a heat source for the chiller. We can group the absorption systems as single, half, or double effects based on the regeneration of the solution and thermal operation cycles. The double-effect chillers work at a low temperature [33]. Two more absorption refrigeration techniques that provide superior performance are hybrid systems and diffusion absorption refrigeration (DAR) [34]. Adsorption cooling systems are an uncomplicated way to use solar energy. The efficiency of solar adsorption systems has been the subject of discussion among academics. Solar-powered adsorption systems using zeolite or water and activated carbon or ammonia have COPs of 0.1-0.12 and 0.5, respectively [35]–[38].

3. CURRENT TRENDS PCM FOR MEDIUM AND LOW TEMPERATURE APPLICATION

PCMs are a class of materials that use latent solid-to-liquid phase transitions. The considerable volume shift is difficult to regulate technologically, making other phase changes unattractive. Sharma et al. [31] have classified PCMs into three groups: organic, inorganic, and eutectic materials. The current study's primary target areas are the integration of PCM in home refrigeration and air conditioning systems, large-scale industrial refrigeration, supermarket refrigeration and air conditioning applications, and refrigerated transportation. Building applications [14], [39]–[43] and home refrigeration [44]–[46] have received the majority of PCM application research attention over the preceding 15 years.

3.1 Application of PCM in Transport Refrigeration

Scientists' interest in the food chain has grown dramatically in recent years [47]. Providing a constant space temperature to the cold chain is crucial due to complexities in food quality control and stopping microbial development [48]. Research relevant to this subject has shown significant fluctuations in temperature and humidity at every stage of the food cold chain, particularly during transportation [49], [50]. The packaged food products need a preservation temperature average of 2.0°C higher than the acceptable values for 30% of the items in the display cabinet and 40% in the home refrigerator [51]. Table 1 provides an overview of PCM applications in food packaging and transportation. Researchers have extensively researched the insertion of PCM into the walls of refrigerated containers using both experimental and computational approaches. The table illustrates the potential applications of various PCMs, such as organic, non-organic, synthetic mixtures, and nonmaterial materials, in enhancing system performance and extending the duration of temperature sustainability in refrigerated spaces. Furthermore, the observations in previous studies provide many opportunities for further research in this field.

PCMs and other multi-layer insulating materials have drawn a lot of attention because they have the potential to take on the role of the conventional sandwich wall in refrigerated vehicles [52]–[54]. The literature review suggests that employing a multi-layer PCM wall can reduce the maximum rate of heat transfer from the ambient space into the refrigerated chamber. The most performance-focused wall design is the classic sandwich wall, which uses copper pipes packed with PCM. The PCM packaging of medical products may have been essential for the secure and quick international transportation of temperature-sensitive medical supplies to clinics in light of the ongoing COVID-19 pandemic outbreak [55]. This would be critical in developing countries, where access to cold food chains and refrigeration is limited.

3.2 PCM Application in Food Outlet/Commercial Complex

Depending on the location, size, and percentage of chilled or frozen goods in the selling section, supermarkets typically use 35–60% of their energy for refrigeration [74], [75]. Commercial refrigeration systems can chill a vast array of equipment, including tiny plug-in vending machines, food service cooling devices, and display storage space. We also integrate PCM into large-scale, central supermarket refrigeration systems. This evaluation presents several CTES integration scenarios to which supermarket refrigeration systems can apply. The current studies are focusing on the use of PCM in the cold chain of supermarkets. This review also covers the most recent studies on PCM integration in various chilled beverage coolers and vending machines. Table 2 provides an overview of the literature review on PCM adoption in commercial refrigeration and the consistent research in this field. Finding a sustainable and economically viable PCM for commercial refrigeration is still under intensive investigation.

