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Electrochemistry of Phase-Change Materials in Thermal Energy Storage Systems: A Critical Review of Green Transitions in Built Environments

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Abstract

This article reviews recent research on phase-change materials (PCMs) used in thermal energy storage systems with the aim of enhancing their performance. The study explores various methods to improve heat transfer in PCMs, such as microencapsulation, infill materials, fins and nanofluids. Additionally, it evaluates techniques to boost heat transfer in latent heat thermal energy storage (LHTES) systems and investigates ways to increase thermal conductivity using porous and low-density materials. PCMs store thermal energy, making them suitable for use in solar energy systems when solar energy is not available. The need for eco-friendly alternatives to conventional heating and cooling in global construction and the significant energy consumption of buildings has driven research on this topic. As such, this study additionally examines current advancements in free cooling systems with latent heat storage to identify the key factors affecting their effectiveness. The findings show that using PCMs for overnight cooling maintains the room temperature within the comfort zone and reduces the cooling loads in various climates. Using machine learning methods, this study also compares recent advancements in the use of PCMs in various solar energy systems, including solar thermal power plants, solar air purifiers, solar water heaters and solar appliances. Results derived feature key factors crucial for the optimal selection of PCMs and the challenges associated with sustainable green transitions in built environments.

Keywords: Phase-Change Material (PCM), Thermal Energy Storage (TES), Latent Heat Storage (LHS), Thermophysical properties, Solar photovoltaic, Encapsulated and packed-bed systems

Abbreviations

List of notations used in this study.

ϕ	Laplace limit
ψ	Time series of observation data
ϕ	Time series of model data
ρ_ϕ	Eigen function for Fourier transform of convective supercooling
ν_ϕ	Eigen function for Fourier transform of transient subcooling
Ҝ	Lagrange polynomial multiplier
Þ	Flajolet–Odlyzko constant
Ḧ	Vandermonde polynomial multiplier
ξ	Khinchin–Lévy constant
Ꚍ	Dirichlet integral of convective heat transfer
Ḡ	Dirichlet integral of radiative heat transfer

η	Oscillatory integral operator for thermoelectric energy potential
μ	Oscillatory integral operator for photovoltaic energy potential
Ƴ	Mean squared deviation
Ü	Dirichlet integral of conventional thermophysical module
ζ	Riemann zeta function representing Dirichlet series
θ	Lemniscate constant representing the integral covariance of stochastic data
α	Peak frequency density of observation data
β	Peak frequency density of model data
Ω_θ	Hyper–harmonic median of Dirichlet series
λ_α	Peak wavelength density of observation data
λ_β	Peak wavelength density of model data
Ƙ	Kullback–Leibler divergent coefficient
ω_n	Sylvester sequence of Eigen solutions
Ѵ	Taylor series expansion derivative
R̦̄	Maclaurin series expansion derivative
ƒ	Bessel corrected variance
σ_ϕ	Fourier integral of feedback components
ϗ	Bernoulli continuity coefficient for Gregory's series
$Б_\tau$	Recursive Bayesian Estimation of relative conjugate error

Symbolic variables involved in describing (i) packed bed solar air heater, (ii) overlapped glass plate air heater, (iii) matrix air heater and (iv) honeycomb porous bed air heater.

ξ_m	Fraction melted
$Ѵ_p$	Specific heat (J/kg K)
$H_Ƴ$	Height (in metre)
Δh_p	Heat of fusion per unit mass (J/kg)
$C_Ƴ$	Thermal conductivity (W/m °C)
L_p	Length (in metre)
m_p	Mass (kg) for thickness (p)
$Q_Ƴ$	Quantity of heat stored (in Joule)
r	Radius (in metre)
$S_Ƴ$	Distance between heat pipes, location of shoreline (in metre)
t	Time (in seconds)
T	Temperature (°C or K)
$ƒ_m$	Latent heat of fusion (J/kg)
ρ_m	Density (kg/m^3)

Introduction

The exponential increase in greenhouse gas emissions can be attributed to the rapid combustion of fossil fuels. Approximately 350 billion tons of carbon dioxide has been emitted since the late 1700s [1]. Considerable efforts are being devoted to reducing fossil fuel consumption and increasing the use of renewable energy sources such as geothermal, hydroelectric, wind and solar energy. Solar energy is widely recognized as a highly promising form of renewable energy, owing to its abundant availability and ease of use. Solar energy is projected to supply 21 % of global electricity demand by 2050, as reported by the International Energy Agency, headquartered in Paris, France [2]. Nevertheless, the utilisation of solar energy is not possible without facing drawbacks, including the fluctuating intensity of the sun due to factors such as geographical location, season, time of day and local weather conditions (e.g., clear or overcast skies). Consequently, thermal energy storage systems (TESS) and electrochemical storage are technically feasible approaches for solar energy storage [3]. There are multiple forms of thermal energy storage technologies, including thermochemical storage, perceptible heat storage, latent heat storage and various combinations thereof. Thermochemical heat storage involves chemical processes that occur within a storage container. Latent heat systems harness energy from material phase transitions at relatively constant or constant-to-abroad temperatures. By contrast, sensible heat storage systems utilise an increase in the temperature of a single-phase storage medium to store heat. Research has indicated that latent heat storage systems utilising phasechange materials (PCMs) exhibit greater heat storage efficiency than conventional sensible heat energy storage systems [4]. This advantage is derived from the high energy density of the PCMs during the melting and solidification processes. The utilisation of a phase-change material (PCM) in a Latent Heat Storage (LHS) system results in a significantly reduced volume of constituents required to store an equivalent quantity of energy. Owing to the intermittent nature of renewable energy sources, thermal energy storage is essential for optimising their utilisation. Solar energy is one of the most promising sources of energy. To achieve energy system efficiency and dependability by harmonising energy supply and demand, thermal energy storage is indispensable. The 3 distinct categories of thermal energy storage are sensible heat storage (SHS), latent heat thermal energy storage (LHTES) and thermochemical storage [5]. SHS, or sensible heat storage, is a method for preserving thermal energy through phase-change-independent temperature increases. Variations in the temperature, quantity of storage material and specific heat of the substance influence the amount of energy that is to be stored. LHTES incorporates a storage medium that undergoes a phase transition (solid-liquid, solid-solid or liquid-gaseous) when heated to the transition temperature, and not *vice versa*. A solid-solid transition requires a relatively low energy storage density in relation to the volume of the material, whereas a liquid-gas transition demands a substantial volume of the material conduit. Therefore, in latent heat storage applications, the solid-liquid transition is the most frequently employed transformation, owing to its superior efficiency compared to other processes. Chemical energy storage (also known as thermochemical storage) enables the discharge of thermal energy in response to heat. It operates via reversible chemical and physical processes, and, as opposed to latent heat and thermochemical storage, sensible heat storage requires a larger vessel to accommodate a given thermal energy demand. Despite being in the early stages of research and development, thermochemical storage has demonstrated a remarkable capacity for storing energy. Latent heat energy storage is the most appealing and auspicious among the 3 thermal energy storage methods owing to its compact configuration and capacity to retain energy at an almost constant temperature, which coincides with the phase-transition temperature of the material. Latent thermal energy storage is thus composed of a substance referred to as a phase-change material (PCM).

A wide variety of phase-change materials (PCMs) exist, ranging from organic to inorganic to eutectic in terms of melting and chilling temperatures. Because different materials exhibit distinct properties, the material selection for latent heat storage is application dependent. The selection of phase-change materials (PCMs) requires consideration of their economic viability and availability in addition to their thermodynamic, kinetic, physical and chemical properties. Due to the fact that no single-PCM possesses each of the aforementioned advantageous properties, PCMs are susceptible to undesirable behaviors and characteristics that diminish their utility in Latent Heat Thermal Energy Storage (LHTES) systems. A constraint of PCM is their inadequate heat conductivity, which hinders the phase transition and diminishes the performance of the storage device. This phenomenon holds true for nearly all categories of pure phase-transition materials, excluding metallic materials. A limited thermal conductivity can potentially affect the charging and discharging processes, which involve energy absorption via dissolution and energy recovery via solidification. An additional issue associated with phase-change materials (PCMs) utilised in latent heat thermal energy storage (LHTES) systems is their susceptibility to corrosion upon contact with storage containers or conveyance conduits. Fatty acidand salt hydrate-based PCMs have a higher propensity to induce corrosion. Hydrated salt PCMs are susceptible to phase segregation, supercooling and thermal instability at high temperatures, and a multitude of research endeavours have therefore been undertaken to address the aforementioned issues in an effort to improve energy storage protocols. Bait [6] reviewed the heat transmission characteristics of phase-change materials (PCMs), with particular attention given to encapsulated PCMs. Numerous studies have devoted substantial amounts of time to theoretical and experimental investigations in an effort to enhance heat transfer in LHTES [2-5]. The publications indicate that there is a scarcity of review studies that specifically examine how to improve heat transfer in low heat transfer electrode systems (LHTES) to mitigate the issue of inadequate thermal performance caused by low thermal conductivity. Therefore, this review article focuses on recently developed heat pipes and other methods for enhancing the heat transfer in LHTES systems that have not been previously covered in reviews.

The proliferation of comfort-oriented innovations has emerged in response to the international population's increasing aspirations to experience a higher standard of living. Weaknesses in natural systems are a consequence of global warming and greenhouse gas (GHG) emissions. Renewable energy sources, including but not limited to solar radiation, ocean waves, wind, hydropower and biogas, etc., have significantly contributed to the restoration of natural equilibrium and fulfilment of the increasing energy needs of the worldwide population. Although renewable energy sources currently provide only 1 % of the world's energy, there are ongoing initiatives to substitute fossil fuels with more ecologically sustainable alternatives. In power-generation systems, concentrated solar collectors and parabolic troughs are examples of renewable technologies. As such, considerable research has been conducted on direct steam generation. Photovoltaic, wind and solar MED technologies are frequently used in the water-desalination sector. Despite ongoing advancements, solar technology requires novel enhancements to optimise its efficacy. As anticipated and investigated by Barbhuiya *et al.* [7], air conditioning and refrigeration systems are now necessities rather than luxuries. Considerable effort has been devoted to the development and enhancement of novel technologies to improve the quality of life. This study therefore also examines the application of PCM in absorption cooling systems. Bharathiraja *et al.* [8] conducted an analysis of closed- and open-cycle solar air conditioning and dehumidification systems, during which he compared several patterns. Based on this analysis, the absorption cycles exhibited greater potential than the heat-powered cycles. It is often noted that open-cycle systems, which independently regulate temperature and humidity, can provide superior air conditioning, whereas double-effect LiBr-water absorption chillers may attain greater COPs. To ascertain the prospective demand for solar-cooling technologies, Boujelbene *et al.* [9] examined more than 50 solar-powered cooling initiatives implemented throughout Europe, and found that 40 - 50 % less energy consumption is possible with solar-assisted refrigeration systems at a cost of 0.07 €/kW. Chai *et al.* [10] examined research patterns that propelled progress in the field of solar-assisted air conditioning. According to their research results, the primary emphasis of the research community has been on developing cost-effective collectors capable of attaining higher output temperatures and efficient chillers capable of operating at low temperatures. Intermittent solar radiation is a significant disadvantage in solar-powered cooling systems. Thermal storage aided in temperature stabilisation hence often fail to offer a viable fallback solution. Consequently, it is assumed that the thermal storage applications, when technically enhanced, can play an essential role in solar-assisted thermal systems. As a consequence of the heightened investigation into thermal energy storage technologies in this regard, numerous evaluations have been conducted, focusing specifically on the effectiveness and suitability of sensible and latent heat storage (PCM) in diverse environments. However, although complex temperature ranges are necessary for refrigeration and cooling in these systems, the experimental scope is limited to a single temperature range, that is, frigid or heated. Chen *et al.* [11] conducted research on control strategies for solar cooling systems and thermal energy storage devices. In particular, for those manufactured at temperatures exceeding 100 °C, the variety of thermal storage systems utilised in solar-cooling applications was the primary area of interest. Cheng *et al.* [12] compiled a variety of studies on solar collectors and thermal energy storage devices for solar thermal applications. More so, Biyouki *et al.* [13] conducted a comprehensive review of phase-change materials (PCM) utilized in cold storage. The authors focused on the performance of PCM in residential refrigeration, specifically in relation to evaporators. Diaconu *et al.* [14] conducted an exhaustive examination of phase-change materials (PCM) for cold storage, including all varieties and applications. Their enquiries have focused on air conditioning and ice storage as distinct topics. There has been no evaluation of the impact of phase-change materials (PCM) on condenser performance or PCM in solar cold storage. Considerable research has been devoted to examining a wide range of designs, methodologies and improvements in order to identify possible avenues for augmenting the efficacy of solar absorption systems. The other recently reported evaluations did not concentrate on a single application in particular; rather, they encompassed various PCM categories, appropriate applications, integration and other commonplace factors [5-9]. Duraivel *et al.* [15] described in detail the design procedures utilised in liquid-solid PCM storage systems. Aziz *et al.* [4] examined a substantial bulk of research pertaining to the improvement of heat transfer in phase transition materials for the purpose of thermal energy storage. Hence, this review article examines the application of phase-change materials (PCMs) in several components of solar energy-powered absorption refrigeration systems that function at varying temperatures over the course of a cycle. The objective of this study is to provide an exhaustive examination of the determinants that should be considered when selecting a phase-change material (PCM) for implementation in diverse solar absorption system components functioning at varying temperatures. These elements also comprise strategies for integration, approaches to development, challenges and resolutions. Dimensionality analysis and correlations, empirical correlations and parameter definition, Log Mean Temperature Difference (LMTD), Conduction Transfer Functions (CTF) and numerical models constitute some of these elements. This article is intended to present a comprehensive review of research conducted on phase-change materials (PCMs) for a variety of heating and cooling applications over a temperature range of −15 to 150 °C. It evaluates their impact on performance and categorises them according to the system being investigated. The evaluation also consists of academic manuals on the utilisation of PCM to enhance the absorption capacities of lithium bromide-water (LiBr-H_2O) and aqua-ammonia (NH_3-H_2O) systems, as well as selection criteria and the conceptual foundations of the approach. Various sorption cooling methods exist, including desiccant cooling, chemisorption, adsorption and absorption. Electrochemical and ejector-refrigeration techniques are also included in this category. All techniques generate heat at different stages of operation, which affects the Coefficient of Performance (COP) of the system.

The subsequent section provides an overview of the absorption cycles and various techniques for distributing the correct PCM throughout the various components of a refrigeration cycles. Solar-powered refrigeration can be achieved by either thermal or electrical means. Thus, it is feasible to employ both the thermomechanical and sorption-based thermal techniques. This study details the most prevalent techniques used in the development of PCM storage systems. A thorough examination of recent advancements in various methodologies has been aimed at improving the heat transfer in latent heat thermal storage systems. Although highly conductive particulates or materials are used to increase the thermal conductivity of PCM, expanded surfaces, such as fins and heat pipelines, are primarily employed to increase the heat transfer area, according to the article's key finding. All the notations and mathematical variables defined in this study have been listed on the title page of this article. Machine learning techniques were explored in this study to determine how the electrochemistry of PCMs in LHTES systems can be optimised to enable renewable energy transitions in built environments [1,2].

Materials and Methods

Historical milestones

There are substantially more greenhouse gases in the atmosphere than previously thought. Some studies have predicted that greenhouse gas concentrations will increase substantially in the coming decades. A discernible surge in awareness has occurred regarding energy conservation methodologies across diverse sectors, including construction and transportation. Construction facilities consume an estimated 40 % of the global energy usage and 30 % of CO_2 emissions, making them a substantial contributor to energy consumption. Significant amounts of this energy are required to maintain the well-being of building occupants. Fabrykiewicz and Cieśliński [16] posited that this scenario is poised for significant growth in the future owing to several factors, including population growth, increasing demand for comfortable environments and structures, and a lifestyle transition that will lead to an increased amount of time spent indoors. HVAC systems are commonly employed to regulate the temperature inside a building in order to enhance the purity of indoor air and provide thermal comfort. The excessive energy consumption of these systems negatively affects both environmental and human health. Complications are also generated when the energy demand reaches its peak. Thermal energy storage (TES) and alternative sustainable technologies can mitigate the increasing energy requirements of buildings by storing surplus energy for subsequent utilisation. Thermal energy storage (TES) systems, which harness natural cold energy generated by nighttime temperature fluctuations, have the potential to provide thermal comfort, energy conservation, and peak load reduction. Nighttime air temperature reduction enhances the efficacy of the night cooling mechanism. As reported in the literature, night cooling pertains to the mechanism by which frigid energy from ambient night air is stored within the primary structure of a building. Free cooling is the practice of storing nighttime frigid energy in a designated thermal-storage unit for daytime use. According to previous research, free cooling is most effective in regions where daytime and nighttime temperatures differ by 12 - 15 K. Thermal energy storage (TES) devices are capable of storing energy for fleeting or extended durations at high or low temperatures. TES processes are classified as sensible heat, latent heat, thermochemical energy storage and their respective combinations. The recent developments and characteristics of thermochemical energy storage (TES) have been detailed in several published reviews. To choose an optimal storage system for a specific application, it is vital to understand the advantages and disadvantages of different TES technologies. The heat generated and dissipated during reversible endothermic chemical reactions involving the dissociation and synthesis of chemical molecules is utilised by thermochemical energy systems (TCES). TCES systems offer a broad temperature range, secure and reliable storage, a high energy density (even when the temperature remains constant) and convenient portability. However, additional drawbacks include inadequate mass-and thermal-transfer capabilities in high-density environments. They are costly and their long-term operation is poorly understood. Ongoing research has focused on reversible thermochemical processes. However, the widespread implementation of this technology is hindered by technical and financial obstacles. Sensible heat storage (SHS) exploits the increase in the temperature of a substance without undergoing phase transition. The ratio of the stored heat to the temperature rise represents the heat capacity of a given storage medium. The 2 categories of SHS substances are solid SHS substances, which include minerals, metals, and construction materials; and liquid SHS substances, which include water and oil. Gases are unsuitable for storing heat or cold because of their inadequate heat capacities. Water is considered superior to commonly used substances because of its substantial volumetric heat capacity of 4,187 kJ/m³ K, which is nearly double that of concrete, and considerably greater than that of other construction materials. Further information regarding the thermal properties of various SHS materials that are frequently employed in construction work can be found in the literature [7-13]. Some of these limitations include restricted storage capacity, size and unsuitability for numerous practical applications owing to significant temperature fluctuations during charging and discharging, which result in a narrow temperature range. Latent heat storage (LHS) stores energy during the phase transitions of a substance, such as evaporation or dissolution, without any observable alteration in temperature. In recent decades, there has been considerable interest in the application of Latent Heat Storage (LHS) to Thermal Energy Storage, owing to its efficacy and superiority over alternative thermal energy storage (TES) materials. Although the energy densities of LHS compounds are frequently greater than those of SHS chemicals, they are approximately 5 times lower than those of TCES. The feasibility of implementing an LHS is superior to that of a TCES, owing to its reduced cost and complexity. Latent heat transfer, which occurs as a nearly isothermal process when phase-change materials (PCMs) absorb and release heat at a constant temperature or within a restricted temperature range, maintains thermal comfort more effectively than sensible heat storage (SHS).

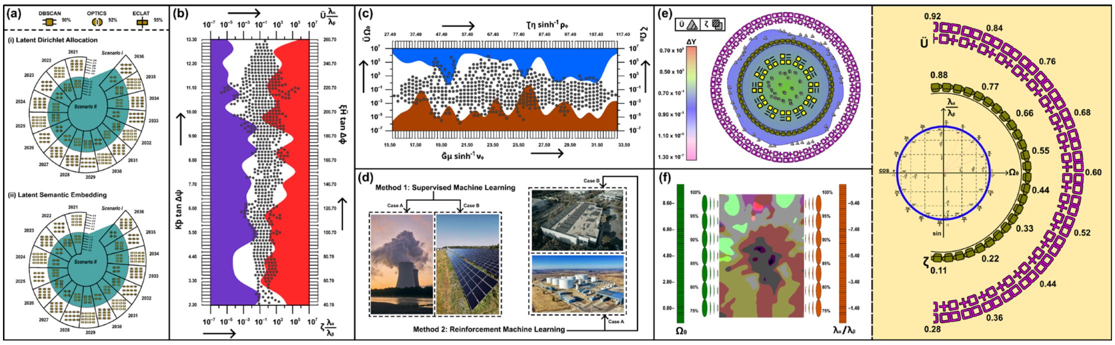

Figure 1 (a) Latent heat thermal energy storage prototype using a eutectic mixture of $KNO_3/NaNO_3$ and expanded graphite fins to improve heat transfer, thermal performance of finned tubes in LHTES units, wherein the fins improve energy storage and release and that smaller fin pitches shorten melting/solidification periods, all expressed as differential allotment of apriori machine learning algorithms across 2 separate scenarios over a 15-year timescale, designated as per a principal component analysis of the data discussed in Section 2, with melting process of RT82 in a TTHX system considering (i) inside tube heating, outside tube heating and both sides heating methods for charging, (ii) internal fins in PCM-based heat sink system promote rapid melting, followed by low melting after the PCM in the inter-fin regions has been liquefied, providing better performance regardless of PCM type; (b) Fibonacci sequences illustrating heat pipes boost charging and discharging rates in shell-and-tube LHTES systems for solar thermal power plants, based on 3D computational analysis establishing how HP integrated configurations affect LHTES system thermal performance; (c) Projected cytometry describing how higher-porosity aluminium foam accelerates steady-state temperature and how 95 % copper porous form boosts solid/liquid phase transition thermal conductivity, wherein paraMn-based LHTES system discovered that the bulk density of the expanded natural graphite matrix correlates with thermal diffusivity and latent heat storage capacity, with significant Marks-Kendall metric, based on scatter plots of Trellis-density correlations between metal foams and expanded graphite in cylindrical containers and PCM heat transfer improvement in thermal energy storage systems. Adding porous materials boosted heat transfer from 250 to 300 °C, examined the

melting process of Al_2O_3/n-octadecane nano-PCM, and discovered that increasing nano-particle mass fraction reduced natural convection heat transfer; (d) Effect of carbon nanoparticles doped in PCM on LHTES system thermal performance, greater latent heat value for all samples than pure wax, produced and examined a heat storage nanocomposites unit with paraMn wax and multi-walled carbon nanotubes represented via clockwise schematics of case studies incorporated for the machine learning analysis; (e) Polar Akima Interpolation of varying MWCNT volume fractions affecting stearic acid heat transfer and thermal performance during charging and discharging, while being more effective than graphite in paraMn-based nanocomposite PCM, and the transient hot-wire method at elevated temperatures measured thermal conductivity of composite PCMs, wherein the geometry of the nanofillers strongly affects thermal conductivity, and GNPs showed the greatest potential for thermal conductivity enhancement with moderate energy storage capacity, rectified via Python t-SNE Dimensionality Reduction elucidating PCM had heat pipes with fins on their condensers to improve temperature distribution and melting rate, 30 kW $LiBr/H_2O$ single-effect absorption cooling system with 90 m^2 of double-glazed flat-plate collectors, utilizing PCM slurries instead of water enhanced thermal performance but lowered solar collecting efficiency; (f) Normalized Laplace transform of high phase-change enthalpy and minimal subcooling, hydroquinone and D-mannitol were chosen as PCMs for 140 - 200 °C Erythritol as PCM improves domestic $LiBr-H_2O$ solar absorption cooling system efficiency. Their investigation focused on the hot side temperature needed for efficient functioning.

An important factor that distinguishes LHS compounds from other SHS compounds is their seamless integration, specifically within lightweight structures and preexisting buildings. Because of their reduced volume and weight, PCMs have the potential to significantly augment the mass effect. PCM systems are anticipated to be 5 - 14 times more efficient than conventional SHS systems, which necessitates additional space for accumulator accommodation. A comparison of the weight and volume of various LHS and SHS materials necessary to store 106 kJ of energy during a 15 K increase in temperature is presented in **Figure 1(a)**. Additionally, LHS can be incorporated into SHS systems to improve their performance or utilised for suitable storage. The inadequate thermal conductivity and thermal instability of PCMs are the primary factors that restrict the performance of LHS systems. Despite their high cost, PCMs are readily available in a wide variety of forms and at various temperatures. Extensive research on PCMs and the proliferation of PCM manufacturers worldwide are expected to contribute to a reduction in current pricing. Almost 4 decades ago, initial investigations of the application of PCMs for space heating and cooling were conducted by Boujelbene *et al.* [9]. At present, PCM products are accessible in an extensive array of container geometries, including tubes, spheres and panels, and in various forms, including polymers, granules, dust and powder. Owing to their heterogeneous nature, exterior and interior building envelopes can be incorporated into structures by using a multitude of methodologies. Phase-change materials (PCMs) have been applied in diverse systems, such as photovoltaic (PV) panels, Trombe walls, solar chimneys and nocturnal solar water/air heating or cooling. PCMs are occasionally incorporated in indoor furniture. LHS has been the focus of evaluation on numerous occasions. Evaluating advancements in PCM materials, improving heat transmission, devising mathematical models for latent heat problems, and integrating PCM into buildings have constituted the majority of these studies.

Although the integration of PCM in building technology for free cooling has been the subject of research for over 25 years and numerous system constructions and evaluations, few studies have specifically addressed this topic. This study aims to revise and enhance prior assessments in this field, focusing specifically on the application of PCM for free cooling in structures. This review aims to analyse recent advancements in free-cooling systems that utilise latent heat storage, investigate strategies for increasing efficiency, and assess the key variables that influence thermal performance. The paper begins with an overview of latent heat storage devices, followed by an analysis of their advantages and disadvantages. In Section 3, numerous structural applications of PCM are discussed, with an emphasis on their advantages. The latest discoveries regarding free cooling with PCM storage devices are summarised and arranged in chronological order in Section 4. In Section 6, the primary determinants influencing the efficacy of free-cooling systems are examined in conjunction with appropriate adjustments that can be implemented to rectify these determinants. In accordance with the research examined, this study emphasises the principal benefits of implementing PCM energy storage in free cooling. Fang *et al.* [17] have undertaken an extensive literature review pertaining to PCMs in renewable energy refrigeration systems that utilize solar absorption. This paper presents a comprehensive examination of phase-change materials (PCMs) and the techniques employed to improve them for absorption refrigeration systems. This article presents a comprehensive analysis of several key topics, including phase-change material enhancement techniques utilised in thermal storage systems, latent heat thermal storage systems, appropriate material selection for storage systems and the cost analysis of storage systems. In addition, it provides a comprehensive explanation of the design processes for thermal storage systems, including issues, solutions, heat transmission, PCM behaviour and system repercussions. Concluding remarks regarding the potential enhancement of system output through material selection predicted based on material heat balance, dissipation and operating temperature. Farid *et al.* [18] conducted research on the supercooling of phase-change materials in energy storage systems that utilise heat. In this study, the design processes employed in supercooled heat storage systems, the thermal energy storage capabilities of supercooled liquids, the measurement and extent of supercooling, the variables that influence supercooling magnitude, and the subsequent impact on the output capacity were investigated. A comprehensive literature evaluation of the PCM thermal storage system, characterised by a melting temperature range of 0 - 250 °C, was conducted by Kumar *et al.* [19]. According to this study, organic compounds and salt hydrates are the most suitable phase-change materials for applications at temperatures below 100° C. At temperatures around 100 °C, eutectic mixtures containing urea are advantageous, whereas eutectic mixtures containing inorganic salt hydrates are most suitable for applications occurring between 130 and 1,250 °C. Multiple applications may benefit from the combination of sodium and potassium within the temperature range of approximately 170 °C. This study investigated potential applications, heat transfer enhancement techniques and latent heat storage system designs. GaneshKumar *et al.* [20] conducted an evaluation of heat transfer techniques in PCM thermal storage systems, wherein they contrasted and emphasized the deficiencies of traditional non-transportable PCMs. In this study, 3 portable PCM system concepts were described. PCM slurries, direct-contact PCM systems, and dynamic PCM systems are included. This review investigates several heat transmission enhancement techniques documented in the literature. This work compiles research on phase-change storage systems, including the flux of PCM throughout the storage system. A comprehensive assessment of heat storage devices utilising phase-change materials (PCMs) was conducted by Gao *et al.* [21]. In this study, a comprehensive analysis of the heat transfer system design process, heat transfer optimisation strategies during the charging phase, and the selection of the PCM and its heat transfer characteristics was conducted. Through experimental and computational investigations, the performance of $NH_4Al(SO_4)_2 \cdot 12H_2O$ as a novel inorganic phase-change material (PCM) for solar thermal storage systems was assessed. One of the most significant findings of this study is that low-density residential structures exhibit greater efficiency when PCM is enhanced. Cheng *et al.* [12] conducted an assessment of methods to enhance heat transfer in thermal storage systems utilized in parabolic trough solar farms. The objective of this study was to assess commercially available phase-change materials (PCM) and determine the most effective method for enhancing heat transfer within the system. It was discovered that 3 commercially available phase-change materials (PCMs) could be utilised within the operating temperature range of parabolic trough plants. Potassium nitrate, sodium nitrate and a solution composed of potassium nitrate and potassium chloride comprise these substances. They confirmed that the aluminum fins functioned properly in the temperature range 250 - 330 °C. Additionally, a comprehensive examination of energy storage devices utilising PCM was conducted in the aforementioned studies [13-16]. The primary objective of this research is to assess the approaches, investigations and computational frameworks currently employed to augment heat transfer in PCM-based thermal storage systems. As a result of this research, the optimal PCM design for a variety of heat-transfer applications will be determined with greater certainty. The literature review is organised according to 3 primary geometries and configurations of thermal storage devices: Encapsulation, packed bed and shell-and-tube.

The papers under examination were categorised according to the following factors: Study methodology (experimental models, numerical models or both), PCM type, melting temperature range, heat transfer fluid type, PCM operation (charging or discharging), storage system dimensions and heat transfer characteristics. In this study, methods for enhancing the thermal conductivity, fins, infill materials, nanofluids, nanoparticles and heat transfer intensification are examined. This course provides an in-depth analysis of thermal energy storage techniques, focusing specifically on phase-change materials (PCMs) and latent heat thermal energy storage (LHTES). In addition to previous research findings, this study investigates the design and configuration of thermal storage systems, techniques for enhancing heat transmission, and theoretical and practical analyses of systems employing phase-change materials (PCMs). Recent advancements in PCM-based thermal energy storage systems have sparked renewed interest in packed-bed and encapsulated thermal storage systems (ETSSs). The aforementioned systems exhibit enhanced efficiency and higher storage densities, and numerous studies have documented the performance analyses of these systems. In research on storage systems, the designs, configurations, PCM materials, heat transfer enhancement techniques and flow and heat transfer processes during charge and discharge have been investigated. Bait [6] presented a comprehensive summary of several published studies on heat transfer in thermal storage devices based on PCM. An exhaustive examination of previously published research pertaining to packed-bed thermal storage devices was conducted. In their recent publication, He *et al.* [22] conducted an exhaustive examination of numerous numerical models pertaining to PCM packed bed systems. In this study, the attributes, parameters, correlations and constraints of several methodologies are investigated in depth. The primary results of the modules were assessed and emphasised. Nian *et al.* [23] conducted an exhaustive examination of the outer materials utilised to enclose the PCM in high-temperature thermal storage devices. A multitude of substances capable of encapsulating phase-change materials (PCMs) at high temperatures were uncovered during the course of the investigation. The components consisted of calcium carbonate, titanium dioxide, silicon dioxide, nickel (including nickel alloys), sodium silicate, carbon and stainless steel. Hosseini *et al.* [24] conducted a study that examined solar household water-heating systems utilising PCM. An in-depth examination was conducted on the characteristics of heat transfer within residential solar heating systems in addition to approaches to promote heat transfer and their applications. In another study, Hu *et al.* [25] examined encapsulation methods for phase-transition materials used in heat-storage devices. The thermophysical properties of inorganic phase-transition materials constitute primary areas of interest. A comprehensive analysis was conducted on a range of inorganic phase-change materials (PCMs), encapsulation classification protocols, approaches to enhancing thermal conductivity and the properties of the encased materials. Conclusions were drawn regarding the implementation of encapsulated inorganic phase transition materials in solar thermal storage systems. Chai *et al.* [10] devised a computer model to evaluate and forecast the thermal efficacy of packed-bed cylindrical latent-heat thermal storage devices. Spherical receptacles filled with paraffin wax were positioned within the storage container and submerged in heat-transmission fluid flow. Hyun *et al.* [26] conducted an experimental investigation into the charge process within cylindrical heat storage chambers that utilized various phase-change materials (PCMs). Two cylindrical capsules composed of 3 concentric red copper cylinders were horizontally positioned in the water reservoir. One of these containers contained 3 distinct phase-change materials (PCMs): Stearic acid, divided paraffin and lauric acid. The sole contents of the second tube were paraffin slices. The charging process was considerably enhanced by utilising a multiple PCM (MPCM) capsule, as opposed to a single PCM (SPCM), as demonstrated by the experimental results. Overall, the dissolution time of the MPCM capsules was significantly reduced by 37 - 42 %. The authors discussed the capsule diameters associated with melting, the spectrum of phase-change temperatures, and the input temperature of the heat-transfer fluid. The findings indicated that the solidification time of the MPCM capsules exceeded the duration of the procedure, resulting in a 15 - 25 % decrease in the charging time. Iranmanesh and Moshizi [27] performed an empirical and analytical investigation of the isothermal phase of a phase-change material (PCM) that was stored in a vessel. A computer model was constructed using the enthalpy of melting. The inner wall of the capsule-solidified layer exhibited a high thermal resistance, which accounted for the diminished heat transfer coefficient that occurred during solidification. An increase in the temperature of the heat transfer fluid input resulted in a reduction in both the charging time and the melting point. The increased mass flow rates of the heat-transfer fluid resulted in a decrease in the charging time. The charging and discharging processes were substantially influenced by capsule size, which was the second most significant finding. The shortened melting point and increased storage efficiency are the outcomes of compact capsules. The results obtained were consistent with those of the investigation conducted by Ismail *et al.* [28], who used numerical analysis to assess the thermal efficacy of a cylindrical thermal storage unit containing PCMs encased in spherical capsules.

Jalilian *et al.* [29] conducted an experimental investigation of the thermal characteristics of storage systems that utilise paraffin in spherical containers throughout freezing and thawing processes. The Reynolds number and temperature of the input were the 2 parameters that were analysed. The temperature distribution within the spherical capsules and storage receptacle was documented during both procedures. The disparity between the heat release rate during solidification and the heat removal rate decreases the surface temperature relative to the interior temperature of the capsule during freezing and thawing. Moreover, as the Reynolds number increases, the duration of the phase transition during freezing and thawing decreases, even at lower input temperatures. The phase-change period of the capsule in the first layer was shorter than that in the seventh layer. In addition, the phase-change period was shorter near the periphery of the capsule than in the central region. In contrast to the interior, the periphery of the tank exhibited greater porosity. Jayathunga *et al.* [30] experimentally investigated the thermal properties of a system comprising spherical PCM capsules that were randomly dispersed within a cylindrical storage vessel. The results were utilised to provide greater insight into the temporal duration of the solidification and melting processes within the spherical capsules, as well as the temperature distribution. Kareem *et al.* [31] experimentally and numerically investigated the thermal properties of a packed-bed thermal storage system comprising of spherical containers. The principal aim of this study was to investigate the impact of parameters, including the working fluid entrance temperature, mass flow rate and capsule temperature, on the charging and discharging processes. Additionally, an assortment of material containers was investigated, and the numerical results substantiated the approach used to model the dynamic characteristics of the isothermal phase transition procedure. This was the case because this strategy circumvented the necessity of explicitly addressing the boundary conditions of the phase-change system. Considerable investigations have been conducted on cylindrical and rectangular containers. The capacities and surfaces for convective heat transmission were identical for both the container types. They found that as the volume of both types of containers increased, the time required for melting progressively increased. When subjected to an equivalent heat transmission area and volume, the rectangular container melted at a faster rate than the cylindrical container did. Karwacki and Kwidzinski [32] suggested that PCMs could be enclosed in rectangular containers. By observing the behaviour of a PCM melted in a spherical capsule, they investigated buoyancy and spontaneous convection. The results were validated by employing a numerical solution generated using the computational fluid dynamics (CFD) software, FLUENT. Initially, conductivity-driven convection was the predominant process; however, as the volume of the liquid section expanded, buoyancy-driven convection became more significant. Through natural convection, the molten PCM rises to the uppermost region of the sphere. The uppermost portions of the sphere melted prior to the lower regions. The computer results indicated that the temperature distribution in certain regions of the sphere fluctuated erratically owing to the presence of an unstable fluid layer. Kermani *et al.* [33] conducted an experimental investigation on heat transmission on an isothermally heated sphere in a uniform, downhill flow utilizing a micro-foil heat sensor (HFS). This investigation focused on opposing flow mixed convection, which occurs when the unconstrained flow moves in the opposite direction to the driven flow. Two scenarios were examined and discussed. Initially, isothermal spheres measuring 3 mm in thickness and 50 mm in outer diameter were used. In the second scenario, solid PCM capsules with a 1 mm thick exterior glass diameter were utilised. n-Octadecane was also added. Three distinct airflow patterns, each with a Grashof number (Gr) of 3.3×10^5, were investigated. In the range of Reynolds numbers (Re) below 240, chaotic flow is observed; between 240 and 500, 2-dimensional stable separated flow is characterised; above 500, 3-dimensional unstable separated flow is predicted. The time-averaged local Nusselt number (Nu) was calculated using the experimental data. Khan *et al.* [34] constructed a mathematical model to forecast the thermal efficacy of packed bed storage devices utilizing C++ computer software. The Nusselt numbers for the 3 distinct patterns are shown in **Figure 1(a)**. An analysis was conducted on thermal storage systems of various shapes and dimensions, with the computational model providing predictions for temperature distribution, thermal energy stored within the unit and energy consumption. The experimental findings pertaining to pure forced convection, as documented by Khan *et al.* [35], are depicted by the dotted lines.

Recent developments

Kong *et al.* [36] conducted a theoretical and experimental investigation into the effect of a carbon-fiber brush on the thermal conductivity of a thermal energy storage system. Several methods for enhancing heat conductivity through the utilisation of carbon fibre brushes have been examined. These consist of carbon fibre encapsulated in a cylindrical capsule, carbon fibre brush encased in a cylindrical capsule, carbon fibre brush, PCM composite surrounding tubes and carbon fibres encased in a cylindrical capsule in an arbitrary arrangement. The investigation revealed that the increase in the heat conductivity was substantially influenced by the type of brush used. The thermal conductivity remained largely unaffected by the arbitrary arrangement of the fibres. The transient thermal responsiveness of the brush/PCM composites improved with an increase in the brush diameter. Nevertheless, the response remained unchanged when the diameter of the brush exceeded the distance between the tubes because of the heightened thermal resistance at the tube wall. The heat exchange rate was significantly increased by enveloping the tube with the bristles during the charging and discharging processes. Korres *et al.* [37] conducted experimental and computational investigations on heat-transfer enhancement techniques utilising carbon brushes and fibre chips in their shell-and-tube thermal storage system. For the experimental investigations, glass wool was used to insulate 4 steel cylinders positioned vertically within a cylindrical acrylic resin container. Carbon-fibre pieces measuring 5 mm in length and 10 μm in diameter were used to fill the container. The thermal conductivity of the PCM n-octadecane was 0.34 W/m K. The substance was then introduced into the container. Three distinct varieties of fibres were utilised in accordance with their thermal conductivity levels: Low (k_f = 5 W/m K), medium (k_f = 190 W/m K) and high (k_f = 500 W/m K). The carbon-fibre nanoparticles substantially enhanced the heat transfer rate in the PCMs based on a comparison between the experimental outcomes and the calculated values. The carbon-fibre granules experienced a lower total heat transfer than the carbon brushes owing to the thermal resistance near the heat transfer surface. To examine the transient heat transport in a shell-and-tube thermal storage system, T_{rp} utilises both experimental and computational methods. By utilising a non-isothermal phase transition, he was able to formulate a mathematical model that he subsequently implemented as a FORTRAN program. As the experimental data corroborated the numerical results, it was determined that the high Prandtl numbers of the Heat Transmission Fluid (HTF) impeded heat transmission to the phase-change material (PCM). Consequently, a negligible quantity of heat is transmitted downstream via the Heat Transfer Fluid (HTF) and a substantial quantity is transferred to the phase-change material (PCM) upstream.