Table 1. Principal outcomes of PCM use in food packaging and transportation

PCM installation	Experimental (E) / Theoretical (T)	PCM (Tm [ºC])	Outcomes	Ref
Refrigerated wall	E	RT5 (5)	Peak heat transfer decrease (29.1%); Peak shift (between 2 and 2.5 hours); Average reduction in heat transfer (16.3%)	[56]
Vehicle refrigerator wall	T/E	PCM panel Energain (21)	Average 25% decrease in daytime heat transfer.	[52]
20-foot ISO container's side wall	T/E	RT35HC (35)	Peak shift lasts for three hours. The peak heat transfer reduction is 20%. The typical reduction in heat transfer is 4.5%.	[57]
Vehicle refrigerator wall	T/E	RT35HC (35)	Peak shift reduction in heat transmission (5.5 to 8.5%); peak shift (3.5 to 4.5 hours).	[54]
Vehicle refrigerator wall	T/E	Intertek Composite PU/PCM C18 (18)	(0.3 to 4.1%) average reduction in heat transfer	[58]
Food storage box	T/E	PT-15 (-15); RT-2 (2); PT-63 (63)	Increased storage time (380% to 400%)	[59]
jar for storing ice cream	T/E	E-21 (-21)	Product temperature declines while stored at room temperature (10 K)	[60]
jar for storing ice cream	E	E-21 (-21)	The product's surface temperature decreased to 17 K during a heat load test.	[61]
containers for chilled food	T/E	RT5 (5)	Enhanced capacity to withstand heat; 6.7% longer ham shelf life	[62]
Bags for packaging blood	E	Mixture of n-alkanes (4.8)	6 hours of proper storage temperature (8 times more)	[63]
PCM-HEX system for transporting chilled goods	T/E	Solution of inorganic salts in water (-26.8)	Cost savings of between 51 and 86.4% per year; storage stored at -18ºC for 10 hours	[64], [65]
Mobile refrigeration system	E	Sodium chloride, glycerol solution, water (-18)	Energy costs decrease from 74.2% to 91.4% during off-peak hours.	[66]
Railroad refrigerated container	E	Paraffin wax RT5 (5-12)	COP 1.84 and a maximum container discharge time of 94.6 hours.	[67]
Refrigerated container	T	RT3 HC1 RT5 RT8 HC (4-5)	Energy consumption decreased by 61%, 57%, and 35% with PCM.	[68]
Refrigerated truck	E	E-26, E-29, E-32 (-15)	Keep a refrigerated area at 5.1 hours at 81 km/h speed.	[69]
Portable box for cold chain	E	RTO, RT2HC, RT3HC, RT4HC, RT5HC, RT8HC	46.5 hours maximum cooling duration, and 90.7% highest discharge efficiency	[70]
Wall for refrigerated trailer	E	SP-24 (-20)	Maintained at 20ºC over 24 hours, whereas a 6 mm PCM layer reduced energy use by 86% in 22 hours.	[71]
Refrigerated truck box	T	RT3HC, RT5, RT8HC, RT10HC (-4)	Higher thermal efficiency by RT10HC, and 87.56% greater than RT3HC.	[72]
Vehicle refrigerator wall	E	Sodium carbonate decahydrate (SCD) composite PCM	Fruit preservation time extended with preparing PCM.	[73]

Table 2. Principal outcomes of PCM use in commercial refrigeration

Setup of the System	Theoretical (T) Experimental (E)	PCM (Tm [ºC])	Primary outcome (value)	Ref.
A shelf with a PCM	E	2% borax in deionized water (-0.5)	Defrosting causes the food's temperature to drop by 3.5 K and the temperature peak to drop by 1.5 K.	[76]
PCM-equipped cabinet	E	RT3 is 2.5, RT4 is 3.8, and RT5 is 5.2.	Product temperature difference was reduced by 80%, and product temperature fluctuation was reduced by 83.3%.	[77]
Air duct in cabinet with PCM	T/E	Nucleating agent-infused water (-2)	Reduction of 2 K from the maximum cabinet temperature; energy savings of up to 5%; reduced compressor start/stop cycles (27%)	[78], [79]
Cabinet with fin-tube PCM	E	Ice/water (0)	The maximum cabinet temperature has been lowered by 1 K	[80]
Cabinet air duct with PCM	T	Ice/water (0)	1.7 kW PCM-HEX cooling duty; 6 kWh of storage per meter of width; high storage capacity	[80]
Air duct with PCM	T	Ice/water (0)	Reduced maximum cabinet air temperature (10 K) during defrost	[80]
PCM in CO_2 refrigerator	T	Ice/water (0)	Reduction in total energy usage of 14.4% and a peak compressor power reduction of 50%	[81]
PCM in CO_2 refrigerator	T	Ice and water (0); PCM (15)	15% reduction in peak compressor power and a 5.6% overall energy consumption decrease	[82]
PCM in CO_2 refrigerator	T	Ice/water (0)	Energy savings (5% to 68%)	[83]
A bottle cooler's air ducts include PCM-HEX	E	Ice/water (0); RT4 (4)	Energy savings (4–10%) and increase in compressor cycle time (118%)	[84]
PCM bottle cooler	T/E	Ice/water (0)	The ratio of compressor on/off dropped from 36% to 26%.	[85]
PCM in dispenser of cold beverages	E	Ice/water (0)	reduction in energy use (15%)	[86]
PCM-based cascaded CO_2 refrigeration	E	Not Specified	Using PCM, reduce energy usage	[87]
PCM in supermarket refrigerators	T	HS01, E-3, RT0, RT2HC, A2, A3,	PCM HS01 reduces power consumption the most, and greater effect on valve opening and closing as well as compressor on/off switching.	[88]