A computer analysis was conducted to determine how various geometric properties and operating conditions of the heat transfer fluid (HTF) influence heat transfer during solidification and dissolution [29]. To accomplish this, the transient temperature distributions of the HTF, phase-change material (PCM), and tube walls were monitored. Kumar *et al.* [38] conducted an experimental investigation to examine the consequences of dynamic melting within a cylindrical shell-and-tube heat exchanger. Four distinct PCM flow rates were examined in this study. The findings indicated that an increase in the PCM flow rate by twice the HTF flow rate led to a substantial improvement in both melting time and effectiveness. This study suggests that dynamic melting may serve as a viable method to augment the heat transfer in the presence of phase transitions in PCM. Lacroix devised a numerical model based on enthalpy. The temporary behaviour of the shell-and-tube storage unit, featuring a PCM on the shell side and a circulating HTF in the conduit, was predicted by the model. The validity of the model was validated by comparing it with experimental data, and the effects of various geometric and thermodynamic properties on the heat transmission were investigated. For optimal operation, the shell radius, mass flow rate and intake temperature must be appropriately selected. Bahramei *et al.* [5] conducted experimental investigations into the charge and discharge mechanisms of a thermal energy storage system utilising a shell-and-tube apparatus. Asphalt and paraffin wax are the dual-PCMs under investigation. Experimental investigations were conducted to examine the temperature distribution, heat dissipation during discharging and heat stored during charging of various storage compounds. Lee *et al.* [39] conducted an experimental study to determine how natural convection and a number of design/flow parameters affected the charging and discharging of ice within a shell-and-tube structure. Following a temporary phase during which conduction served as the primary method of heat transfer, natural convection subsequently emerged as the prevailing approach. The flow rate, inlet temperature, shell diameter and thermal conductivity of the tube material significantly influenced the charging and discharging processes. A numerical model was devised by Li and Tang [40] to represent the charging and discharging of PCM heat transfer with an emphasis on energy imbalance. The model was validated using experimental results, and an extensive level of concurrence was observed between them. The primary factors contributing to the energy disparity were identified as the temperature range during solidification and melting in addition to the supercooling issue that transpired during the cooling process. A metal foam was identified by comparing the outcomes of the symmetrical and asymmetrical models. The metal foam was composed of 95 % porous aluminum foam, and the substances contained within it were air and water. Robust concurrence was observed when the model was validated using experimental data from Li *et al.* [41]. The findings of the study indicated a positive correlation between fluid conductivity and effective thermal conductivity, implying that the heat conductivity of the solid phase determines the overall effective thermal conductivity. Li *et al.* [42] utilised experiments and computational models to investigate the forced convection in metal foams with high porosity. The experiments used aluminum metal foam that had been inundated with air and water as the fluid medium. The experimental data were compared to the numerical results obtained by Dai *et al.* [43]. Because of the high conductivity of the solid matrix, the foam-air compound had no discernible effect on thermal dispersion. Conversely, significant thermal dispersion was observed in the foam-water composite. Kermani *et al.* [33] conducted a simulation and experimental evaluation of heat storage in a phase-change regenerator comprising n-octadecane adhered to a porous silica substrate by capillary forces [44]. Carbon dioxide was used as the heat transmission medium in a phase-change regenerator. A significant amount of thermal energy dissipation was identified by comparing the experimental output temperature with the anticipated value. As much as 50 % of the energy contained in the experimental unit may be discharged into the environment via end plates. Furthermore, a comprehensive examination of the net front movement predictions and empirical data revealed substantial concurrence, encompassing 60 % of the bed volume. Jalilian *et al.* [29] conducted an experimental investigation of the chilling of deionised water in saturated porous media. The spherical glass spheres utilized in the experiment had respective diameters of 1.59 and 6 mm. The permeabilities of these balls were determined to be 1.6×10^{-9} and 2.85×10^{-8} m^2, respectively. Natural convection was significantly impeded by the porous medium during solidification, thereby impeding fluid velocity.

Lu *et al.* [45] conducted experimental and computational evaluations of fluid phase shift in a vertical rectangular enclosure filled with glass beads that functioned as a porous matrix. Upon examination of the experimental data and the numerical results, a strong correlation was observed. The findings revealed that the porous media significantly influenced both conduction in the solid fraction and spontaneous convection in the molten fraction. The thermal behaviour of phase-change material (PCM) heated from 1 side of a rectangular thermal storage system was analysed using a computational model developed by Lum *et al.* [46]. This study examined the effects of fins positioned at angles of −30, −15, 0 and +15 °. Fins exhibiting an inclination of −15 ° had a greater impact on the heat transmission process and overall melting time than fins featuring an alternative angle, as determined by this research. In this study, the effects of the fin length and heat flux input on PCM melting were examined. The heat-transfer mechanisms were significantly influenced by the length of the inclined fins. Matapour *et al.* [47] constructed an exhaustive model to analyze the heat transmission efficacy of metal foam-filled pipes. By applying a 2-equation heat transfer model and the Brinkman-extended Darcy momentum model, exact velocity and temperature distribution data were acquired. The results indicate that the metal insulation caused a 40-fold increase in heat transfer. Despite exhibiting a greater pressure drop, a metal foam characterised by diminished porosity and pore density demonstrated superior efficacy in heat transfer. The researchers then investigated the effect of the metal foam on the phase transition of paraffin during solidification and dissolution. The study found that the incorporation of a metal foam additive substantially accelerated the heat transmission during the solidification and melting phases. The extent to which heat transmission was enhanced was determined by the composition and structure of the metal foam. An inventory of recent studies focused on augmenting heat transmission through the utilisation of infill materials is presented in **Figure 1(a)**.

A multitude of variables are assessed during investigations, including the type of phase-change material (PCM), research methodologies, charging and discharging processes, validation techniques, and filling materials. Ho and Gao conducted an experimental investigation to ascertain the impact of alumina (Al_2O_3) nanoparticles on the thermo-physical properties of paraffin (n-Octadecane) during the melting and chilling phases. These findings indicate that the melting and freezing characteristics of paraffin were marginally modified by the introduction of the Al_2O_3 nanoparticles. An analogous outcome was achieved through the application of nanoparticles to enhance the thermal conductivity. The thermal conductivity of paraffin nanoparticles increased significantly with increasing temperature, resulting in a more pronounced Brownian motion. A significant concurrence was observed when the dynamic viscosity and density of purified paraffin were compared to the values reported by Mellouli *et al.* [48]. These results suggest that increasing the concentration of Al_2O_3 nanoparticles led to a substantial increase in the dynamic viscosity. Furthermore, paraffin that had been saturated with nanoparticles was investigated by Mushan *et al.* [49]. Copper, aluminum and copper/carbon nanoparticles have been employed to enhance the heat-transfer efficacy during the freezing and melting phases. The study findings revealed that paraffin-incorporated nanoparticles exhibited a significantly higher heat-transfer rate than unadulterated paraffin. In addition, nanoparticles did not have a substantial impact on the dissolution and chilling temperatures. The study found that the number of Cu nanoparticles was higher than that of the Al and C/Cu nanoparticles. Oskouei *et al.* [50] empirically examined the impact of Ag nanoparticles on the thermal conductivity of PCMs. Tetradecanol (TD) was employed as the phase-change material (PCM) in the conducted experiment. Several thermal analysis techniques, including differential scanning calorimetry (DSC), powder X-ray diffraction (XRD), transmission electron microscopy (TEM) and thermogravimetry (TG), were used. As the quantity of Ag nanoparticles increased, the thermal conductivity of the composite material increased. The impact of Al_2O_3 nanoparticles on paraffin wax in a concentric double-pipe heat exchanger was investigated by Pathak *et al.* [51] using numerical simulations executed using FLUENT software. A significant level of concurrence was observed when the thermophysical properties of paraffin saturated with Al_2O_3 nanoparticles were compared with those reported by Poorshakoor and Darab [52]. The study findings indicated that the incorporation of Al_2O_3 nanoparticles into paraffin wax significantly altered the charging-discharging rates of thermal energy in comparison with unadulterated paraffin. Similar improvements were observed in the heat-transfer rate and thermal conductivity of the composite materials. Furthermore, an increase in the volumetric proportion of Al_2O_3 nanoparticles results in a corresponding increase in the viscosity of the composite material, thereby enhancing the efficacy of heat transmission via natural convection [34-48]. The researchers replicated the experiment conducted on a square enclosure that received heat from both vertical and downward directions [53]. The results of the investigation indicated that the thermophysical properties of paraffin wax coated with nanoparticles were enhanced compared with those of unadulterated paraffin. The effects of volume percentage on the solidification and dissolution of paraffin wax containing CuO and Al_2O_3 nanoparticles were investigated. The findings of this study demonstrated that substituting CuO nanoparticles with Al_2O_3 nanoparticles substantially enhanced the thermal conductivity of paraffin wax. Rahi *et al.* [54] successfully resolved the 1-dimensional Stefan problem pertaining to the solidification of a nanoparticle-enhanced phase-change material (NEPCM) within a restricted slab. Water and cyclohexane, 2 phase-change materials (PCMs), were chosen for the investigation, in addition to titanium, copper oxide, alumina and copper nanoparticles. An empirical analysis of the model was undertaken by the authors in a subsequent study [55]. The chilling process was determined to be solely dependent on the volume proportion of the nanoparticles and unaffected by the type of nanoparticles. As determined by the experiments, the addition of 5 % nanoparticles to NEPCM substantially accelerates the freezing rate. The refrigeration process was unaffected by nanoparticle volume fractions of 1 and 2 %. Khodadadi and Razaghi [56] conducted analytical research on the impact of nano-copper particles on the thermal conductivity of PCM and natural convection within a square storage model. FLUENT was used to simulate the fluctuations in the buoyancy force and density by employing the Boussinesq approximation model. A comparison of the results of this model with those of other authors is presented in references [210-213], which indicates that the datasets are generally in good agreement. The study found that an increase in the nanoparticle concentration resulted in a decrease in the latent heat of the PCM. According to the findings, as the mass fraction of dispersed particles increased, so did the solidification fraction. This was because of the increased thermal conductivity and decreased latent heat. Rokhforouz and Sheikholeslami [57] obtained comparable outcomes through a numerical investigation of solidification in a rectangular 3-dimensional container containing a PCM and nanoparticles. The inhibitory effect of nanoparticles on natural convection has been identified as the primary cause of heat conduction in both solid and liquid phases of heat transfer. Arunkumar *et al.* [3] conducted an investigation into the experimental behavior of exfoliated graphite nanoplatelets (xGnP) loaded with paraffin wax. The impact of xGnPs on the thermal conductivity, melting temperature, melting time and latent heat capacity of paraffin was investigated. These results indicate a direct correlation between the increase in xGnP concentration and thermal conductivity. The latent heat storage capacity of the paraffin/xGnP composite PCM remained unchanged because the incorporation of xGnPs did not result in a reduction in latent heat. Sady *et al.* [58] conducted an experimental investigation to see how $BaCl_2$-containing TiO_2 nanoparticles solidify and dissolve. The solution underwent a reduction in supercooling owing to the incorporation of nanoparticles, which substantially increased the thermal conductivity and heat transfer. Salmon *et al.* [59] employed fractal theory to simulate the effective thermal conductivity of a PCM liquid containing nanoparticles. In this study, the effects of the particle size and surface adsorption were investigated. When the particle concentration was less than 0.5 %, the model and experimental data exhibited a high degree of concordance. Sathishkumar *et al.* [60] determined the ideal ratio of dispersed particles to PCM to enhance heat transfer and energy storage by employing a theoretical formula that compared PCM with and without dispersed particles. As the fraction of particles increases, the cumulative energy storage capacity decreases because of the reduced volume occupied by the PCM. The instantaneous increase in surface heat flow caused by particle incorporation accelerated the energy storage process. The results of this study indicate that the thermal conductivity of the dispersed fraction has an impact on the ideal quantity of dispersed particles required to maximise the stored energy.

An analogous investigation on planar solidification was conducted by Seifi *et al.* [61]. An experimental assessment of the thermal conductivity of a mixture of nanoparticles and a fluid was performed by Shang *et al.* [62]. Al_2O_3 and CuO nanoparticles with sizes of 28 and 23 nm, respectively, were utilised. The outcomes of combining 2 distinct types of nanoparticles with a range of fluids, including filtered water, motor oil, vacuum-pump fluid and ethylene glycol, were investigated. The impact of the combination preparation method on the thermal conductivity was also examined. Filtration, mechanical milling, and polymer coating of the particles were investigated. The measured thermal conductivities were compared to various theoretical predictions. The observed thermal conductivity deviated from the reported values owing to the use of particles of varying diameters. They found that the thermal conductivity of the mixture increased with decreasing particle size, and varied according to the dispersion method. Sharma *et al.* [63] investigated latent energy storage experimentally and computationally using a phase transition material containing dispersed single-wall carbon nanotubes (SWCNTs), multiwall carbon nanotubes (MWCNTs) and carbon nanofibers (CNFs). A high degree of concurrence was observed when comparing the results of the numerical model with the experimental data. Shen *et al.* [64] illustrates the physical model and 2-dimensional configuration of carbon nanotubes (CNTs) that are incorporated into the theoretical model. Based on the experimental findings, the wax/SWCNT composite demonstrated the most substantial increase in latent heat, followed by the wax/MWCNT composite. The wax/CNF blend exhibits the least improvement. The theoretical model investigates how the mass fraction, size and type of nanoparticles affect intermolecular attraction within the mélange. SWCNTs were found to have a higher molecular density than MWCNTs and CNFs, resulting in a greater amount of latent energy. Subramaniyan and

Ponnusamy [65] conducted an exhaustive examination of the theoretical and experimental approaches used to enhance the thermal conductivity of phase transition materials. In an effort to increase the heat conductivity, they implemented metal materials, carbon materials, oxides as inlays or modifications, and a fin-augmentation strategy. In conclusion, an examination and comparison of different methodologies were undertaken. New techniques for increasing the thermal conductivity of paraffins using carbon have been introduced by Sutheesh *et al.* [66]. The preparation, characterisation and application of the thermal conductivity of carbon nanotubes, as well as the fabrication of the composite PCM with (ExP)/n-eicosane (C_2O), were the primary objectives of this study. According to the results, the mixtures possessed favourable physical characteristics and attributes. The thermal conductivity was enhanced to a greater extent by carbon nanotubes than by (ExP)/n-eicosane (C_2O).

Several studies have documented the use of nanoparticles to improve heat transfer in PCMs [67-73]. The investigations were categorised according to phase-change material (PCM) substances, nanoparticle varieties, research methodologies, charging or discharging processes and validation procedures. It was demonstrated that higher mass concentrations of microencapsulated phase-change material (MEPCM) additives were less effective at high mass flow rates because of the reduced residence time of the additives. Wu *et al.* [74] investigated the impact of various microencapsulated products on the heat transition in gas-fluidised bedding. Microencapsulated phase-change materials (MEPCM) were formed with paraffin and octadecane nuclei encased in cross-linked nylon, gelatin and polymethylene-urea shells. The research findings indicated that the PCM encapsulated in octadecane/gelatin exhibited greater heat transfer efficacy. Furthermore, the heat transmission increased by 85 % during the phase transition compared to the solitary phase. Several studies have documented the use of nanoparticles to improve the heat transfer in phase transition materials [75-79]. Studies were categorised using various metrics and standards that mirrored those used in the previously presented tables.

Design principles

Latent heat storage (LHS) utilises heat stored through processes such as vaporisation or dissolution (solid to liquid or liquid to gas and *vice versa*) within a specific operational temperature range that is virtually constant for purified substances. This is an advantage of an LHS. The storage capacity of LHS with a solid-liquid PCM (QLHS) can be determined using **Figure 1(b)** data, which includes the heat of fusion per unit mass (Δh_p), specific heat (V_p), average specific heat between T_m and T_i (V_{pi}), average specific heat between T_f and T_m (V_{ps}) and a fraction of the molten material. Many studies have elucidated the factors that warrant consideration when selecting materials for latent heat storage. These studies suggest that phase-change materials (PCMs) should possess beneficial thermophysical, chemical, kinetic and economic characteristics. When choosing a PCM for a specific application, it is vital to consider a high enthalpy of fusion and a phase-change temperature within the required operating range. To mitigate confinement issues, an optimal PCM should exhibit additional favourable thermophysical characteristics such as elevated density, specific heat, thermal conductivity, congruent melting, minimal volume variation during phase transition and low vapour pressure at operational temperatures. In addition to possessing properties that prevent corrosion upon encapsulation, nontoxicity, noncombustibility, nonexplosiveness and compatibility with building and container materials, PCMs should demonstrate negligible deterioration, even after multiple cycles. These characteristics are essential for their extended use (**Table 1**). To possess kinetic characteristics, phase-change materials (PCMs) must undergo consistent solidification and melting at a constant temperature with phase segregation, a high nucleation rate to prevent supercooling and a solidification rate that meets the heat retrieval requirements of the storage system. In terms of both quantity and cost, PCM must be affordable. Despite the availability of numerous PCM devices in the market, locating one that fulfils all the criteria for optimal thermal storage may prove challenging and necessitate meticulous system design. To store latent heat, phase transitions, including solid-solid, solid-gas, liquid-gas and solid-liquid transitions, can be utilised. Transition materials from the solid to liquid or solid to solid states are the only materials of practical interest. These categories demonstrate the following characteristics and results: As solid-crystalline PCM materials transition from a crystalline to a non-crystalline state, they retain heat. Owing to the deficiencies of commonly employed solid-liquid PCMs, which necessitate sufficient encapsulation to impede liquid leakage, an alternative method has emerged. However, encapsulation increases product price and reduces the density of the system. Containers are not required when solid-state phase transition materials are used. Another advantage is their reduced volumetric expansion compared to that of solid-liquid PCMs. This characteristic enhances the design flexibility and cost-effectiveness and eliminates the need for containers. Solid phase-change materials regrettably possess a diminished latent heat capacity. Solid-solid latent heat storage materials that exhibit promise include pentaerythritol [$C_5H_{12}O_4$], pentaglycerine [CH_3-C-(CH_2-OH_3)], neopentyl glycol [$(CH_3)_2$-C-(CH_2-OH$)_2$] and their respective mixtures, which are utilised for space heating and process heat applications. When comparing the thermal performance of a Trombe wall constructed with these compounds to that of conventional concrete, a significant improvement can be observed: Solid-gas and liquid-gas phase-change materials (PCM), despite possessing considerable latent heat, are seldom employed for heat storage owing to their inconvenient and impracticable container volume requirements. This hinders their widespread implementation in thermal energy storage, as solid-liquid phase transition materials have a lower latent heat capacity than their liquid-gas and solid-gas counterparts. However, they are frequently utilised in thermal energy storage systems because of their negligible volume change (≤ 10 %), which contributes to the energy efficiency of the system. The investigation and manufacturing of Latent Heat Storage (LHS) materials, including solid-liquid phasechange materials (PCMs), are extensive. Consequently, an extensive variety of alternatives can be used to accommodate the different operating temperatures. Yuan *et al.* [80] introduced a comprehensive classification system for phase-change materials (PCM) in his exhaustive investigation. This system has been widely applied and referenced by numerous scholars.

Solid-liquid PCMs can be broadly classified into 3 categories according to their chemical composition: Eutectics, inorganic compounds and organic chemicals. The enzyme and melting temperature range classification of substances suitable for latent heat storage was proposed by Zhang *et al.* [81]. Organic solid-liquid phase-change materials (PCMs) typically exhibit chemical stability, broad temperature stability and substantial latent heat of fusion. Moreover, these compounds exhibit minimal or no supercooling when frozen. They dissolve congruently, exhibit minimal latent heat of fusion loss, are noncorrosive, and are frequently compatible with other building materials. Paraffin-based and nonparaffin-based organic phase-change materials (PCMs) are 2 variables. Paraffin organic PCMs, denoted by the chemical formula [C_nH_{2n+2}], are saturated hydrocarbons composed of an assemblage of n-alkanes that are linear hydrocarbon chains. The melting point of the PCM is proportional to the number of carbon atoms in the paraffin formula. Wax paraffins have a broad melting point range of approximately 70 °C and are inexpensive, dependable, safe and noncorrosive. Low vapour pressure and negligible segregation during the phase transition contribute to their storage density, which ranges from 120 to 210 kJ/kg. Differential Scanning Calorimetry (DSC) research by Zhang *et al.* [82] demonstrated that paraffin compounds do not substantially lose their thermal properties despite undergoing multiple heat cycles. On the other hand, paraffin waxes possess unfavorable characteristics such as significant variations in volume, elevated combustibility, restricted thermal conductivity of around 0.2 W/m K, and incompatibility with plastic containers. Non-paraffin organic molecules such as sugar alcohols, glycols and fatty acids possess advantageous thermal properties that aid in melting and freezing transitions. Fatty acids, comprising carbon (C), hydrogen (H) and oxygen

(O), are denoted by the general formula $[CH_3(CH_2)_{2n}\cdot COOH]$, where n represents the atomic number, and are the most intriguing class of molecules. Fatty acids exhibit a comparatively elevated heat of fusion, varying between 155 and 180 kJ/kg, in addition to a melting and freezing range of approximately 16 - 65 °C. The 6 most prevalent categories of fatty acids, each consisting of 8 - 18 carbon atoms per molecule, were caprylic, capric, myristic, palmitic and stearic acids. Fatty acids, which belong to the non-paraffin family, are extensively used owing to their advantageous properties. However, their high flammability restricts the availability of compounds with transition temperatures that are suitable for human thermal comfort. When the phase transformation temperature exceeds 100 °C, sugar alcohol organics can be utilised in waste heat recovery applications and solar plants at temperatures below 200 °C. Despite being 2 to 3 times more expensive than paraffin phase-change materials (PCMs), they comprise the largest subset of the latent heat storage (LHS) group. These substances exhibit variability in toxicity, undergo thermal instability and exhibit specific corrosion characteristics. Organic solid-liquid phase-change materials (PCMs) have been extensively employed owing to their evident benefits. However, their moderate flammability, high volume change, and inadequate heat conductivity must be regulated through the container selection and system design.

Table 1 Comparison of required mass and weight of LHS and SHS substances to store 10^6 kJ with $\Delta T = 15$ K [68-77].

Items	Sensible heat storage		Latent heat storage	
	Rock	**Water**	**Organic PCM**	**Inorganic PCM**
Required weight of storage (kg)	68,000	17,000	5,500	4,680
Required volume of storage (m^3)	33	18	6.7	2.8

According to the literature, phase transition materials with melting/solidification temperatures between 20 and 30 °C are deemed adequate for use in construction [73-81]. The organic solid-liquid PCM alternatives listed in **Figure 1(a)** are viable options for space heating and cooling temperature regulation in buildings, and salt hydrates, metallic alloys and molten salts are all examples of inorganic solid-liquid phase-change materials (PCMs). In general, they possess a substantial volumetric latent heat storage capacity and a high latent heat of fusion, both of which are approximately double those of organic molecules. Inorganic compounds are more cost-effective than their organic counterparts, undergo less volumetric variation during melting and possess a thermal conductivity of approximately 0.5 W/m K. Prominent deficiencies such as corrosion, breakdown and overcooling have the potential to impair the properties of PCM and diminish the system's long-term efficacy. The inorganic substances listed in **Figure 1(c)** are viable options for the regulation of indoor temperature via heating and cooling mechanisms, and the phase transition materials that have received the most attention and research attention are salt hydrates. Various salt compositions were used to achieve the desired phase-transition temperature. The transformation of salt hydrates from solid to liquid is induced by the removal or addition of water molecules; this process is thermodynamically analogous to solidification or dissolution. There are 2 potential dissolving states for hydrate salts: Anhydrous salt and water, or salt hydrate containing fewer molecules of water. The classification of the melting process as congruent, incongruent or semi-congruent is contingent on the composition. Salt hydrates are reasonably toxic, inexpensive and noncombustible, and exhibit acceptable thermal properties. Additionally, they can be placed in plastic containers. The principal obstacle associated with the use of salt hydrates as a medium for energy storage is the incongruent melting. The inability to completely dissolve the crystalline salt can be attributed to insufficient water discharge during crystallisation. The hydrate or anhydrous salt often settles at the base of the container because of the disparity in density, which reduces the likelihood that it will combine with water during the subsequent solidification stage. Consequently, salt hydrate may solidify or dissolve permanently, and its quantity may diminish with each load-unload cycle. This issue can be resolved by applying thickening agents, mechanical churning or compositional modification. Additional concerns regarding phase segregation and supercooling have been borne by those using salt hydrates. To prevent liquid-phase supercooling prior to crystallisation, nucleating compounds may be introduced, which may be maintained in a small frigid zone to function as nuclei or rough heat-exchanging surfaces may be employed on the container walls to facilitate nucleation. Thickening agents, revolving storage systems and direct-contact heat exchange can be used to prevent salt segregation. Molten salts and certain metallic phase-change materials (PCMs) have the following properties: High thermal conductivity, low specific heat, minimal volume change and high heat of fusion per unit volume. Owing to their significantly high transition temperatures, these materials are extensively utilised in processes, such as waste heat recovery and solar power generation, which operate at 200 °C. Frequently, eutectics consist of multiple components characterised by low melting temperatures, which undergo simultaneous solidification and dissolution to merge their crystal structures. In contrast to alternative phase-change materials (PCMs), eutectics have the advantage of allowing for modified melting points via the amalgamation of different proportions of component weights. Etictic phase-change materials (PCMs) are favoured for construction-related heating and cooling applications because of their single melting temperature, high volumetric thermal storage density and benefits associated with congruent melting and freezing. Limited data exists regarding the thermophysical properties of eutectic PCMs. The use of certain fatty eutectics with PCM wallboards is contraindicated because of their potent odour. **Figure 1(d)** shows the prevalent eutectics of the organic and inorganic compounds used in construction. Several renowned multinational manufacturing corporations manufacture phase-change materials (PCMs) on an international scale, such as EPS Ltd. in the United Kingdom, Cristopia Energy Systems in France, PLUSS and TEAP in India, Climator in Sweden and Rubitherm GmbH in Germany. **Figure 1(e)** shows a compendium of the thermophysical properties of several commercial phase-change materials (PCMs) with melting and solidification temperatures ranging from 19 to 30 °C.

Chemical composition

A phase-change material (PCM) solidifies and thaws in discrete transformation phases via heat-transfer fluid (HTF) or heat-source exchange. To develop, evaluate and enhance LHTES systems, it is critical to understand the modelling techniques and heat transfer characteristics of the phase transformation process. The Stefan issue pertains to the phase-change phenomenon observed in phase-change materials (PCMs), which encompasses not only stationary boundaries within the PCM domain but also a dynamic boundary-separating phase. Solidification and liquefaction are 2 thermal processes used in latent heat storage. Storage occurs when thermal energy is absorbed and assimilated by a solid phase-change material (PCM), which causes melting. Through the liquid solidification process, the latent heat energy is extracted from the PCM. During solidification, the PCM undergoes a phase transition, in which it first dissolves into a solid, then transforms into a mushy state, and ultimately back into a liquid state. It is an inexpensive material with intermediate density, ductility, and suitability for heat transfer systems. Several studies have provided evidence for the utility of fins in diverse configurations and shapes for LHTES systems. Considerable research effort has been devoted to LHTES concepts that utilise a hot/cold Heat Transfer Fluid (HTF) for heat storage and retrieval, similar to solar air or water heaters. A heat sink reservoir-functioning system is commonly employed in electronic cooling applications and employs a hot/cold boundary wall. Heat-sink-based LHTES systems omit the need for a heat-transfer fluid (HTF); instead, fins are positioned within the phase-change material (PCM). Fins are frequently affixed to the side of a phase-change material (PCM), which possesses a reduced relative thermal conductivity in heat transfer fluid-based Latent Heat Thermal Energy Storage systems. Zhao *et al.* [83] conducted an experimental investigation of PCM solidification in a finned vertical tube, considering both conduction- and natural-convection-controlled heat transmission. It was observed that conduction dominated heat transmission when the liquid temperature approached its melting point. However, once the liquid temperature surpassed its melting point, the natural convection was assumed to be controlled. Zhou *et al.* [84] investigated the phase-change phenomenon occurring within a cylindrical annulus featuring rectangular axial fins affixed to the inner tube's outer surface, employing the finite difference method. The authors discovered that the incorporation of fins into latent heat storage devices improved their thermal performance. By numerically analysing the transitory behaviour of the system, Abdel-Mawla *et al.* [85] examined a shell-and-tube storage unit comprising a heat transfer fluid (HTF) within the interior tubes and a phase-change material (PCM) on the shell side. In light of the natural convection of the PCM that was dissolving, parametric investigations were conducted to examine the impact of different parameters and the presence of fins on the storage unit's thermal behavior. The performance was enhanced by the annular fins at moderate flow rates and low HTF inlet temperatures. Abdelkareem *et al.* [86] conducted research on enhancing the heat transmission in a thermal storage system by incorporating a cylindrical vertical tube filled with PCM and an internal longitudinal fin. The total solidification period for a finned configuration in a heat-transfer fluid (HTF) system comprising 2 tubes, 1 cylindrical and 1 vertical, is approximately 1/n that of a fin-free design, where n denotes the number of fins. The negative aspects of the internal finned tube design include the challenge of affixing fins to the interior tube containing PCM. According to literature, this is considered a significant obstacle to the implementation of this arrangement. Aghakhani *et al.* [87] investigated the solidification process of a phase-change material (PCM) within a larger tube containing an externally filtered heat transfer fluid (HTF) tube. The investigation revealed that although the fin thickness had no discernible impact, increasing the number of fins resulted in an approximately 14 % reduction in the solidification rate. Ahmed *et al.* [88] numerically investigated the efficacy of a Latent Heat Thermal Energy Storage (LHTES) system with enhanced Heat Transfer Fluid (HTF) tubes in a solar thermal power plant using the enthalpy method. The phase-change material (PCM) utilised a molten salt mixture consisting of 80.55 % LiF and 19.5 % CaF_2. They evaluated 3 modified finned tubes in addition to a smooth heat transfer fluid (HTF) tube. The 3 types of tubes are helical-finned, dimpled and cone tubes. According to the results, the melting durations of the dimpled, cone-finned, and helically finned tubes were reduced by 19.9, 26.9 and 30.7 %, respectively. Oskouei *et al.* [50] discovered that by increasing the HTF inlet temperature, mass flow rate, and fin height, the PCM heat charging rate can be accelerated and the charging time reduced. Al-Mamun *et al.* [89] investigated the melting of paraffin wax in a thermal storage system comprising vertically organised fins positioned between a heated and chilled horizontal finned-tube configuration. The experimental data illustrated the formation of buoyant flows near the vertical fins. This flow accelerated the melting of the solid wax and generated a descending draft along the solid surface, which was subsequently cooled. Al-Rashed *et al.* [90] conducted an experimental investigation of a low-temperature thermal storage system employing sodium acetate trihydrate ($CH_3COONa_3.H_2O$) as the phase-transition material, utilising both finned and unfinned tubes. This study assessed the influence of water flow rate and input temperature on the heat transfer coefficient during chilling. The study revealed that the heat transfer coefficient of the thick-finned tube system was approximately double that of the unfinned tube system. In contrast, heat transmission was unaffected by narrow fins. Alagumalai *et al.* [91] conducted an experimental assessment of the heat transmission characteristics in an LHTES unit, both with and without finned surfaces, throughout the solidification and melting phases, utilising paraffin as the phase-transition material. The impact of the fins on the melting rate was negligible, with natural convection serving as the predominant means of heat transfer throughout the melting process. Conduction was the predominant mode of heat transmission during solidification. These results demonstrate that the solidification period of the fins decreased by 40 %.

Ali *et al.* [92] examined the impacts of various fin characteristics, such as fin spacing, fin diameter, and HTF flow parameters, on a shell-and-tube LHTES system. According to these findings, the dimensionless energy storage increased as the fin radius and spacing decreased. Ali *et al.* [93] conducted an experimental investigation into the heat transmission properties of stearic acid melting processes within a thermal storage unit. An outer tube, electrical heating rod and PCM comprise the apparatus, which is designed to occupy the space between the annuli. Round fins encircled the heating rod to augment heat transfer with the PCM. The fin facilitates enhanced heat conduction and natural convection, thereby influencing the thermal characteristics of the melting process. The incorporation of fins into the PCM led to an estimated 3-fold increase in thermal conductivity. The reduction in fin pitch resulted in an augmentation of the melting process. Almasri *et al.* [94] investigated 3 horizontal concentric tube storage units: As shown in **Figure 1(f)**, 2 of the units had circular and longitudinal fins, whereas the control PCM unit had no fins. Following an empirical examination of the thermal efficacy of 3 distinct configurations, the researchers ascertained that the system incorporating longitudinal fins exhibited the most favourable thermal response throughout the melting process. Alva *et al.* [95] devised a thermal energy storage prototype by incorporating extended graphite (EG) fins with high conductivity and a eutectic composition of KNO_3/$NaNO_3$ as the phase-change material (PCM) to enhance heat transfer efficiency. They utilised a quasi-static mathematical model to assess the thermal performance of EG/PCM, which was subsequently validated through experimentation. Basalike *et al.* [96] assessed the thermal efficiency of an air heat exchanger system comprising a PCM by utilising tubes with fins, both internally and externally. Their findings indicated accelerated energy transfer from the PCM to air, resulting in an increase in the temperature of the exhaust air. Cabaleiro *et al.* [97] state that fins enhance the energy storage and discharge capabilities of an LHTES unit. A reduction in fin pitch results in an increase in the surface area of the heat transmission and a subsequent decrease in the volume of the PCM, both of which abbreviate the melting/solidification period. Chavan *et al.* [98] conducted an experimental study to examine the impact of incorporating longitudinal fins on the processes of melting and solidification within a shell-and-tube LHTES system. The findings revealed that the melting time decreased by 12.5 and 24.52 % when the HTF inlet temperatures were 80 and 85 °C, respectively. In a computational fluid dynamics (CFD) investigation, Christopher *et al.* [99] utilised Y-shaped fins within a shell-and-tube LHTES system. The unit achieved a 24 % improvement in the system efficacy, as indicated by the data. According to the findings of researchers, long-term operation requires smaller angles, whereas short-term operation is better adapted for Y-shaped fins with broad angles between the branches. Cui *et al.* [100] investigated the impact of operating parameters and fin geometry on the solidification and melting processes of phase-change materials (PCM) within fin and tube heat exchangers. The commercial implementation of triplex-tube heat exchangers (TTHX) may be advantageous in the culinary, beverage and pharmaceutical sectors. Three-concentric-tube heat exchangers have recently been developed in the energy-storage industry. Latent heat applications involve the placement of a phase-change material (PCM) between 2 heat-transfer fluids (HTFs), with 1 HTF traversing the inner tube and the other traversing the annulus outside the tubes. Cui *et al.* [101] employed a 2-dimensional numerical model and computational fluid dynamics (CFD) to examine the melting rate of a phase-change material (PCM) within a triplex finned-tube heat exchanger. Pure conduction and natural convection were investigated as potential heat-transfer mechanisms. This study indicates that augmenting the fin thickness does not significantly affect the melting rate; however, the length and quantity of the fins have a substantial effect. The TTHX form required 34.7 % less time to dissolve completely, with most fins. By employing computational methodologies, Deng *et al.* [102] examined the solidification of PCM in a TTHX while analysing the effects of internal and external fins and considering both pure conduction and natural convection. The results suggest that the impact of fin length was significantly greater than that of fin girth. The TTHX form, which contained the highest number of fins, solidified 35 % faster than the other forms. When examining the melting process of RT82 in a TTHX system, Dhaidan *et al.* [103] considered charge techniques, including inner tube heating, dual-side heating, and outer-tube heating. They evaluated 3 distinct configurations, as depicted in **Figure 1(a)**: A TTHX with internal fins, an arrangement of exterior fins and a TTHX with internal-external fins.

A comparative analysis revealed that the PCM melting rate did not differ significantly between the 3 configurations. In contrast to the TTHX-lacking fins, the incorporation of internal-external fins significantly decreased the complete melting time of the PCM by 43.3 %. Heat rejection, or heat sinking, is a common application of LHTES, which is employed in chill photovoltaic cells and electronic devices. PCM-based heat sinks effectively and passively absorb dispersed heat from a component to chill its surface without requiring mechanical input. HTFs or heat transfer fluids are not utilised in heat sink systems. In contrast, direct contact between the surface and the phase-change material (PCM) or its container results in the transfer of heat. Fins are frequently incorporated into PCM to improve the heat-transfer mechanism in such systems. Fins are frequently employed as constituents of heat-sink systems. Ding *et al.* [104] conducted a transient simulation of the PCM melting process in a heat sink featuring an air-exposed open-top, vertical internal fins, and a horizontal base maintained at a constant temperature. The results indicate that the temperature and geometric properties of the system affect the transient melting of the PCM. A quantitative investigation was conducted by Du *et al.* [105] regarding the performance of a rectangular heat sink unit utilising a PCM and internal fins. According to parametric research, the vertical placement of the unit in relation to the ventilation direction resulted in a heat transfer rate twice as high as that of the horizontal placement. When fins were extensively disseminated, the minimum augmentation rate increased by a factor of 3. Eckert *et al.* [106] evaluated the thermal performance of a rectangular heat sink system both with and without interior fins. The findings indicated that although augmenting the fin thickness produced a comparatively moderate enhancement, the spherical and vertical fin counts enhanced the overall thermal efficiency of the heat sink. As stated by researchers, heat conduction is the primary mode of heat transfer during the initial melting phase. Feng *et al.* [107] devised an analytical model to forecast the rate of phase transition material fusion within a metal enclosure equipped with internal fins. By facilitating the transformation of PCMs within the interstices of the fins into a liquid, rectangular horizontal fins accelerated the melting process and induced deceleration during the melting process. Ganesh and Omprakash [108] discovered that internal fins improve the efficacy of PCM-based heat sink systems irrespective of the PCM type. Gao *et al.* [109] investigated various configurations of heat sink units based on PCMs, encompassing honeycomb cavity architecture, parallel fin arrangement, cross fin arrangement, and single cavity, all of which utilized PCMs with distinct melting points. An increase in the number of fins facilitated heat dispersion into the PCM, leading to reduced peak temperatures in the heat sinks. **Figure 2(a)** shows the aggregation of the experimental and numerical investigations of finned LHTES systems. The review results indicate that fins enhance heat transmission in LHTES systems during phase transition irrespective of composition and shape.