4. EFFECTS OF PCM ON REFRIGERATION PERFORMANCE SYSTEM COMPONENTS

The type of thermal load, efficiency of system components, working refrigerant, and ambient conditions are the primary factors that affect how much electricity a residential refrigerator uses [89]. It can be challenging to reconcile the need for increased efficiency with the desire for lower costs. Refrigerators used in homes can have their performance improved and their ability to save energy increased by [90]:

- Using compressors with high efficiency
- Advanced circulation techniques for the optimization of control systems
- Increasing the thickness of the insulation or utilizing innovative thermal insulation materials can improve the system's thermal insulation.
- Enhancing the condenser's and evaporator's ability to transfer heat

Refrigerator manufacturers are dealing with two key issues: energy efficiency and environmental restrictions. As a result, a comprehensive examination of household refrigerators is required to determine their energy efficiency and degree of sensitivity to factors such as insulation type, ambient temperature, compressor size, and refrigerant type [91]. This article emphasizes the use of PCM in freezers to improve their efficiency. We refer to PCM thermal storage as green energy because it closely resembles a natural occurrence [92]. The PCM's isothermal energy storage method and high energy storage density make its fusion enthalpy suitable for a variety of thermal applications. Currently, PCM is one of the most promising methods for storing thermal energy. Utilizing this thermal energy in homes can improve food quality and refrigerator efficiency [46]. PCM adoption in refrigeration systems has two main objectives: reducing temperature fluctuations and increasing system performance [93]. Testing results show that during the cooling cycle, the fresh food compartment of the refrigerator can have temperature changes as low as 0.5 °C, from 4 °C [94].

4.1 PCM Thickness

The PCM thickness has a major effect on a refrigeration system's performance because an increase of approximately 40% in PCM was linked to an improvement in COP of 6% [95]. By prolonging the compressor's off time, increasing PCM thickness has the effect of decreasing the on-off time ratio [96]. The load should determine the PCM thickness, as thicker PCM applications incur higher costs and initially require more compressor effort to firm the PCM [93]. Marques et al. [44] employed a numerical model to examine the impact of PCM thickness on phase change duration. The PCM used pure water. The results also demonstrated that by adding a 5 mm PCM slab, the refrigerator could run continuously for three to five hours without a power source.

After selecting PCM, figuring out how much to use is essential. It is possible to determine the minimum volume of PCM [45], [97]]. The energy (E) stored in PCM in a compartment is determined by:

$$E = \rho V \lambda \tag{5}$$

The sensible heat variations in this equation are disregarded, while the PCM's density, minimum volume and enthalpy of fusion are represented by constants *ρ, V and λ,* respectively.

The inevitable heat gain that the compartment experiences from the surroundings is:

$$Q = (UA)_{Cold}(T_{ambient} - T_{Cold}) \tag{6}$$

where U is the overall heat coefficient in W/m^2 K, and A is the surface area in m^2.

The rate at which energy is transferred during the compressor's OFF time (t_{OFF}) is equal to the stored energy in PCM.

Consequently [45], [97], provides the PCM minimum volume:

$$V = \frac{t_{OFF}[(UA)_{Cold}(T_{ambient} - T_{Cold})]}{\rho \lambda} \tag{7}$$

During the off time of the compressor, PCM compensates for the heat transfer through the compartment walls, therefore the actual PCM need is typically more than that of *V*.