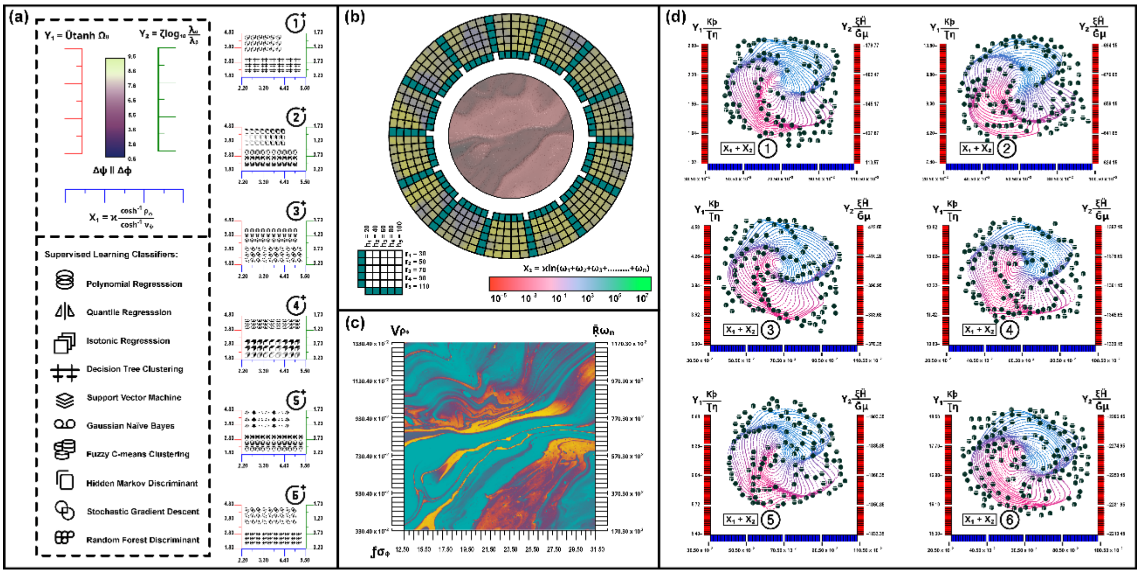

Figure 2 (a) Machine learning appraisal of PCMs in 4 storage unit/heat exchanger set-ups in a 45 kW LiBr-H_2O solar absorption cooling system found that multitube design melts/charges quickly, while longitudinal fin design melts uniformly and can discharge without subcooling PCM encapsulation (thereby (i) enhancing heat transfer surface area, (ii) minimizing phase segregation to boost thermal conductivity, (iii) heavily limiting PCM volume variation with operating temperature, (iv) avoiding leakage during phase-change operation systems cycle in under 24 h sun collectors at different sun radiation levels), where vapor condenses into water in the dephlegmator and the condenser cools refrigerant at high pressure by rejecting heat to the environment through expansion valves (Note: refrigerant enters the evaporator and absorbs load heat before going to the absorber through a pre-cooler), all represented as stacked hierarchical band structure (simulated in 6-sets via nominal range sensitivity analysis) of supervised learning classifiers within the Trellis-density correlations, clustered by double Y-axes' offsets in standard XY scale; (b) Sankey-visualization of stacked histogram plots illustrating a normal distribution of 10 kW aqua ammonia absorption system and 5 kW NH_3-H_2O absorption system, which utilise flat plate heat exchangers, experiencing cooling failure due to a decline in COP with generator temperature, that is caused by an overfeed of evaporator PCM as a heat transfer fluid, (which reduce the charging time to 58 and 86 % for high HTF mass flow rate and low HTF inlet temperature, respectively, wherein the reduction in charging time is attributed to factors such as the material's thermal conductivity, storage container design, mass flow rate, insulation, gravity, known issues with the material, and nano-particle suspension), depicted alongside a spectroscopic packing of Bland-Altman density data pertaining to a 50 MW CSP power plant with heat exchangers, wherein steam turbine, dry cooled condenser, and nourish water heaters, pumps, helper hardware, cold granular tank, hot tank with liquid PCM (in the base form, 24 % of the aggregate salt amount is superheated during the day and stored in the hot energy tank); (c) Exergy efficiency of parabolic trough collector systems from 10 to 30 %, where the melting temperature affects the generator temperature, which influences the evaporator temperature demand. Generators operate best between 80 - 120 °C for subzero temperatures and 60 - 105 °C for cooling, depicted as Schoeller-Contour profile of Hydroquinone, Potassium Thiocyanate, and D-mannitol with greater thermal storage testing water and paraffin, as well as PE-HD foil and aluminum-compound film as 2 PCM (and paraffin as PCM for LHTS systems, depicted alongside a spectroscopic packing of Bland-Altman density data; (d) Stochastic cylindrical resonances highlighting the covariance of PCMs in the building fabric under floors, higher ceilings, windows, shutters and ventilated double-skin facades employing PCMs clustered by double Y-axes' offsets in standard XY scale.

According to the data in **Figure 2(a)**, the majority of studies have examined the relationship between the fin shape and thermal transfer. The impact of the fin count on the thermal response of storage units has received limited attention in scientific research. The results indicated that the rates of PCM solidification and dissolution increased. In contrast to devices employing non-PCMs, which position the fins externally to the PCM and do not influence the HTF flow, this configuration substantially reduces pressure. The feasibility of developing more innovative fin designs was substantiated by a computer analysis conducted by Ghasemi *et al.* [110]. An area of investigation that could be explored is the thermal performance of a finned LHTES system considering the fin count. The HP connects the HTF and PCM via a thermal conduit by means of evaporation and condensation of the working fluid in the evaporator and condenser, respectively, and the heat pipe (HP) connects the HTF and PCM via a thermal conduit. Highpower is an effective method for accelerating the charging and discharging of phase-change materials (PCM) in Latent Heat Thermal Energy Storage (LHTES) systems. This is particularly advantageous in systems characterised by recurring charging and discharging cycles, such as energy recovery systems, heat sink devices and ventilation and heating systems. Various shapes and sizes are utilised in the production of heat pipelines that operate autonomously from external power within predetermined temperature thresholds. The 2 main types of heat pipes are wick-assisted or screen-mesh heat pipes and wickless or gravity-assisted heat pipes, which utilise distinct operational fluids. To maximise the thermal energy storage, the dimensions, geometric configuration and operating temperature range of the storage system determine which form of the heat pump and working fluid are utilised. Shell-and-tube configurations are prevalent in HP storage systems and are effective in enhancing the heat transfer. The cylinders of the carapace, which contain phase-change materials, permit high-temperature fluids to traverse or pass over them. Ghodrati *et al.* [111] conducted a numerical analysis of a solar thermal power plant's high-temperature shell-and-tube latent heat thermal energy storage system in conjunction with heat exchangers. The simulation evaluated the charging and discharging modes in 2 scenarios of the HTF flow pattern, and determined that the inclusion of HPs substantially accelerated the charging and discharging rates. During melting, the phase-change material (PCM) adjacent to the heat-transfer fluid (HTF) conduit retains approximately 13 % of the energy initially held in the PCM near a solitary heat pipe (HP). Ghosh *et al.* [112] conducted research to determine how the number, orientation and arrangement of heat pipes affect the thermal efficacy of an LHTES system. An assessment of the long-term efficacy of HP-embedded topologies was conducted using 3D computational research that incorporated the solidification (discharging) and melting (charging) mechanisms. Model 1, with 4 HPs, was found to be more efficient during both charging and discharging processes. A study conducted by Goel *et al.* [113] examined the dynamic performance of an LHTES system assisted by an HP during cyclic charging and discharging cycles. This study investigates the influence of operational variables and heat pipes (HPs) on the charging and discharging capabilities of a Latent Heat Thermal Energy Storage (LHTES) system. A 2-dimensional numerical model was employed to analyse the transient response of the system, considering the impact of the HP spacing. The following actions were evaluated: (i) exclusive charging; (ii) concurrent charging and discharging; and (iii) exclusive discharging. HP spacing was determined to be the most significant factor in regulating the dynamic responsiveness of the system. Each unit exhibited an energy efficiency of 97 % and the most energy-efficient unit exhibited the smallest HP spacing. Qamar *et al.* [114] conducted an investigation into the impact of high pressure (HP) on the rate of phase-change material (PCM) dissolving within a vertical cylindrical container. In contrast, the melting rates obtained by heating an isothermal surface, a solid rod, or a hollow tube were compared with these findings.

Parametric investigation showed that the PCM melting rate increased significantly more with the HP-assisted method than with a rod or tube. This study indicates that the melting rate increases with increasing condenser length and HP diameter. By utilising heat pipelines, cascaded latent heat storage systems can employ 1 or more channels for charging and discharging. To optimise the heat-transfer rate between the HTF and PCM, the HPs were oriented perpendicular to the HTF flow direction. Alshammari *et al.* [115] devised a thermal network model to examine the effectiveness of LHTES systems incorporating cascaded PCMs and embedded HP/thermosyphons. The signals traverse the channels. Furthermore, exergy analysis was conducted to determine the optimal LHTES configuration. The results indicated that the ((PCM) achieved its maximum exergy efficiency at the lowest melting point. In addition, over the course of a 24-hour charging-discharging cycle, the cascade LHTES system produced perhaps 10 % more energy than the highest-performing non-cascade Latent Heat Thermal Energy Storage (LHTES) system. Alimonti *et al.* [116] conducted an experimental investigation on a Latent Heat Thermal Energy Storage (LHTES) system utilizing heat pipes (HP) and fins. According to their research, the heat transmission during solidification in the HP-assisted configuration is approximately double that in the fin-assisted LHTES and non-HP, non-fin configurations. An additional arrangement of significance that shares parallels with the cascaded storage system is the PCM heat-pipe heat exchanger. The heat transfer fluid (HTF) channels establish thermal contact with the condenser and evaporator sections of the heat pipe, whereas the phase-change material (PCM) is positioned centrally within the HP. To facilitate the cooling of the evaporator section and heating of the condenser, the PCM was charged and discharged simultaneously. Newly developed gravity-assisted HP thermal storage units (GAHP-TSUs) with promising industrial applications have been developed. **Figure 2(b)** summarises several investigations of heat pipe-augmented LHTES systems. Given that the majority of the research on the experimental use of heat pipelines to improve heat transmission in LHTES systems is numerical, future research must be more targeted (**Table 2**). Owing to the possibility of working fluid leakage, the technical difficulty of integrating heat pumps (HPs) with LHTES systems is a primary impediment to additional experimental research in this field. A more comprehensive understanding of the practicality of employing heat pipelines in storage environments will lead to this endeavour.

Table 2 Latent and sensible heat storage variation with temperature for solar thermal power plants with linear Fresnel (LF) collectors based on an MLSPCM TES tank configuration comprising an additional fossil heater.

PCM compound	Melting temperature (°C)	Heat of fusion (kJ/kg)
Butyl stearate	21	142
Propyl palmitate	22	187
Paraffin C_{16}-C_{18}	19.5 - 22.5	153
Polyethylene glycol E 600	21 - 26	147
Dimethyl sabacate	22	122 - 138
Octadecyl 3-mencaptopropylate	23	144
Paraffin C_{17}	22.7	214
n-Heptadecane	23	216
Paraffin C_{13}-C_{24}	23 - 25	191
Octadecyl thioglyate	27	92
Lactic acid	27	185
1-Dodecanol [$CH_3(CH_2)_{11}OH$]	28	201
Vinyl stearate	28 - 31	123
Paraffin C_{18}	29	245
n-Octadecane	29.2	246

PCM compound	Melting temperature (°C)	Heat of fusion (kJ/kg)
Methyl palmitate	31	207
Methyl stearate	32	172
Capric acid	32.1	159

Most published research disregards the impact of heat pipe quantity and alignment on the thermal efficiency of LHTES systems [78-93]. It is imperative to consider these effects when implementing system improvement. According to the literature, using various PCM families is a method for improving the heat transmission in LHTES systems. The thermal efficiency of the system is enhanced by employing multiple PCMs to sustain an even temperature differential between the PCMs and the Heat Transfer Fluid (HTF) throughout the charging and discharging cycles. There is a scarcity of experimental research in the current literature regarding the application of multiple PCMs in Latent Heat Thermal Energy Storage (LHTES) systems. Multiple investigations, including those conducted by Landelle *et al.* [117], demonstrated that the latent heat storage increased by 15 %. Hameed *et al.* [118] conducted an experimental investigation to compare single and cascaded PCM topologies utilizing a melting temperature ranging from 150 - 200 °C. The data indicate that the implementation of cascading phase-change materials (PCMs) resulted in a 19.36 % increase in effectiveness. By utilising a cascaded arrangement, the temperature difference between the input and output of the HTF was displayed more consistently. When employing multiple phase-change materials (PCMs) in Latent Heat Thermal Energy Storage (LHTES), it is necessary to select PCM pairings with melting temperatures suitable for the intended application. **Figure 2(c)** shows a compilation of numerous studies that have examined enhanced latent heat thermal energy storage systems employing multiple phase-change materials. A considerable number of investigations have been conducted on diverse phase-change materials (PCMs), thereby creating an opportunity for more comprehensive experimental scrutiny. The primary objective of numerous heat-transfer enhancement technologies, including fins, heat pipelines and various PCMs, is to increase the heat-transfer area. It is evident from the review that fins are utilised more frequently in published studies than in heat ducts and other PCMs. This may be attributed, at least in part, to technological advancements that have facilitated the arrangement of fins in storage systems, thereby stimulating increased experimental research. Despite their considerable potential in this domain, insufficient experimental research has been conducted on the application of heat pipes and other phase-change materials (PCMs) to enhance heat transmission. It is critical to exercise caution when integrating heat pipes (HPs) into Latent Heat Thermal Energy Storage (LHTES) systems to prevent leakage of HP working fluid. Enhancing the thermal conductivity of phase-change materials (PCMs) is critical for increasing the thermal efficacy of LHTES systems. The thermal conductivity of phase-change materials (PCMs) can be enhanced through the incorporation of low-density components, dispersion of high-conductivity materials or nanoparticles, or the addition of porous materials with high thermal conductivity to the fundamental PCM.

In the following sections, investigations into increasing the thermal conductivity of PCM are detailed, along with suggestions for future research. By incorporating porous materials into the PCM, the thermal conductivity is enhanced, thereby enhancing the thermal performance of LHTES systems [89-116]. The most frequently employed technique in LHTES systems to enhance the thermal conductivity of conventional PCMs is the impregnation of porous materials. The main factor contributing to this disparity is the significantly higher thermal conductivity of the porous material compared with that of the purified PCMs. Hamzat *et al.* [119] identified that the cost-effectiveness of fabricating a form-stable composite PCM by integrating expanded graphite and paraMn is attributed to the absence of encapsulation requirements and additional expenses for heat transfer enhancement. Based on these findings, it is possible to derive the advantages of composite PCM for thermal energy storage applications. Hariss *et al.* [120] investigated the effect of expanded graphite (EG) on the thermal conductivity of a paraMn-based PCM. The PCM composite containing 10 % EG was found to be the most suitable for LHTES applications owing to its stable properties, high thermal conductivity, sufficient melting temperature and latent heat storage capacity. Hassan *et al.* [121] conducted experiments to examine the heat transmission properties of a composite PCM composed of paraMn wax and aluminum. Researchers have investigated the effect of the porosity and pore size of the form on their melting rates. According to these findings, aluminum foams with greater porosity reach a steady-state temperature more rapidly than those with lower porosity. The findings of this study indicate that foams characterised by larger pore sizes achieve a more stable state than those with smaller pore sizes. Researchers discovered that the porosity and pore size of the foam influenced both conduction and convection heat transmission. To enhance the functionality of the wax/aluminium foam composite, it is critical to select the optimal porosity and pore size values. Tchanche *et al.* [122] investigated the thermal efficiency of a solid/liquid phase transition LHTES system employing eicosane as the phase-change material and a copper porous form with a 95 % porosity. The effective thermal conductivity increased significantly with the addition of copper form, from 0.423 to 3.06 W/m K, according to the study. Consequently, the freezing and dissolving periods of the PCM were reduced from 375 to 250 min. Hassanpouryouzband *et al.* [123] discovered that the thermal diffusivity of composite PCM manufactured from graphite and paraMn increased when the graphite form possessed a smaller pore size and thicker ligament. A greater capacity for latent heat storage was achieved in graphite, owing to its thinner ligaments and larger pores. The investigation conducted by Hinojosa *et al.* [124] assessed the effect of various densities of expanded natural graphite matrices on the efficacy of a paraMn-based LHTES system. The data indicate that there is a nearly linear relationship between the bulk density and thermal conductivity of expanded natural graphite, mass ratio of paraMn wax in the expanded natural graphite matrix and latent heat of the composite. Wu and Homa [125] utilised metal foams, expanded graphite, and $NaNO_3$ as phase-change materials (PCMs) in an experimental investigation into the enhancement of heat transfer in thermal energy storage systems. The results of the investigations were compared in cylindrical containers with and without expanded graphite and metal foams. Compared to unadulterated $NaNO_3$, the addition of porous materials during the heating phase at 250 - 300 °C increased the rate of heat transmission by approximately 2.5 times.

Previous research has focused on improving the heat transfer in inorganic phase transition materials to develop high-temperature latent heat thermal energy storage systems [93-112]. Carbon nanotubes (CNT), nanowires (NW) and nanopowders including Al, CuO, Cu and SiC are required for this purpose. The thermal conductivity of conventional phase-transition materials is enhanced when nanoparticles are incorporated. Husainy *et al.* [126] examined aluminum powder as a potential means of increasing the thermal conductivity of paraffin wax in a solar collector with a small PCM. According to the test results, the charging time was reduced by 60 % when aluminum powder was added to the wax. The utilisation of a greater quantity of heat was achieved during the discharge process when aluminum powder was added to paraffin wax, as opposed to using paraffin wax alone. Ismail *et al.* [127] examined the melting characteristics of Al_2O_3/n-octadecane nano-PCM in an unevenly heated square vertical container. They investigated the impact of dispersing nanoparticles on heat transfer, as illustrated in **Figure 2(d).** The study revealed that an increase in the mass percentage of nanoparticles in nano-PCMs impedes the transmission of natural convection heat in the melting region of the enclosure, as opposed to conventional PCM. Javadi *et al.* [128] investigated the thermal conductivity and viscosity of n-octadecane/TiO_2 nanoparticles through experimental means. The findings of this study indicate that heat conductivity exhibits a non-monotonic pattern in both liquid and solid states. The maximum increase in the thermal conductivity of the solid phase was observed at a nanoparticle concentration of 3 wt. %. Jebasingh and Arasu [129] examined the effects of carbon nanoparticles applied to PCM on the thermal efficiency of LHTES systems. Three distinct types of nanoparticle samples were investigated: Carbon nanofibres, single-walled carbon nanotubes and multiwalled carbon nanotubes (MWCNT). The data indicate that the latent heat value of each sample was greater than that of the purified wax. Numerous studies have indicated that the application of MWCNTs to enhance the thermal conductivity has garnered considerable interest. According to Ji *et al.* [130], the thermal conductivities of carbon nanotube-palmitic acid (PA/CNT) and PA/MWCNT composite phase-change material (PCM) increase as the mass fraction of CNTs and MWCNTs increases. Jiang *et al.* [131] synthesized and analyzed the thermal properties of a nanocomposite unit consisting of paraMn wax and multi-walled carbon nanotubes for heat storage. The thermal conductivity increased by 35.0 % in the solid state and 40.0 % in the liquid state. Jilte *et al.* [132] investigated the impact of dispersed multiwalled carbon nanotubes in liquid paraMn on heat transmission. Research has demonstrated that augmenting the volume fraction of carbon nanotubes (CNTs) results in an enhancement of the thermal conductivity of the composite material, irrespective of temperature fluctuations. Junaid *et al.* [133] determined experimentally the effect of varying volume fractions of MWCNT on the heat transfer and thermal efficacy of stearic acid during the charging and discharging phases. Although the utilisation of MWCNT significantly enhanced the thermal conductivity, it impeded the natural transport of liquid stearic acid. The discharge rate of the storage system increased exclusively when the volume fraction of the additive was less than 5.0 %. In contrast to the findings of Kalidasan *et al.* [134], the incorporation of MWCNTs into paraMn as a PCM resulted in greater efficiency than the use of graphite. In their experimental study, Kalnæs and Jelle *et al.* [135] examined the impact of different carbon nanofillers on the thermal properties of paraMn-based nanocomposite PCM. The experimental setup included carbon nanofibres, graphene nanoplatelets (GNPs), and short and long multi-walled carbon nanotubes (MWCNT). The thermal conductivities of the solid-phase samples at high temperatures were determined using the transient hotwire method. The nanofiller forms were found to have a substantial effect on the thermal conductivity of composite phase-change materials (PCMs), as determined by researchers. Although their energy storage capacity was relatively limited, GNPs demonstrated the greatest promise in terms of enhancing thermal conductivity.