4.2 Effects of Phase Change Temperature (PCT) on PCM Performance

Refrigerators have two main goals: food preservation and maintaining a chilled space at the required low temperature. Therefore, the quality of the food and the effectiveness of the refrigeration system directly depend on the phase change temperature (PCT) of the PCM when used. The PCT is important because the selected PCM's melting point must be sufficient to work with the thermostat's temperature range. A PCM with a high PCT enhances the system's COP by consuming less energy. The increased temperature inside the compartment, however, has a negative impact on the food products and reduces their quality [98]. However, an extremely low PCT maintains an extremely low temperature within the storage cabinet, improving the food's quality. The cabinet's temperature must remain above zero to prevent food from freezing [84]. Therefore, to be considered acceptable, a PCT must maintain these two top and lower extremes. When selecting PCM, the PCT undergoes necessary modifications [93].

4.3 PCM's Impact on Thermal Loads

Because of the inverse relationship between refrigeration system performance and thermal loads, a refrigerator's performance declines as thermal loads rise. You can use PCM to enhance a refrigeration system's performance, but it is crucial to understand how PCM reacts to various loading conditions. According to Azzouz et al. [98], [99], even when PCM is present, the coefficient of performance (COP) decreases as the heat load increases. This is because there is insufficient time for phase shift to occur, increasing thermal stress and causing the PCM to partially melt [100]. Khan and Afroz [101] assert that an increase in thermal load lessens the sub-cooling effect of the condenser due to its higher working pressure and temperature.

4.4 Effect of Ambient Temperature on PCM's Performance

The temperature outside has a big impact on how well PCM works in the refrigeration system [93]. Higher ambient temperatures [88] lead to a decrease in the system's Coefficient of Performance (COP) due to increased condensation pressure, temperature, and cabinet air temperature. A high heat load affects the PCM's melting and freezing times, as well as its charging and discharging times. This is necessary for the compressor to withstand the heat load as well as the charging PCM [102]. Cold temperatures cause a decrease in PCM performance. When running with a low thermal load, the compartmental temperature drops more quickly. As a result, before the compressor cuts off, the PCM does not have enough time to solidify [101].

4.5 PCM Application in the Evaporator

The evaporator in a household refrigerator uses both forced and free (natural) convective heat transfer [103]. A naturally cooled evaporator has a low rate of heat transmission, which lowers the temperature inside the cabinet. However, the forced convection evaporators ought to have more stable temperatures. Conversely, forced convection has several disadvantages, including increased energy consumption and food weight loss due to the strong air movement [94]. To address these problems, the evaporator can benefit from PCM. The thermosyphon evaporator with the PCM works better than the forced cooled evaporator and provides additional cooling capacity [104]. The PCM extends the compressor's operating duration. As the PCT increases, the COP rises. However, because the refrigerator is self-sufficient and the melting of PCM ensures its cooling capability, it reduces the overall working time. Using PCM increases cooling capacity and COP by 87% and 74%, respectively[105]. Table 3 compiles the merits and limitations of PCM integration in an evaporator.

Table 3. PCM's benefits and drawbacks when used in an evaporator

Advantages	Disadvantages
• Performance improvement of systems [44], [98]–[100], [106], [107] • Assistance in the event of power disruptions [107]–[109] • Reduction of refrigerator noise [110]–[112] • Shorter overall compressor ON time ratio [98], [105] • Reduction in the consumption of electricity during peak hours [113], [114] • Decrease in overall cost [106]	• Higher condensing temperature [104] • Higher condenser to cabinet heat transfer rate • Longer cycle-long compression ON time [98], [105]

Azzouz et al.'s experiment [100] revealed that adding PCM in the refrigerator increased COP by 10% to 30%. The thermal load and the PCM's properties determined the degree of amplification. A refrigerator may function continuously without an electrical source for five to nine hours because of the enthalpy of fusion storage. In the PCM capsules, using eutectic aqueous solutions rarely compromises the system's ability to maintain chilled products. Khan and Afroz's experiment utilized a PCM-based fridge with only one door and an evaporator [115]. The study found that the higher evaporator temperatures for 5W and 10W loads increased COP, reduced compressor effort, and improved evaporator heat transfer. Depending on the thermal loads and PCM, we found that the higher evaporator temperatures were 2–5 °C higher.