Additional studies have reported the thermal characteristics of carbon nanofibres (CNF) and carbon nanotubes (CNT) incorporated into phase-change materials (PCMs) such as soy wax and paraMn wax [136-140]. To create composite phase-change materials, cellulose nanofibres (CNF) and carbon nanotubes (CNT) were combined at 60 °C. The contamination concentrations of the nanotubes and wax were 1, 2, 5 and 10 % by weight. Carbon nanotubes (CNT) and cellulose nanofibers (CNF) both increase the thermal conductivity of the composite material, as shown by the results. CNF are more effective than CNT owing to their uniform matrix dispersion. Kumar *et al.* [141] used a palmitic-stearic acid (PA-SA) eutectic composition as a PCM and CNTs to generate diverse Latent Heat Thermal Energy Storage (LHTES) composite phase-change materials (PCMs). The study findings indicate that the PA-SA/CNT composite PCMs exhibit elevated freezing temperatures but reduced thawing temperatures compared with pure PA-SA. In composite phase-change materials (PCMs), thermal conductivity is directly proportional to the bulk percentage of carbon nanotubes (CNTs). Heat pipes, each featuring fins connected to the condenser portion of each pipe, were introduced into the PCM either individually or in groups of pipes. As the length of the fins increased, the temperature differential within the phase-change material (PCM) in the container decreased, resulting in a more uniform temperature distribution within the PCM, according to the study. In addition, the rate of PCM melting was accelerated by natural convection, leading to a 30 % reduction in the total charging duration. Lachheb *et al.* [142] were able to simulate a high-temperature LHTES system in 3 dimensions using finned heat pipes. A vertical cylindrical container was filled with phase-change material

(PCM) in the form of a eutectic mixture of potassium and sodium nitrate with a melting point of 220 °C. Increasing the number of heat pipelines expedites the charging process by reducing the thermal resistance of the system.

Laouer *et al.* [143] analysed the thermal efficacy of a Latent Heat Thermal Energy Storage (LHTES) system featuring a finned heat pipe (HP) throughout the solidification phase. Compared with the standard configuration, the stored energy in the 12-HP design increased by 140 %. Li *et al.* [144] focused on a solar LHTES system comprising multiple PCMs and fins designed solely for charging purposes. Their investigation revealed that different PCMs melted at a higher rate, whereas the HTF exit temperature remained constant. An investigation was conducted using heat pipelines and metal foils to accelerate the solidification and melting of a phase-change material (PCM) in a Latent Heat Thermal Energy Storage (LHTES) system. This study employs a combination of computational and experimental methods. Compared to a standard copper rod with the same physical dimensions as the heat conduit, the HP-foil configuration transmitted heat at a faster rate, as demonstrated by the results. In contrast to solid metallic extended surfaces, the incorporated HP-Foil technique implements a reduced amount of metal, potentially leading to a more economical and lightweight design than traditional methodologies. Li *et al.* [145] designed and developed a fin-copper foam unit containing paraMn. The comparison analysis revealed that the copper foam/paraMn composite featuring a 1.0 mm fin possesses an effective thermal conductivity of 11.4 W/m K. This value is 3.7 times greater than that of the copper foam/paraMn composite lacking the fin and 42.2 times greater than that of pure paraMn. To determine the effects of the LHTES system inclination, Liang *et al.* [146] examined 6 configurations for enhancing heat transfer: HP-Foil-PCM, HP-Foam-PCM, HP-PCM, Rod-PCM, Foam-PCM and non-enhanced PCM. The research findings revealed that conduction-dominated heat transfer acted as the primary catalyst, with no discernible impact of system orientation on the solidification rates across all cases examined. In the absence of foils or foam, the orientation of the system during the melting cycle causes natural convection, which substantially modifies the liquid fraction history. The utilisation of heat pipelines lined with foils or foam results in elevated rates of solidification and dissolution, as opposed to a system that offers no gains. Licht *et al.* [147] conducted transient computational research on a metal foam-augmented LHTES system with embedded heat pipelines. It was observed that, as the pore density of the metal foam increased, the increase in the heat transfer rate during charging diminished because buoyancy-induced convection currents could not form. An earlier study [127] examined numerous endeavours that integrated the 2 enhancement methodologies for LHTES systems. In most studies, finned heat pipes have been used to improve the heat transfer. Additional innovative techniques, including fins, multiple PCM configurations, metal foam fins and metal form-heat pipelines, are still in their infancy, but could provide future researchers with intriguing topics to investigate. An overview of the literature concerning the mathematical modelling of enhanced LHTES systems is presented in **Figure 3(a)**. Energy analysis and the second law are not utilised in most research endeavours. Consequently, conducting energy analyses of enhanced LHTES systems could become an important area of study in the future.

Mechanical components

Latent heat-storage materials have been utilised in thermal applications for many years. They are categorised based on the physical modifications that they undergo to absorb and discharge heat. **Figure 3(b)** shows the benefits and drawbacks of organic and inorganic PCMs, in addition to their impact on solar cooling applications. Change materials (PCMs) are highly suitable for solar cooling applications because of their consistent phase-change temperatures, absence of phase segregation, ability to impede supercooling and non-corrosive characteristics. Paraffins and non-paraffins are 2 types of organic compound, with paraffins possessing several beneficial characteristics and a limited number of significant drawbacks. Non-paraffinic substances comprise the largest category of latent heat storage materials. They include esters, alcohols, fatty acids and glycols. However, these materials also have several drawbacks. Thermal stability is essential for withstanding cyclic loads. Supercooling is the most undesirable characteristic that drastically reduces the thermal performance. Despite the widespread use of inorganic phasetransition materials in high-temperature solar applications, maintenance is often cited as a significant obstacle. They freeze in frigid weather, and become difficult to manipulate in humid weather. Solid salts, salt hydrates and metal alloys are constituents of these materials. Most research has been conducted on salts and salt hydrates, which belong to the category of inorganic solid-liquid phase-shift materials. The reduced volume change during the phase transition was a result of the high latent heat of fusion per unit volume, low thermal stress and enhanced thermal conductivity. The proportion of anhydrous salt in the water fluctuated during dissolution. This type of melting can be categorised as congruent, incongruent or semi-congruent. Liu *et al.* [148] identified several significant disadvantages associated with inorganic salts in their review. These include, but are not limited to, volume change, low heat conductivity, subcooling (salt hydrates), corrosiveness and high costs. Metals with low melting points and their alloys are ideal for use as liquid metals in latent heat storage materials, owing to their exceptional thermal conductivities. They have superior heat transfer capabilities compared with conventional PCMs owing to their low heat of fusion per unit weight, high electrical conductivity, and minimal volume change. This substance has extensive solar applications owing to its ability to meet the stringent requirements of large-scale power facilities. Eutectic materials are mixtures of 2 or more organic or inorganic compounds with low melting points and comparable freezing and melting points. The melting point of the eutectic mixture could be modified by adjusting the weight proportion of each element. The resultant mixture possesses the distinctive characteristic of a melting point that can be precisely adjusted to meet the given demand. An abundance of opportunities for solar cooling applications have been unveiled, as these materials acquire novel properties. In addition to their flammability and limited heat conductivity, organic PCMs offer several advantages over inorganic PCMs. Inorganic phase-change materials (PCMs) are readily available, inexpensive, noncombustible and possess remarkable thermal conductivity and heat-storage capabilities. Determining the precise PCM thickness and location of the solid-liquid interface constituted the exclusive objectives of the 2 models. To fabricate a specialised miniature PCM solar collector, Hinojosa *et al.* [124] submerged a solar absorber in solid paraffin wax. During the charging procedure, the average heat transfer coefficient increased substantially owing to natural convection. Increasing the water mass flow rate, on the other hand, is the only method to maximize the usable heat gain during the discharge. The 53.5 °C was the melting point of paraffin wax. Lizana *et al.* [149] investigated a single-effect absorption cooling system consisting of 30 kW LiBr/H_2O and 90 m^2 of double-glazed flat-plate collectors. The efficacy of the system was replicated and tested using a 1,500 L hot-water reservoir to ensure a consistent flow of hot water. Situated at a 30 ° inclination toward the vertical, a flat-plate solar collector measuring 1 m in length and 0.125 m in depth implemented a transient finite-volume model to forecast the heat absorption and storage. The collector-incorporated PCM slurries and water at different concentrations (10, 15, 20, 25 and 30 %) had a melting point of 65 °C. By retaining heat for a prolonged period with the PCM slurry, a greater proportion of solar energy was conserved, but at the expense of a reduced solar collection efficiency. This was because of the decreased specific heat capacity of the PCM relative to that of water. In contrast to water-in-glass evacuated-tube solar collectors, PCM-integrated solar collectors exhibit diminished heat transmission and inferior thermal performances [150].

Malwe *et al.* [151] conducted a mathematical analysis of an evacuated tube heat pipe solar collector that was integrated with PCM in the overhead reservoir in order to operate as a latent heat storage system. The vessel was equipped with a finned heat exchanger to supply thermal energy to water during motion.

The LHESS header was affixed to the heat pipelines of evacuated-tube collectors. The revised system outperformed the baseline system in terms of thermal management and the efficiency remained constant as the flow rate increased. They recommended conducting additional parametric investigations regarding the topic, and material selection was the first and most crucial phase in developing latent heat thermal energy storage. To determine the PCM, the enthalpy of fusion and melting point are considered. The thermal specifications and the requisite temperature range for a given application are the primary factors that determine the material. The physical and chemical characteristics of the PCM and its disadvantages were considered during the selection process. Various temperature ranges are specified for each application, as shown in **Figure 3(c)**. Numerous studies have compiled a list of phase-change materials (PCMs) and their thermophysical properties for potential applications. Thermal analysis in the laboratory employs a heat flux differential scanning calorimeter (hf-DSC) to evaluate the heat storage capacity of phase-change materials (PCMs) under conditions of continuous heating or cooling. Various phase-change materials (PCMs) been implemented in solar cooling applications in accordance with the specific temperature range required. Masood *et al.* [152] investigated a variety of PCMs with melting points ranging between 80 and 100 °C for use in solar cooling systems. Subcooling, incongruent melting and allotropic phase transitions were identified as issues of PCM with high latent heat encounters. Furthermore, commercially available eutectic compounds, such as PlusIce A82, S83 and S89, exhibit a reduced heat of fusion and enhanced stability. Mitra *et al.* [153] chose D-mannitol and hydroquinone as phase-change materials (PCMs) for applications spanning 140 - 200 °C temperature. The storage temperature range was determined by utilising the highest collector output temperature and the lowest chiller input temperature. The heat of fusion was calculated as at least 150 kJ/kg. In laboratory experiments, hydroquinone was chosen over the alternative phase owing to its high phase-change enthalpy and minimal subcooling. The choice of D-mannitol was predicated on its advantageous melting range and robust heat-of-fusion. The primary emphasis of their selection criteria was on the ideal melting temperature and the elevated heat of fusion. The phase-change materials (PCMs) used by Monicka *et al.* [154] had melting points ranging between 100 and 130 °C. In one study, erythritol was utilised as a phase-change material (PCM) to increase the efficacy of a residential LiBr-H_2O solar-absorption cooling system. Their experimental focus was primarily on determining the temperature at which the heated side of the system should operate effectively. Erythritol was selected because of its appropriate melting temperature of 117.7 °C and the determination that the generator operating temperature for the LiBr absorption system should be less than 120 °C. Their selection criterion was the ability to provide a near-constant thermal source and a high energy density. To facilitate operation within a temperature range of 90 - 120 °C, a phase-change material (PCM) was integrated with Thermomax vacuum tube solar collectors. Muzhanje *et al.* [155] conducted an experiment utilising 3 phase-change materials (PCMs) in a 4.5 kW LiBr-H_2O solar absorption cooling system: Erythritol, RT100 and magnesium chloride hexahydrate. The experiment was conducted using storage units/heat exchangers in 4 distinct configurations: No fins, circular fins, longitudinal fins and multitube systems. A longitudinal fin design generates a more uniform melting and is optimal for discharging without subcooling. According to this study, the multitube design is the most effective for rapid charging and melting. The quantity of phase-change material (PCM) necessary to satisfy the highest demand for a duration of 4 h was computed. The primary considerations in selecting phase-change materials (PCMs) are the appropriate melting temperature, high heat of fusion and design characteristics. Significant latent heat levels may result in acceptable minor sub-cooling characteristics. Franco *et al.* [156] have provided a summary of research concerning solar thermal applications utilizing phase-change materials (PCMs) as well as their conclusions regarding the implementation of Latent Heat Thermal Energy Storage (LHTES) systems. N'Tsoukpoe *et al.* [157] utilised calcium chloride hexahydrate as a phase-change material (PCM) in a lithium bromide-water absorption chiller operating at low temperatures and achieved a maximum coefficient of performance (COP) of 0.8. It was discovered that the implementation of the PCM facilitated the preservation of the low operating temperatures of the solar collectors, thereby promoting enhanced heat absorption. Cost-effective high thermal capacities can often be achieved by utilising nitrites. Nair *et al.* [158] conducted a numerical analysis of a flat-plate collector utilising a slurry PCM, and found that it exhibited an efficiency enhancement of +0.08. compared with traditional water-based technologies. An average annual increase of 20 - 40 % was observed in the heat conversion efficacy. Owing to the increased demand for pumping energy (a design limitation), they were unable to resolve issues associated with PCM concentrations of 50 % or higher. The thermophysical properties of phase-change materials (PCMs) can be modified by adjusting their chemical compositions or physical configurations. The risk of phase separation was reduced and the area for heat transmission was expanded by encapsulating the PCM on a small scale. It increases the thermal conductivity, reduces the PCM contact with the external environment, and governs the volume change of the PCM in an efficient manner as the operating temperatures increase to prevent leakage during the phase shift. Encapsulation with PCM is a commonly employed technique in the fabrication of cooling systems, wherein air flows through planar containers filled with the PCM. Encapsulated PCM offer a significant opportunity to increase the solar-absorption cooling efficiency of LHTS systems. Nasajpour-Esfahani *et al.* [159] investigated the efficacy, energy-storage capacity and release properties of encapsulated paraffin wax. The microcapsules exhibited enhanced energy storage and release capabilities, ranging from 145 to 240 J/g. The efficiency is affected by the cross-linking agent, emulsifying time and core-to-coating ratio. Encapsulation requires a specific exterior material, owing to the simplicity of its production. Naveenkumar *et al.* [160] have compiled a list of materials suitable for microencapsulation and macroencapsulation at high temperatures with regard to thermal stability. Encapsulating organic phase transition materials can be achieved through chemical, physicochemical or physical-mechanical means.

An encapsulated organic phase-change material (PCM) is an exceptional medium for thermal energy storage (TES) that can be customised to meet specific requirements using a range of methodologies that have been thoroughly investigated. The physical characteristics of encapsulated PCM particles, such as mechanical strength, chemical composition, and thermal stability, are heavily influenced by their shape. Nazir *et al.* [161] utilized melamine-formaldehyde (MF-3) resin to encapsulate paraffin wax, which led to the formation of 5 distinct types of encapsulations. By employing thermogravimetric analysis, they successfully identified the increased levels of thermal stability. The implementation of binary emulsifiers is critical for preserving thermal stability. The future applications of these materials in thermal storage systems are intriguing. Exhaustive summary of various types, applications, and methodologies for microencapsulation [162]. Among the various types of absorption refrigeration cycles are combined vapour absorption systems, absorption heat transformers, absorber-heat-recovery or absorption refrigeration cycles with GAX, self-circulation, osmotic membranes, combined ejectors, and sorption-resorption cycles. Nevertheless, owing to the favourable results they produced, only a limited number of patients underwent a thorough examination. A compilation of solar thermal refrigeration systems by Odoi-Yorke *et al.* [163] focuses on absorption and adsorption systems. The investigation is comprehensive and employs a variety of techniques to examine aqua-ammonia and LiBr-water absorption systems at various operating temperatures. In recent years, considerable research has been devoted to single-effect (solar) absorption refrigeration systems, primarily because of their enhanced energy efficiency and financial viability. In contrast to a compressor, which is utilised in a vapour compression cycle, this method generates a chilling effect through an absorber and a generator. To convert the low-pressure concentrated refrigerant solution from the absorber into pure vapour at high pressure in the condenser, the generator is externally heated via a solar collector circuit or an auxiliary heating device. This increased the temperature of the solution. In contrast to the traditional vapour-compression technique, absorption produces a pressurised refrigerant with minimal or no electrical energy consumption. Continuous and intermittent operations are the 2 most frequently implemented absorption-refrigeration cycles. The following section elaborates on these cycles.

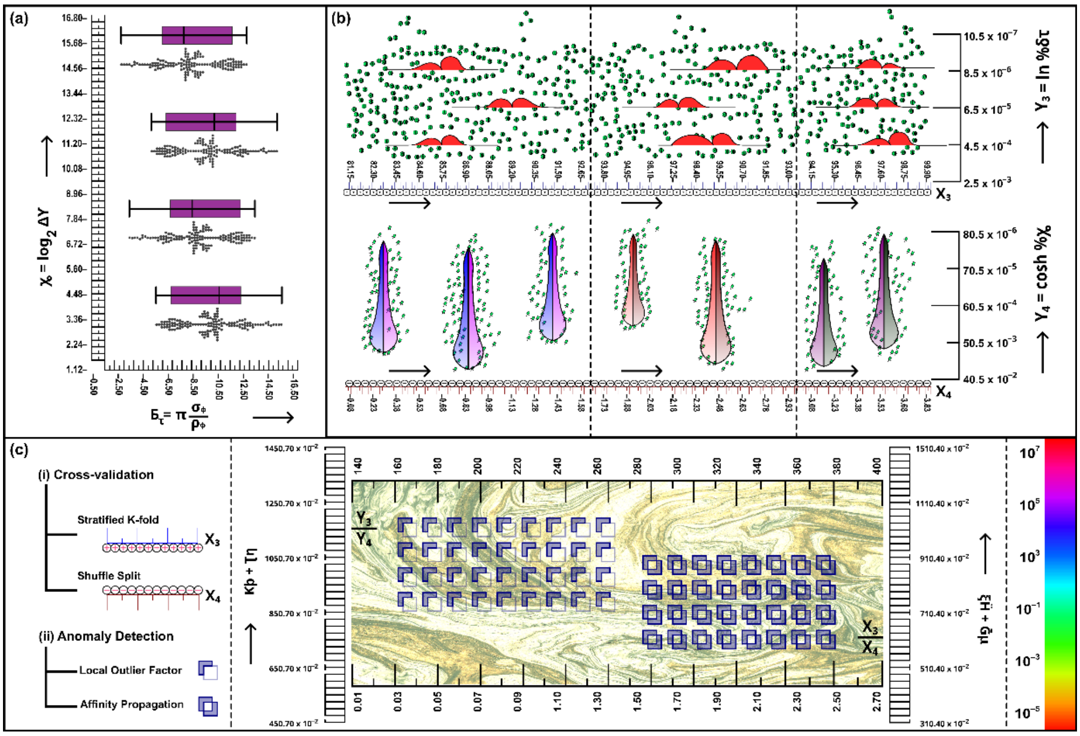

Figure 3 (a) PVT/PCM systems offering better temperature control than standard PVT systems while also storing up to 33 % more heat, expressed via simulation results of techniques pertaining to stabilization of fatty acid composites: Microencapsulation, electrostatic spinning, polymer mixes and adsorption PCMP cycle stability testing employ DSC and thermostatic chambers' segregation is an important issue in cold thermal storage systems and reduces the energy storage capacity of the LHES system transient heat transfer phenomenon in a shell-and-tube heat exchanger with water as HTF expressed as Notched box-chart with outliers (Note: Double-skin facade hybrid PV/PCM systems lower monthly cooling energy demand by 20 - 30 %, while systems with internal blades reduce PV/PCM system temperature rise by 30 °C after 140 min compared to a single-level aluminum plate); (b) Verification of experimental results using a cylindrical latent heat thermal energy storage device packed with paraffin PCM spherical balls integrating a packed bed cylindrical LHTES device into a Slovenian house's mechanical ventilation system was studied (Note: The free cooling device improved comfort and reduced mechanical system size) illustrated as raincloud and grouped-violin plots; (c) Posthoc verification of the data plots pertaining to design and optimize a revolutionary PCM cooling system called Indirect Evaporative and Storage Unit (IESU) for household use in Amman, Jordan's Mediterranean environment, wherein an optimized design saved 80 % of yearly cooling demand with 170 J/g latent heat of fusion at melting temperatures between 21 and 25 °C.

Continuous operation system

The system operates in a cycle lasting less than 24 h, during which generation and absorption occur concurrently. The solution was facilitated by using an electric pump for systemic circulation. The system consists of the following components: a generator, condenser, evaporator, expansion valves, solution pump and absorber. Variable quantities of solar radiation are directed at the collectors, which, in turn, heat the generator. To ensure a consistent heat supply, either an auxiliary heating unit or thermal storage system may be employed. The condensation of water vapour from the feeble solution returns to the generator via heat transfer in the dephlegmator. Condensation requires water vapour at a reduced temperature to facilitate heat transfer. The vapour was extracted from the concentrated solution exiting the absorber. Under intense pressure, the condenser cooled the refrigerant by expelling heat into the atmosphere. The evaporator (EVAP) receives the refrigerant via the expansion valves. Once the load absorbed heat, the refrigerant proceeded in the direction of the absorber (ABS) through a refrigerant pre-cooler (RPC) positioned before the expansion valves, and the initial solar absorption system developed by Worsaee-Schmidt utilised solid absorption ($CaCl_2/NH_3$). Lithium bromide (LiBr)-water and aqua-ammonia (NH_3-H_2O) absorption systems, which operate on a liquid cycle, have subsequently undergone the most comprehensive research on solar absorption refrigeration technologies. Aqua-ammonia systems are typically employed for subzero refrigeration applications, whereas LiBr-water systems are frequently used for air-conditioned structures that utilise water as the absorbent and purified ammonia as the refrigerant. In LiBr-water absorption systems, water functions as a refrigerant and lithium operates as an absorbent. However, within each instance of continuous operation cycles, the operating temperatures fluctuate to some extent depending on the specific application. Systems with single, double and triple effects require varying temperature ranges to accommodate various solar thermal heat input methods, which causes an increase in the evaporator and COP temperatures. Omara *et al.* [164] constructed a 10 kW aqua ammonia absorption system utilising flat plate heat exchangers. The system achieved a Coefficient of Performance (COP) ranging from 0.58 - 0.74. In 2012, Omara *et al.* [165] devised a 10 kW system that operated at reduced generator temperatures and achieved a COP of 0.6. Their evaporator temperature was higher than that of Orozco *et al.* [166] and could not be adjusted owing to design constraints. Five kW ammonia-water absorption system with a coefficient of performance of 0.65 is being operated. Inadequate cooling in the evapor 16 °C (T_{evap} = 16 °C) can be attributed to the diminishing coefficient of performance as the generator temperature increases, as described by Pandey *et al.* [167]. The predominant factor contributing to the noncompliant behaviour was the overfeeding of the evaporator and not the design specifications. Similar effects were noted by Parameshwaran *et al.* [168] when the generator temperature increased, underscoring the importance of conducting a thorough parameter assessment when designing a system. Numerous attempts to construct a solar absorption system, including the critical characteristics and component temperatures, are shown in **Figure 3(a)**.

Intermittent operation system

The intermittent operating system differs from the continuous operating system in 2 aspects. This method generates pressure by isochorically heating the refrigerant solution in the generator, as opposed to using a solution pump. A combined generator and absorber component (GEN/ABS), which functions as both an absorber and a generator during the day, obviates the need for an additional absorber. This cyclical process can operate for an entire day (24 h) in a single cycle while consuming negligible amounts of electrical energy. Intermittent operation systems have been the subject of comparatively less research interest than continuous operation systems, owing to their comparatively lower coefficients of performance (approximately 1/2 to 1/3). Pathak *et al.* [169] developed a compound parabolic concentrating (CPC) collector and an ammonia-lithium nitrate mixture to simulate an intermittent absorption refrigeration system. They achieved an ice production capacity of 11.8 kg at a generator temperature of 120 °C using an efficiency that varied between 0.15 - 0.4. In an experimental study, Paul *et al.* [170] utilised a CPC collector system to achieve an evaporator temperature of −11 °C and a COP of 0.083 at a refrigerant concentration of 50 %. An increase in the solution concentration results in a reduction in the initial temperature of the generator and an increase in the maximum operating pressure. In the 2012 experiment, an identical apparatus was examined, with and without water, serving as an absorbent. A 24 % increase in the solar coefficient of performance was observed upon addition of water to the working fluid mixture. They determined the input variables and implemented the system at the required COP using inverse and direct artificial neural network (ANN and ANNi) approaches in the same year. A substantial level of agreement (R > 0.986) was observed between the experimental and simulated values for the 6-6-1 configuration (6 inputs, 6 hidden neurones and 1 output neuron). Pereira *et al.* [171] conducted experimental research on an intermittent absorption system that exhibited a Coefficient of Performance (COP) of 0.487 and maintained an average minimum refrigeration temperature of 4 °C. It is recommended to shield the refrigerated cabinet from direct sunlight and cover and conceal it. In addition, the solar collector should be screened at the end of the generation cycle to prevent additional heat from entering the system.

Energy-exergy nexus

The PCM can be efficiently charged and purged, as required, owing to the design of the storage reservoir. The most prevalent form of PCM storage unit is the shell-and-tube heat exchanger, in which the PCM is contained on the shell side. Experiments were conducted on a second storage vessel comprising 196 transverse square fins and 49 U-shaped tubes, arranged in a square configuration. Because of the addition of fins to the storage system, less PCM could be stored. Consequently, the bulk of the PCM decreased from 170 to 155 kg. **Figure 4(a)** presents the primary attributes of the storage containers, emphasising the distinctions in the diminished PCM capacity and the enhanced heat transmission area facilitated by the fins. The design of the storage unit is determined predominantly by the amount of heat required by the system. It is essential to strive for a moderate scale to ensure practical and financial feasibility. In addition, the thermal adequacy level, which is determined by the standby duration and working temperature, is used to prevent icing. The selection of the phase-change material (PCM) and design of the heat exchanger unit are significantly affected by the effective heat transfer and distribution within the latent storage. The thermal properties of PCM include cooling and thawing patterns within the PCM container. The thermal conductivity of the material significantly affected the outcome. Thermal conductivity can be increased by either decreasing the distance between the tubes in a shell-and-tube configuration or by incorporating vents onto the heating surface, which improves the heat transfer. Heat transmission is significantly affected by various factors during the charging and discharging processes. These factors include the design of the storage container, rate of mass flow, insulation, gravity, material complications, such as phase segregation and suspension of nanoparticles. Pereira *et al.* [172] investigated the charging and discharging characteristics of a triplex tube heat exchanger featuring both external and interior fins, subjected to fluctuating constant and aberrant HTF input temperatures. The study revealed that alterations in the input temperature and HTF mass flow rate led to corresponding decreases of 86 and 58 %, respectively, in the charging time. This indicated that the PCM melting process was influenced by the HTF inlet temperature to a greater extent than by the bulk flow rate of the HTF. In an experiment conducted by Prakash and Ravindra [173], decanoic acid was utilised as a phase-change material (PCM), and a vertical cylinder was charged and discharged under different flow rates and conditions. The principal obstacle in achieving enhanced performance is the thermal conductivity of the PCM, which hinders natural convection in the molten PCM and prohibits direct heat transfer between the 2 temperatures. Prakash *et al.* [174] conducted a numerical analysis of a range of phase-change material (PCM) within a flat-plate collector. The relationship between the concentration of the PCM and average temperature exhibited a significant upward trend. Because water is more viscous and dissipates heat at higher temperatures more rapidly than the sum of all PCM concentrations, it possesses a greater amount of total stored energy. According to Preet

[175], 2 of the 3 phase-change materials utilised in the solar hot water heater experiment failed to dissolve to a percentage within the designated time period. The fact that a fraction of the PCM retains its liquid state during discharge underscores the importance of the thermal characteristics when choosing and evaluating a PCM to meet specific temperature demands. Recently, Punniakodi and Senthil [176] conducted an exhaustive investigation into the thermal behaviour of phase-change materials melted in containers of various configurations (rectangular, spherical, cylindrical and annular). An extensive examination of PCM-enhancing strategies, system portability, and their impact was conducted by Qiao *et al.* [177]. When analysing the thermal interface behaviour during the charging and discharging processes, it is vital to consider the Stefan or movable boundary concerns. Analytical and numerical methods have been employed in solid-liquid interface research [178]. To enhance the design of TES systems, it is necessary to conduct a more thorough examination of the potential empirical correlation pertaining to the behaviour of the interface. Raut *et al.* [179] conducted a theoretical investigation of the thermodynamic efficiency of a solar power plant that utilises phase-change material. Their study indicated that the incorporation of a phase-change material (PCM) could enhance the exergy efficacy of a parabolic trough collector system by 10 – 30 %. Furthermore, empirical evidence has demonstrated that an elevated PCM melting temperature corresponds to greater exergetic efficacy. The temperature recorded at the output of the collector field at 505 kPa was 265 °C. Rebelo *et al.* [180] conducted an energy and exergy analysis of a latent heat storage system utilizing PCM $CaCl_2 \cdot 6H_2O$ within a custom-designed solar collector. They determined that the energy efficiency was 2.2 % with an actual energy efficiency of 45 %. Reddy *et al.* [181] examined the feasibility of installing and operating a 70 kW $LiBr/H_2O$ absorption system in a medical center with a 50 L/m^2 hot water reservoir holding 11,500 L. A repayment period of 24 years was anticipated in the absence of government support, with a possibility of increasing to 50 % (2017). A thorough examination of the existing technological barriers, the level of commercial development, and economic prospects is suggested.

Heat exchangers

Heat exchangers facilitate the transfer of thermal energy between 2 fluids at different temperatures. An absorption system comprises 2 distinct categories of heat exchangers: Liquid-liquid heat exchangers (generator, absorber, etc.) and liquid-vapour heat exchangers (condenser and evaporator). Only the effective temperature differential and mass flow rates of the fluids differ in the thermofluid characteristics between the generator and absorber liquid-liquid heat exchangers. The significance of the material selection lies in the specific heat of the fluid and not its impact on the performance of the heat exchanger. The integration of multiple heat exchangers utilising a phase-change material (PCM) is summarised.

Generator

The generator was primarily utilised to supply heat to evaporate the refrigerant. For the same purpose, absorption refrigeration systems and solar thermal technologies have been integrated using efficient heat exchangers. Extensive research has been devoted to optimal component-level thermodynamic modelling of absorption cooling systems to determine the optimal component temperatures that will result in improved performance. The optimal nighttime temperatures for the generator, system COP and evaporator to absorb and retain the surplus heat were determined. Several studies on absorption cooling systems that detail the thermodynamic properties of generators are summarised in **Figure 4(b)**. Generators can be heated by various methods. The primary heat source of the system is a heat storage tank positioned on the heated side; however, electricity is required to circulate the heat transfer fluid (HTF). Righetti *et al.* [182] conducted numerical research on a vertical generator and PCM (erythritol) for forced convective heating in an NH_3-H_2O solar absorption air-conditioning system coupled to a focused parabolic collector field. To replicate the operation of a real stainless-steel generator that incorporated 1-meter-long coaxial tubes, a TRNSYS model was created. The generator was equipped with an auxiliary furnace and hot water storage reservoir linked to the hot water used to charge the PCM tubes. Additional heating requirements can be reduced by employing a phase-change material (PCM) during periods of high demand and low radiation. Rostami *et al.* [183] conducted a numerical and analytical investigation into the process of paraffin wax (PCM) melting in a cylindrical vessel equipped with 1 or more vertical spiral tubes that functioned as heaters. The helix radii were modified by modifying the tube shape and the properties, including temperature distribution and melting percentage, were investigated. They proposed that numerical simulations and scale analysis can be combined as a practical means of advancing the design process. In complex vapour compression heat pump systems, preheating the attenuated solution that enters the generator and boiling binary mixtures have been compared to analogous endeavours. Consequently, it is promising to investigate the utilisation of heat exchangers as generators in absorption systems. The innovative application of heat exchangers employing phase-change materials (PCM) as generators in solar absorption systems requires further study. The melting point and enthalpy of a suitable PCM may be crucial for the generator, and may function as a secondary heat source if the generator is properly designed. As stated in Sections 2.3., the temperature demands of the generator and evaporator were directly proportional. The majority of generators in a single-effect absorption cooling system operate most efficiently at temperatures ranging from 60 to 105 °C for cooling purposes, and from 80 to 120 °C for subzero evaporator conditions. The Coefficient of Performance (COP) appears to be unaffected by variations in the level, including the use of unconventional refrigerants such as Zn_2Cl_5/NH_3 or $NaSCN/NH_3$. The melting temperature is the principal determinant when considering a PCM for a specific application. The efficiency with which the generator produces the vapour refrigerant is determined by the enthalpy of the system and thermal conductivity of the PCM. Phase-transition materials that can be selected from a variety of organic, inorganic and eutectic combinations are shown in **Figure 4(c)**, compiled by Sadeghi *et al.* [184]. The materials and properties of a variety of commercially available phase-change materials (PCMs) that are suitable for absorption cooling systems operating at 60 - 105 °C and refrigeration absorption systems operating at 80 - 120 °C are detailed in **Figure 1(a)**. The generator was primarily composed of stainless steel. This enables the utilisation of inorganic phase-transition materials without concern for their corrosive nature. **Figure 2(a)** provides a comprehensive definition of the primary selection criteria, emphasising that (i) a high heat of fusion ensures a steady and sufficient heat distribution, as required, and no phase separation or flammability is observed at high temperatures. There are periods during which the actual temperatures may exceed the predictions. D-mannitol (162 - 170 °C), potassium thiocyanate (173 °C) and hydroquinone (168 - 173 °C) exhibited a more extensive thermal storage range. Therefore, these materials are viable alternative materials. An excess of heat can be stored for subsequent utilisation in the TES system, which is linked to the main system and necessitates calculations contingent on the standby heat demand.

Absorber

Absorber is the most vital component of absorption refrigeration and conditioning systems. A falling-film absorber is the most frequently employed absorber. It operates by absorbing refrigerant vapour through the falling film of a solution that passes over chilled horizontal tubes. A strong correlation existed between the discharge rate of the solution and the rate of heat transfer in the absorber. Absorption induces heat dissipation, which reduces its efficacy. By absorbing heat, cooling pipelines accelerate the absorption rate. Absorbers are physical and chemical heat exchangers that convert vapours into liquids. Consequently, as performance increased, the absorber became cooler. The absorber temperatures were presented in accordance with the information obtained by Safari *et al.* [185] for several solar-run absorption systems.

Figure 1(b) provides data regarding the absorber temperatures (25 - 35 °C) corresponding to the different working fluids. Comparing the conditions with and without PCM-B, the temperature difference is approximately 10 °C. Conversely, the temperature difference with PCM-A was approximately 5 °C. The figure illustrates the development of a dynamic mathematical model with the objective of enhancing the efficacy of a refrigeration system that employs a PCM and variable-frequency compressor. The liquid refrigerant streaming into the gas region of the condenser was conceived as a means of increasing the accuracy of the model at low compressor velocities. The model predicted 8 % of the test data accurately. The predictive capability of the model for superheating and subcooling was limited because of its intrinsic reliance on average characteristics as opposed to regional distribution factors. To facilitate system stabilisation and regulate fluctuations in chilling demand, a reservoir was incorporated into the refrigeration system during Phase 3. The placement of the PCM tank between the compressor and evaporator was motivated by favourable outcomes in a previous investigation [154]. By positioning the PCM at this location, the average and maximal intake temperatures of the refrigerant were simultaneously reduced. In addition to using PCM-A to modulate the condenser pressure between the compressor and condenser, an additional PCM heat exchanger was incorporated into the bypass to control the minimum condenser temperature at low ambient temperatures. They asserted that these restrictions substantially contributed to energy conservation. Finally, the condenser pressure and temperature were substantially stabilised even at low ambient temperatures. Said *et al.* [186] investigated the shape-stabilized paraffin/high density polyethylene (HDPE) composite phase transition material to which expanded graphite (EG) and graphite powder (GP) were added. The addition of EG to the PCM resulted in a 4-fold increase in the thermal conductivity (0.31 - 1.36 W/m K). They integrated an improved PCM into a residential refrigerator for heat storage. Condenser heat is stored in the refrigerator during the compressor operation and discharged when the compressor is deactivated. By allocating additional compressor starts, a reduction in the condenser's intermediate temperature of 2.3 °C and outlet temperature of 6.3 °C was achieved. Overall, this led to a 12 % improvement in the energy efficiency. The data were subsequently employed to validate a dynamic numerical model that forecasted an approximately 19 % increase in COP. However, owing to the fully charged phase-change material (PCM) and the decreased ambient heat dissipation during the off-time period, the total heat leakage per 24 h increased. Regarding the cost and energy consumption of various refrigeration system components containing PCM in varying quantities and sizes, additional research should be conducted in the future. Samylingam *et al.* [187] conducted a recent investigation into 2 phase-change materials (PCMs) that have the potential to be incorporated into a standard household refrigerator: The block copolymer fixed organic paraffin derivative and water and paraffin, and PE-HD foil and aluminum composite film. The temperature at the outlet of the condenser decreased by 5 and 8 °C when water and copolymer compounds were utilised, respectively. A 10 % reduction in power consumption was achieved by considering the following variables: (a) apparatus selection, (b) method for describing the PCM before and after testing, (c) number of cycles and (d) rates of heating and thermal cycling techniques. Fatty acid composites can be stabilised through the following 4 processes: a) adsorption, b) polymer mixtures, c) electrostatic spinning and d) microencapsulation. DSC and thermostatic chambers were used to validate the cycling stability of the PCM. A compilation of the techniques employed to thermally stabilise PCM can be found in a review by Sarbu and Sebarchievici [188]. Thermal stability is not synonymous with form stability; the latter is concerned with enhancing the performance and safety of PCMs through encapsulation and shape-stabilisation techniques. Several PCMs have been identified based on their toxicity and health risks. Because poison vapour is generated by paraffins, care must be taken when handling salt hydrates.

Corrosion

The relatively recent application of PCM in solar absorption refrigeration has been a subject of limited research. The majority of their findings pertained to the impact of PCM enhancements on the overall performance of the system, rather than conducting continuous experiments to investigate particular effects, such as corrosion on the used containers. Consequently, research pertaining to the application of PCM in solar absorption refrigeration is insufficient and requires further examination, because water is notorious for its corrosive characteristics. In solar-absorption cooling systems, it is the most frequently employed medium for storing heat and chills. Additional materials with greater latent heat of fusion must possess deleterious properties for intended applications. With tremendous success, stainless steels have been extensively tested as noncorrosive containers. Javadi *et al.* [189] examined the behaviour of salt-hydrate PCMs (S10, C10, $ZnCl_2·3H_2O$, $NaOH·1·5H_2O$ and $K_2HPO_4·6H_2O$) in the presence of copper, stainless steel, carbon steel and aluminum. After 12 weeks, almost all these substances exhibited a significant propensity for the corrosion of carbon steel. However, $ZnCl_2·3H_2O$ and $K_2HPO_4·6H_2O$ failed to exhibit any corrosive properties towards copper. The experts advised that stainless steel be used for all PCM varieties investigated, whereas carbon steel and copper were found to have significant corrosion risks in cooling and heating applications, respectively. As a result, they proposed that S10, C10, S46, C48, $MgSO_4·7H_2O$ and $Na_2S_2O_3·5H_2O$ could be encapsulated in stainless steel and aluminum depending on the application. Similarly, they suggested that $ZnCl_2·3H_2O$ and $K_2HPO_4·6H_2O$ could be utilised in conjunction with copper encapsulation and stainless steel. Furthermore, Sathishkumar and Cheralathan [190] examined the impact of an inorganic mixture, an ester (PureTemp 23), and 2 fatty acid eutectics (capric acid (73.5 %) combined with myristic acid (26.5 %) and capric acid (75.2 %) combined with palmitic acid (24.8 %) on 5 distinct metals: Stainless steel 304, copper, aluminum, carbon steel and stainless steel 316. In addition, they suggested PureTemp 23 and stainless steels (304 and 316) as corrosion-resistant PCMs. Resistance was observed in copper and stainless steel when exposed to the inorganic salt SP21E. Fatty acids exhibit corrosion resistance to all metals. The corrosive properties exhibited by the remaining combinations varied in intensity throughout the test process.