4.6 Application of PCM in Condenser

A condenser is a heat exchanger. It rejects the refrigerator's heat compression in the surroundings [116]. Refrigeration systems commonly utilize three types of condensers: hot-wall, naturally-cooled, and forced-cooled [94]. PCM's primary goal at the condenser is to lower the temperature. However, compared to the broad range of trials conducted on the evaporator, there are comparatively fewer studies using PCM at the condenser. Using PCM on a condenser increases condenser heat transfer by lowering the condensation temperature, as it extends heat rejection to the compressor's OFF duration [100]. According to Sonnenrein et al. [117], applying PCM to the condenser lowers the condenser temperature while also significantly reducing power consumption. Wang et al. [116] conducted a series of experiments, utilizing various PCMs at different locations within a refrigerator. Wang et al. fitted PCMB, PCMC, and PCMA between the compressor and evaporator, the compressor and condenser, and the expansion valve and condenser. PCMA's position boosted sub-cooling and decreased condenser pressure. Overall, this system increased COP by approximately 6%. The PCMB's temperature dropped before it reached the expansion valve, and the COP increased by 8%. Finally, PCMC reduced the superheating by lowering the evaporator outlet temperature. The authors conclude that you can install the PCM heat exchangers in position A or location B, and they will remain functional. Further research is required to install a PCM heat exchanger in the C position without experiencing pressure drops. Table 4 lists the benefits and drawbacks of using PCM in condensers.

Table 4. The advantages and limitations of PCM use in condensers

Advantages	Disadvantages
• Higher COP [118]–[120] • Reduction in ON-OFF cycles [118], [120] • Lower condensation pressure and temperature [118], [121] • Greater degree of sub cooling[121], [122] • Refrigerator faster stable condition [123]	• Frequent ON/OFF cycles with a compressor [122] • More losses from displacement of refrigerant [119], [122] • Heat accumulation [4]

4.7 Application of PCM in the Compartments of Storage Systems

The compartment section of the refrigerator stores food and other products. Certain experiments have subjected this section of the refrigerator to PCM. PCM commonly covers the sides, floor, and top of the compartment section. A PCM located in the compartment section keeps the temperature safe, is closer to the food, and is more useful in the event of a power outage. When using PCM in this area, it is crucial to take space constraints into account. Due to the limited storage space, the PCM should not occupy a sizable percentage of it. When inserting PCM into the compartment area, it is important to consider its orientation. Marques et al. [124] examined the effects of the PCM slab's orientation inside the refrigerated space. In their study, they used computational fluid dynamics to evaluate placements that were horizontal, vertical, or a combination of both. The scientists observed a more uniform temperature distribution throughout the compartment when they positioned the PCM horizontally, as opposed to vertically. The best outcomes, on the other hand, came from combining the horizontal and vertical orientations; this enhanced air mixing from the horizontal PCM and produced a more uniform temperature distribution. In another study, Marques et al. [44] conducted a test on heat exchange in a PCM box situated at the top of the refrigerator's compartment section. The findings demonstrated that the PCM could run continuously without electricity for anywhere from three to five hours, depending on its thermal load [105].

Table 5. Overview of the recent experimental and theoretical studies on PCM in refrigeration systems

Sl. No.	Type of study	PCM type	PCM Placement	Parameter investigated	Result or Outcome	Ref.
1	E	Eutectic	Compartment	meat drip loss and ice crystal size	Using PCM, reduce meat drip loss and ice crystal size	[125]
2	T/E	Water	Evaporator	Compressor size and Thickness of PCM	When the electricity goes out, operations continue for 3-5 hours. A bigger compressor works well.	[44]
3	T/E	Eutectic	Evaporator	PCM’s melting point, thickness, and heat load	Gain of 5–15% in COP Thermal load affects the PCM selection.	[98]
4	E	Water & Eutectic	Evaporator	Phase change temperature PCM thickness thermal load	10–30% COP improvement depending on the thermal load over a 5–9 hour period during a power Loss	[99]
5	E	Water	Evaporator	Energy consumption Evaporator kind	Temperature increases in the evaporator, 8.4°C. 19.9% decrease in energy use	[103]
6	T/E	Water (plus-Ice 4^0C)	Evaporator & Compartment	Various PCM configurations	12% decrease in energy use, an 8% increase in COP, and stabilization the same temperature	[126]
7	E	Water & Eutectic	Evaporator	Thermal load, and PCM mass	Eutectic is superior to water by 20–27% COP improvement, depending on thermal load.	[115]
8	E	Eutectic	Evaporator & Compartment	Door opening Electrical power loss	Maintaining a 4-6 °C, at cabin during a 3-hour power Loss	[127]
9	E	Eutectic	Evaporator & Compartment	Phase change temperature Electrical power loss	Maintaining the proper temperature for the compartment and the air during a power outage	[127]
10	E	Eutectic	Evaporator	Temperature during phase change Increasing the surface area of the condenser	PCM's 9.4% energy savings are economical. Raising the temperature of the condenser and evaporator	[128]
11	E	Paraffin	Evaporating and condensing units	Temperature of the condenser and evaporator usage of energy	Lower condensing temperature More evaporative temperatures Reduction in energy use More compressors start and stop	[122]
12	T	Eutectic	Evaporating and condensing units	Condition of the condenser and evaporator because of PCM presence	Best results when applying PCM at both the condenser and the evaporator, saving 32% energy	[129]
13	E	Water & Paraffin	Evaporating and condensing units	Phase change temperature	Reduces the condensation temperature 10% electricity savings	[130]
14	E	Eutectic	Evaporating and condensing units	Effects of PCM usage at various locations	Increasing COP by 6-8% Stability of temperature lowering the superheat	[121]
15	T	Eutectic	Evaporating and condensing units	Effects of PCM usage at various locations	COP increase of 8% achieved by reducing sub cooling	[121]

Table 5. (cont.)

Sl. No.	Type of study	PCM type	PCM Placement	Parameter investigated	Result or Outcome	Ref.
16	T/E	Water & Eutectic	Evaporator & Compartment	PCM orientation Phase change temperature Refrigerator kind	Lower compartment temperature when in a horizontal position Eutectic is superior for controlling temperature	[124]
17	E	Eutectic	Evaporator & Compartment	Door opening Defrosting Power loss	Minimizing temperature variations Lowering the temperature rise that occurs when doors are opened and defrosted Cutting down on energy usage	[125]
18	E	Eutectic	Evaporator & Compartment	Compartment temperature Energy consumption Compressor ON time	18.6% decrease in energy use Reduced compressor ON time by 13.6%	[131]
19	T	Water	Evaporator	PCM thickness	Lowering the compressor's ON time extended standard temperature range	[84]
20	E	Water	Evaporator	Effect of ice bank presence	15% decrease in energy use. The ice bank mass must be optimized.	[85]
21	T	Not Specified	Compartment	PCM arrangement	Keeping the temperature constant while the compressor is off	[132]
22	E	Eutectic	Evaporator	Operation of the System with and Without PCM	8.37% energy savings while using 1.5 kg of PCM. 40.59% reduction in temperature fluctuations	[133]
23	E	Eutectic	Condenser	Working with and without PCM	Lowering the condenser's surface temperature. Reducing the compressor's work	[134]
24	T/E	Not Specified	Evaporator	PCM thickness and Frost effect	COP increase Energy consumption decrease	[135]
25	E	Eutectic	Evaporating and condensing units	PCM’s properties and PCM location	At three different PCM locations, increasing system effectiveness	[136]
26	E	Eutectic	Evaporator & Compartment	Phase Change temperature PCM location	The compressor's off-time and pull-down times increased by 6.1 and 78%, respectively. When comparing the daily energy consumption to the system without PCM, it decreased from 14.4% to 18.5%.	[24]
27	E	Eutectic	Evaporator & Compartment	Pulldown time, Energy consumption, TEWI	8–15% reduction in energy consumption, 15–60% less TEWI in comparison with conventional systems.	[137]
28	E	Eutectic	Evaporator	Door-opening tests, Backup duration and comparable energy usage at different PCM masses	When comparing the door-opening tests to the closed-door testing, the corresponding energy consumption was 1.12–1.02 times higher, and as the PCM mass increased, the equivalent energy consumption was reduced.	[21]
29	E	Water & Eutectic	Evaporator	Pulldown time, Energy consumption, TEWI	With 14.3% energy savings and 21.7% less compressor on-time, the 1.0 weight percent Na_2SO_4 solution was the optimum choice.	[138]
30	E	Inorganic	Evaporator	COP, Energy consumption	PCM at 35 weight percent had a COP of 6.23, while the best-case scenario without PCM had a COP of 1.68.	[139]
31	E	Water	Evaporator & Compartment	Energy consumption, Compressor on-off time	5.1% energy savings; 29.41% fewer compressors start-stops.	[140]
32	E	Inorganic	Between condenser & expansion device		7% increase in COP	[141]

5. ROLE OF PCM IN SOLAR ENERGY UTILIZATION

Utilizing solar energy for cooling in rural locations is a practical solution that has numerous benefits, especially when taking environmental concerns into account to prevent grid and off-grid issues [142]. There are two types of solar-powered refrigeration systems: thermal-driven systems and PV-driven systems [143]. In terms of cost, space efficiency, and energy efficiency, PV-driven systems are superior to thermal systems [144], [145]. PV technology is one of the least expensive solutions in terms of operational costs because it requires very little maintenance and repair [146], [147]. PV voltage, compressor type, controller methods, and other factors have all been considered while analyzing the performance of PV-powered refrigeration systems. In order to demonstrate how ambient temperature, thermostat setting, and operational voltage affect a PV-powered DC refrigerator, Daffallah et al. [148] carried out an experimental investigation. The compressor ran longer and used more energy when the same refrigerator received power from 24 V PV collectors instead of a 12 V input, according to their claims.

In their comparison studies for PV-driven cooling, Opoku et al. [149] employed two distinct examples: a DC compressor and an AC compressor. Since the DC refrigeration system in their test lacked an inverter, they replaced the batteries in both units. They maintained that the DC refrigeration approach uses less energy and is more economical. In addition to this study, Sabry et al. [150] examined the electricity consumption trend of a refrigerator with a variable-speed controller powered by an inverter. They inspected the DC refrigerator before investigating the battery-inverter load, battery load, and grid load. As a result, battery-inverter-load systems often use more electricity per day than battery-load systems [9]. Salilih et al. [151] simulated a refrigerator with a variable-speed DC compressor and discovered a correlation between COP rotor speeds. Su et al. used solar power to run the variable-speed DC compressor of a refrigerator [143], taking into account all previous studies. They discovered that the variable speed option boosts PV utilization and cooling capacity when compared to fixed speed settings. Bahloul et al. [152] experimentally tested a solar refrigerator over a period of 23 days and obtained a COP of 1.22 for a 0ºC setting to refrigerated space. Using PCMs in the evaporator, Geete et al. [153] increased the system COP by up to 20%.

A considerable number of publications in the literature support the hypothesis that using PCM is a viable tactic to enhance the possible use of renewable energy in several applications. However, the impact of PCM on freezers with direct PV-driven, variable-speed DC compressors remains unexplored. James Riffat et al. [123] investigated the use of PCM in conjunction with DC refrigerators for off-grid applications. The system simplifies and reduces costs by directly connecting a PV array to a DC refrigerator, eliminating the need for batteries or an inverter. By modifying the DC compressor speed to match the radiation intensity, it is possible to achieve the ideal balance between PV output and refrigeration efficiency. When solar energy is insufficient or it is dark outside, the PCM releases cooling to maintain the necessary cabinet temperature. PCM is effective for daylight-based cold storage and refrigerators. A mathematical model encompasses the entire system, including the PCM packs, refrigerator cabinet, DC compressor refrigeration system, and PV module. MATLAB was utilized to examine the mathematical model, and additional data from the CFD method demonstrated the impact of solar radiation levels, thermostat settings, and the quantity of PCM packs on the refrigerator's cooling capacity. Due to the compressor's high speed, the average COP of the system is 1.7 on days with high solar radiation. However, when the space temperature increases from -2°C to 4°C, the average COP rises to 1.95. The calculations indicate that a DC compressor with 3.6 kg of thin PCM packs and a 1 m² PV module can maintain food at a suitable temperature for two days during a power loss.

6. DISCUSSION ON FINDINGS, CHALLENGES AND FUTURE DIRECTIONS

Considering the provided findings, the primary question is how PCM can advance renewable energy-based cooling technologies. Expanding the market for PCM applications is essential to lowering the cost of production, which will subsequently boost profitability. As a result, the market's demand will rise, opening more chances for development. Examining the use of PCM in refrigerators, solar air conditioning systems, refrigerated vehicles, and commercial applications reveals opportunities for extensive research, given the recent advancements in materials and energy-efficient components of eco-friendly refrigerant systems. A solar thermal sorption system with the application of low- and high-temperature PCMs can provide cost-effective solutions for recent PCMs. However, focused studies should evaluate the maturity of such technologies.

The research on the utilization of PCM in refrigerating vehicles, transport refrigeration, food outlets/commercial complexes, and supermarkets shows promising scope. The commercial-scale implementation of PCM in cold chain food distribution, including transport refrigeration, necessitates the development of new PCMs with high latent heat and low weight. Several studies have highlighted the potential cost savings associated with PCM use; however, we must evaluate the life of PCMs and encapsulation technologies to persuade industrial customers. Maintaining a stable condensing temperature reduces the compressor's maximum operating temperature, thereby enhancing its lifespan. The thermal conductivity and shrinkage of the PCM significantly influence the encapsulation process. Thus, new encapsulation as well as cladding technologies must address the effective thickness and flexibility of the encapsulation methods. Intensive studies are required to determine the cladding positions and cascading of PCMs in accordance with the space temperature. This review found that the use of PCM in the refrigerator's condenser leads to an increase in the COP, a decrease in condensation pressure and temperature, a greater degree of sub cooling, and a longer period of stable system operation. However, studies should focus on the reduction in energy consumption during peak hours, noise level, overall maintenance, size, and cost. Experimental studies have observed that the chemical properties of materials used in low-temperature applications lead to corrosion in system components. Therefore, future studies must focus on non-reactive materials with low melting points for widening PCM applications in the refrigeration and air conditioning sectors.

In modified refrigeration systems with PCMs, researchers prioritize enhancing heat transmission. Researchers can minimize this issue by providing fins and making appropriate use of nanoparticles and metal/carbon foams. However, the study discovered a dearth of published work in this area. Incorporating PCM into refrigerated vehicles has the potential to significantly reduce emissions and save energy in the future. Previous research shows that temperature variations in the surrounding environment caused a small amount of a single PCM layer to melt when applied throughout the wall. This review recommends organizing multiple PCM layers with varying melting temperatures and latent heat capacities in a multi-row or tile pattern as a solution to this problem. This strategy can enhance the thermal performance of refrigerated transportation and help store the most thermal energy from the outside environment. The application of recent tools, such as machine learning, can reduce the complexity with respect to the nature of PCM and the irregular availability of energy sources.

7. CONCLUSIONS

The last few decades have seen a dramatic increase in latent heat storage materials due to the growing need for energy storage and efficiency. The manuscript systematically reviewed the application of PCMs in cooling systems, focusing on their effective utilization of renewable energy. For food preservation, cold chain transport, and small-scale thermal comfort, PCMs can play a significant role in the implementation of renewable energy. This study offers a thorough analysis of PCM applications for thermal control and performance improvement in cooling appliances, including freezers, refrigerators, refrigerated display cabinets, and refrigerated truck trailers. The majority of PCM integration in domestic systems occurs in the evaporator and condenser sections of refrigeration systems, while commercial food preservation and transport primarily use PCM to control space temperature. This study demonstrates the impact of the melting point and thermal behavior of PCMs on their behavior in several applications. Furthermore, the discussions highlight the impact of encapsulation aspects such as thickness, form, configuration, location, and orientation on a system's performance. The study reveals that organic PCMs are the most desired in the condenser section of residential refrigeration systems, while water and eutectic solutions are the most frequently utilized PCMs, particularly in the evaporator and chilling compartment. Instead of a single PCM, the application of multiple PCMs in accordance with the variation in space temperature can be a promising approach. Applying PCM in various refrigeration applications results in energy savings, a decrease in greenhouse gas emissions, a reduction in the total equivalent index of cooling systems, an improvement in compressor life, and enhanced temperature control of food during storage and transport. As part of a roadmap for clean energy, further advancements in the materials science of PCMs could result in innovative engineering solutions for PCM applications in solar thermal systems. Furthermore, we should expand research on the performance assessment of various PCM-assisted solar-thermal systems to incorporate smart approaches, such as artificial intelligence methods.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest" should be included if there is no conflict of interest.

AUTHORS CONTRIBUTION

Jamal Aslam: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft; Review & Editing.

Joseph Sekhar Santhappan: Conceptualization, Methodology, Supervision, Writing – Review & Editing.

NOMENCLATURE

COP	Coefficient of Performance	CFD	Computational Fluid Dynamics
DAR	Diffusion absorption refrigeration	EER	Energy Efficiency Ratio
HVAC	Heating, ventilation, and air conditioning	LHS	Latent Heat Storage
PCM	Phase Change Material	PCT	Phase Change Temperature
SHS	Sensible Heat Storage	TES	Thermal Energy Storage

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