Phase segregation

Incongruent melting, phase segregation and phase separation are terms employed to denote the modifications introduced to the initial design composition of the microscopic phase separation during heat cycles. The primary impact of this issue is on cold thermal storage systems, whereas LHES systems gradually experience a decline in their capacity to store energy. A considerable variety of organic PCMs such as sugar alcohols, fatty acids and paraffins lack phase segregation. Owing to the absence of phase separation, paraffins have been used extensively in solar heating and cooling systems. Sathishkumar *et al.* [191] examined the viability of bischofite as a $MgCl_2·6H_2O$ substitute in a solar thermal energy storage system due to its cost-effectiveness. Bischofite is a byproduct of the non-metallic industry. They concluded that because bischofite dissolves at approximately 100 °C, it can be utilised as a phase-change material (PCM) in solar energy applications. Therefore, phase segregation has become a major concern. Phase segregation issues can be effectively resolved by combining expanded graphite with an encapsulated PCM. Solar devices operating at temperatures exceeding 500 °C typically use salts or salt hydrates. Salt-hydrate phase segregation is a primary challenge. A thickening agent or polymer was introduced into the solution to prevent dense particulates from settling in the salt hydrates and to stabilise the mixture. However, this resulted in a reduction in the storage density. Thickening agents are predominantly composed of polyvinyl alcohol (PVA), cellulose derivatives and highly absorbent polymers.

Container design enhancements

When designing a storage system, it is essential to select appropriate heat exchanger and container dimensions. The initial time of the chiller was determined by the quantity of the PCM introduced. The mass flow rate and HTF properties significantly influenced the stability of the thermal storage unit. Sun absorption cooling systems frequently employ shell-and-tube architectures, with the incorporation of fins facilitating a more uniform heat transmission. An increase in the fin count results in a reduction in the volume of the PCM, which influences both the energy storage capacity and measurements of the desired parameters. Complexity may accompany the design of the helical coaxial tubes used for PCM melting, necessitating exhaustive testing across various system functionalities. Conversely, scale analysis and numerical simulation are well-established methodologies used in the design of thermal energy storage systems. Sathishkumar [192] identified the subcooling issues in the most efficient storage format (multitubes). They proposed the incorporation of longitudinal fins, which exhibited an optimal performance when discharged.

Heat loss

The heat transfer from the solar collector to the evaporator has a significant impact on the Coefficient of Performance (COP) of the system. This differs from simply incorporating insulation to decrease heat dissipation when selecting a container for PCM. The perceptible heat capacity of the energy storage unit is incorporated into the overall energy capacity of the metal container. It is essential to minimise the heat losses to the greatest extent possible to precisely determine the heat storage capacity of the device. This increases the nighttime dependability and Coefficient of Performance (COP) of the solar absorption system. Heat loss may occur depending on the distance between the pipelines and storage unit of the system. Insufficient insulation of a storage container can lead to heat loss. Glass wool is frequently used as insulation for hot water conduits and solar collectors due to its resistance to temperatures of up to 250 °C. Elastomeric foam derived from rubber is utilised in pipelines operating at temperatures between −50 and +105 °C. Marcoberardino *et al.* [193] positioned a generator within a thermal storage unit to minimise heat dissipation and conserve pumping energy. Sha *et al.* [194] insulated a storage vessel with 45 cm of FoamglassTM below, and 24 cm of Rockwool around the perimeters. Extended periods of inactivity may result in halting issues that compromise device storage capacity.

Control

The demand for refrigeration and the presence of sunlight determine the amount of energy deposited in the thermal storage unit. In numerous applications such as SAR systems with thermal storage, the output temperature of the evaporator is typically unaffected by variations in the heat source. Using optimal parameters to optimise the most cost-effective chilling method is possible with the assistance of a precise control program that maximises the exergy. It varies according to the requirements of the system and its application. Shamseddine *et al.* [195] enhanced the LiBr-H_2O absorption system by applying exergoeconomic principles and a genetic algorithm to incorporate a latent-heat thermal-storage unit. They decreased the energy losses while increasing the COP by 3.8 %. To maximise energy efficiency and provide optimal thermal comfort in buildings, complex control algorithms are necessary and a multitude of temperatures and phases can be obtained for phase-change materials, which are utilised in a variety of applications. Limited research has been conducted on phase-change materials (PCMs) in the thermal circuits of solar absorption systems. Determining the appropriate material quality for a specific application is a challenging task. A multitude of investigations has been undertaken regarding widely employed phase-change materials (PCMs), such as erythritol, hydroquinone, mannitol and diverse paraffins. However, an exhaustive database that details PCMs suitable for particular applications, their limitations and potential solutions is lacking. Novel designs are required to examine and improve the efficiency of solar-absorption systems. Mechanical techniques were implemented in each of the 3 cylindrical casings to improve the heat transfer. Circular and longitudinal fins were applied to the HTF tube, which comprised numerous tubes arranged in its centre by a technician. Except for a small region near the bottom, the longitudinal fins vaporise uniformly when charged in a heated circuit. The highest discharge efficiency (82.2 %) was achieved in the absence of subcooling. The maximum energy discharge of the multitube system was achieved with an efficiency of 83.5 %. Insufficient research has been conducted on the effects of the PCM thermal behaviour on the design. Developing a system in which the PCM is integrated into a solar absorption-based cooling system. The mobility of the solid-liquid boundary during charging and discharging is influenced by the heat input parameters, phase-change material (PCM) thermophysical properties and heat storage container design. Determining the precise border location that contributes to a solution is challenging. A comprehensive examination of the heat transport and formulation of phasechange problems was presented in a study by Sharma *et al.* [196]. A PCM-integrated solar absorption cooling system can be manufactured by considering various aspects, such as thermal performance, shape, capacity for storage, method of heat storage, overall cost and application-specific requirements. Thus, both indoor and outdoor heat storage are feasible. An external thermal energy storage (TES) system is employed to store either heat energy for the generator or cold energy for cold storage. It is affixed externally to the circuit. The internal storage system transfers and stores heat to the TES system by using a slurry heat-transfer fluid within the solar circuit. The computational methods described by Sheikh *et al.* [197] were used to examine the thermal characteristics of 2-phase-change materials in a shell-and-tube LHS configuration. Several experimental iterations were conducted to investigate the effects of the operational and geometric parameters (HTF inlet temperature, mass flow rate and length of the PCM section), which were converted into algebraic equations via a volume control technique. The use of n-octadecane as a phase-change material (PCM) increases the efficacy of the Latent Heat Storage (LHS) unit owing to its partial storage and 1 - 2 kg/s mass flow rate. The maximum thermal storage efficiency was identical for both storage technologies. Solangi *et al.* [198] examined the heat gradients in erythritol along the axial, radial and angular axes by implementing an innovative shell-and-tube heat exchanger design. The 4 cylinders provided the most efficient power supply for the LiBr-H_2O absorption system. Soodmand *et al.* [199] conducted an investigation into 2 miniature heat exchangers utilizing water as the Heat Transfer Fluid (HTF) and commercially available paraffin RT35. Upon careful assessment of the mean thermal power values, it was determined that a double-pipe heat exchanger incorporating PCM-encased in a graphite matrix (DPHX-PCM matrix) was the optimal choice. The experimental apparatus consisted of a thermostatic reservoir, pump, valves and heat storage device that could be easily replaced. In addition, a valve system was incorporated. They continued to add solid PCM to the system until it was no longer visible. Subsequently, measurements were conducted every 10 s, and the HTF cleansing was continued immediately with cool water until no liquid PCM was visible. By employing water as the heat transfer fluid (HTF) and paraffin as the phase-change material (PCM), Sun *et al.* [200] conducted a computational analysis of the transient heat transfer process in a shell-and-tube heat exchanger using water as the HTF and paraffin as the PCM. Suzuki *et al.* [201]. The thermocouples were linked to a data collection system using LabView® software to generate data at 10-second intervals. They formulated a restricted collection of principles for the parametric design of LHTS systems, where the stored thermal energy was substantially unaffected by the mass flow rate of the HTF. The fluctuation is determined by the thermal conductivity of the Heat Transfer Fluid (HTF). A linear and immediate effect can be observed on the thermal energy stored and supplied in the LHTS system when the temperature differential between the HTF intake and PCM melting is modified; parametric variations in shape involve outer tube radii that vary between 1.2 and 1.8 during melting process and 1.2 to 2 during solidification, with a dimensionless unit length of 40. Both the energy density and the ratio of the total to latent energy exhibit a decline as the length of the dimensionless tube increases. As the outer tube radius increased, the energy density and ratio of the total to latent energy stored decreased substantially throughout the charging and discharging processes. Tafavogh and Zahedi [202] conducted an experimental investigation to determine the effects of Reynolds and Stefan numbers on the charge and discharging behaviours in a fixed-shape, 5-degree-inclined storage unit utilising 3 distinct paraffins. It was determined that, although the Reynolds number does not influence the overall melting time, a reduced value is more suitable for an energy-efficient storage system. Stefan numbers that are greater substantially reduce the dissolving time. The average increase in the Stefan number was 0.04 for each degree of increase in the HTF input temperature. To decrease the temperature of the HTF (Therminol VP-01), Tariq *et al.* [203] installed an air heat exchanger (20 kWe) and shell-and-tube storage tank equipped with an electrical furnace (24 kWe). Hydroquinone (PCM) and 49 curving tubes with and without 196 square fins were packaged on the exterior side of each container. The heat transfer surface area of the container was 6.6 m^2, with dimensions of 527×273×1,273 mm^3. It could accommodate 155 kg of PCM without fins and 170 kg of PCM with fins. To mitigate the heat loss, Tofani and Tiari [204] positioned a generator inside a reservoir designed to store hot water. To mitigate the heat demand during periods of low radiation and peak loading, Togun *et al.* [205] designed and installed a vertical generator within a thermal storage vessel filled with a PCM. Tony *et al.* [206] conducted a numerical and analytical investigation on a vertical cylinder containing a heat transfer fluid within a helical tube and phase-change material on the exterior. The optimal diameter and pitch of the helix were determined to enhance the efficacy of the heat-storage unit. Tyagi *et al.* [207] proposed several novel design alternatives for auxiliary systems, cooling modes and solar collectors in a single-effect absorption cooling system.

Results and discussion

Statistical inference

Extensive research has been conducted on phase-change materials and their augmentation techniques for solar-absorption refrigeration systems. An extensive examination was conducted on latent heat thermal storage units, focusing specifically on aspects such as material selection, phase-change material (PCM) considerations, augmentation strategies, system analysis and cost evaluation. Summaries were generated in accordance with the PCM method implemented in the solar-assisted absorption refrigeration systems. Considering material preferences based on PCM issues, operating temperature, dissipation and component heat balance to increase the output, the effects of the design processes, obstacles and resolutions pertaining to heat transmission, PCM behaviour, and container design on the system have been detailed. Further investigation is warranted to optimise the application of the PCM selection foundation and approach strategy in the context of solar absorption cooling. The thermophysical properties of the phase-change material (PCM), melting temperature and latent heat of fusion are 3 crucial factors that dictate the PCM selection process for a given application. The primary criteria for selection are a high heat of fusion and precise melting/solidification temperature that does not involve subcooling. Hydroquinone, D-mannitol and erythritol are 3 well-studied Heat Transfer Fluids (HTFs) in the temperature range of 140 - 200 °C, which is ideal for absorption refrigeration systems. The extent of inorganic material subcooling is an additional significant factor that influences the thermal capacity of the system in addition to the temperature at which the material reaches its melting point. Alternative eutectic mixtures may be viable options after examining issues and attempting solutions, and the storage tank design must be meticulously considered to optimise heat absorption and release in LHTSS. Despite being widely regarded as superior, shell-and-tube architectures are limited in scope, owing to their small PCM volume capacity. The effectiveness of the multitube design was evaluated using full charging and discharging tests. An exhaustive analysis of a superior heat exchanger considering the thermophysical properties of phase-change materials (PCM) is yet to be conducted. A comprehensive understanding of the thermal processes involved in the charging and discharging is imperative. The outcome was contingent upon the heat-transfer rate of the PCM and the container design, and the melting point of the PCM was determined to be approximately 10 °C lower than the operating temperature. It is imperative to conduct a comprehensive analysis of PCM enthalpy, heat of fusion, and detrimental properties such as subcooling, phase segregation, and corrosion prior to resource allocation. It is uncommon to encounter commercial phase-change materials with consistent thermal properties that render Plus Ice and similar materials ideal for solar energy storage. Suspicious advancements have been made in the realm of nanoscale and mechanical heat-transfer rate optimisation. Microencapsulation is utilised to increase the heat transfer surface area and address the phase segregation in salt hydrates. The use of nucleating agents to address the subcooling issues in inorganic salt hydrates is an effective strategy. The implementation of this extensively studied technology unquestionably and profitably increases the storage capacity, and through efficient heat exchange of the generator, the input energy can be conserved while the capacity of LHTES systems is expanded. The overall Coefficient of Performance (COP) of the system is affected by the efficacy of the condenser, absorber and evaporator thermal exchangers. Utilising the PCM in the generator and evaporator is more efficient than in the absorber or condenser. Novel methodologies have demonstrated efficacy in the application of phase-change materials (PCM) to customised solar collectors or flat plates. Nevertheless, the hydraulic power remains necessary until the generator is completely submerged in the phase-change material (PCM) of the storage unit. Multiple approaches have been proposed to integrate PCM systems. Although PCM requires a larger initial investment, its energy consumption decreases as its operating time increases.

The integration of a phase-change material (PCM) into a thermal system offers the benefit of thermal stabilisation, enabling a smooth transition between various modes such as cloudy, day and night conditions. Economic factors predominantly influence the extent of potential change. Difficulties with phase-change materials (PCMs) resulting from the high heat of fusion at a particular melting point may necessitate costly repairs such as the incorporation of nucleating agents, encapsulation, or substitution of container material. The balance between these factors is determined by the viability and expertise of a business. The free cooling method with a latent heat storage system, which exhibits sustainable potential, is most effective in areas characterised by daily temperature variations ranging from 12 to 15 K. The majority of the reviewed research indicates that in comparison to conventional air-conditioning systems, these systems can effectively regulate the interior temperature to a comfortable level while conserving over 50 % of the energy in all climates examined. The principal conclusions derived from this review are as follows: The principal factor influencing the effectiveness of free cooling is the temperature at which PCM transitions occur. Erroneous selection of this temperature could result in the PCM failing to completely consolidate or melt during the charging and discharging processes, thereby compromising its cold storage capacity. An additional noteworthy impediment to their application is the limited thermal conductivity of PCMs, which impedes their rate of solidification and dissolution. Hence, it is critical to employ phase-change materials characterised by elevated thermal conductivities, and it is strongly recommended to incorporate enhancements in heat transmission. For all proposed systems, air was used as the fluid for heat transfer. The solidification of PCM may be accelerated, according to studies, by increasing the air flow rate during charging. Additionally, this procedure can be improved by augmenting the surface area per unit volume of PCM. It was determined that an air flow rate 3 to 4 times greater during charging than during discharging is suitable for cooling storage efficiency. A significant variation in the quantity of phase-change material (PCM) storage has been observed in the majority of studies; PCM weights have varied from 6.4 to 30 kg/m^2 of floor area, contingent upon factors such as the local environment, cooling demands and recommended methodology. Considerable research has been dedicated to temperate continental regions, whereas arid environments, where chilling is of utmost importance, have received scant attention. This underscores the necessity for further investigation of cost-free cooling alternatives in arid desert settings. Although considerable research has been conducted on the application of PCMs for energy storage in buildings, practical case studies demonstrating the performance and functionality of PCMs in actual work settings are scarce. It should be emphasised that no research has been conducted to determine the long-term functionality of these devices. The primary factors preventing the practical implementation of PCM in construction are their significant limitations, including segregation, supercooling, restricted thermal conductivity, exorbitant expenses, and scarcity of PCM manufacturers worldwide. Additional research is necessary to move the concept of free cooling utilising PCM energy storage from the theoretical and experimental stages to the actual implementation phase.

Pilot-scale applications

Increasing energy consumption is a consequence of industrialisation, lifestyle changes and global population growth. Energy requirements can be met through the utilisation of fossil fuels, which possess a finite supply or renewable energy sources that are abundant and replenishable. Limited quantities of fossil fuels are accessible and their use has adverse environmental consequences. Renewable energy sources include bioenergy, geothermal, solar and wind energy. These sources are environmentally friendly, sustainable, and have minimal environmental impacts. One of the drawbacks associated with renewable energy sources such as solar electricity is their intermittent nature and restricted daytime availability. To harness solar energy during periods of low solar radiation and store it for later use, a functional energy storage system is necessary. The success of solar energy applications is heavily reliant on energy storage technology, owing to the sporadic and nocturnal nature of solar radiation. Among the numerous forms of energy that can be stored are mechanical, electrical and thermal energy. Lead-acid batteries are primarily used to store energy in solar photovoltaic (PV) cells. Mechanical energy can be stored using pumped hydropower storage (PHPS), flywheels or compressed air energy storage (CAES). PHPS and CAES are advantageous for large-scale utilities, whereas flywheel energy is the most suitable for intermediary storage within these mechanical energy storage systems. This energy-storage device operates independently of the electrical grid. Thermal energy can be stored in various forms including sensible heat, latent heat, thermochemical energy or a combination of these. Sensible heat energy storage is a type of thermal energy storage in which the temperature variations of the material during the charging and discharging phases contribute to its capacity. Specific heat is the quantity of thermal energy emitted or absorbed by a substance in response to changes in its temperature and mass. Latent heat storage involves the transition between the solid and liquid phases, gas and liquid phases and liquid and gas phases. Phase-change materials (PCMs) can achieve latent thermal energy storage by undergoing phase transitions at designated temperatures. Globally, considerable research is being devoted to phase-change materials (PCMs) to rectify the imbalance between supply and demand through the efficient utilisation of solar energy in systems and processes. PCMs gained popularity during the energy crisis that occurred between the late 1970s and the early 1980s, particularly in the context of solar energy applications, such as solar heating. Numerous studies were conducted and published as books and research papers during this period. Wang *et al.* [208] conducted a comprehensive analysis of solar water heaters (SWH) utilizing phase-change materials (PCMs), encompassing both technical and financial dimensions. Technical opportunities include characterisation of

PCM to improve their application in SWHs, development of a novel SWH that can be coupled with PCMs, evaluation of long-term performance and standardisation of SWHs for marketing purposes. The potential economic implications encompass worldwide cost-benefit assessments and the provision of subsidies, particularly in nations endowed with abundant solar radiation. Xiao *et al.* [209] studied the application of phase-change materials (PCMs) for temperature regulation in photovoltaic (PV) systems, including building-integrated PV (BIPV) and concentrated PV (CPV). They discovered that the addition of PCM increased the efficiency of PV systems; however, additional research is necessary to thoroughly comprehend how PCMs solidify and discharge. The current status of investigations regarding phase-change materials (PCMs), which have applications in solar appliances, heating systems and conservatories, has been discussed by Yang *et al.* [210]. It was discovered that no solar energy products, including phase-change materials (PCMs), were commercially available at that time, and it was determined through a review of the relevant literature that there is no comprehensive evaluation of phase-change materials (PCMs) for use in all types of solar energy systems. The primary aim of this study is to present the latest advancements and developments pertaining to the use of phase-change materials (PCMs) within the context of solar energy systems. To provide a comprehensive outline and up-to-date data regarding the utilisation of PCM in solar energy, this research is structured into 8 distinct sections. In the first section, the applicability of phase-change materials (PCMs) to solar energy and initial academic research on the subject are discussed. The second section provides an overview and categorisation of phase-change materials (PCMs) with the intention of elucidating the concept of PCMs and the variety of PCMs that may be employed in solar energy systems. The third section provides a comprehensive analysis of the utilisation of phase-change materials (PCMs) in solar thermal systems, including solar thermal power plants, solar air purifiers, solar water heaters and solar appliances. The 4th section describes the heating and cooling applications of PCMs. In the fifth section, the application of phase-change materials (PCMs) to photovoltaic (PV) panels is discussed. The utilisation of nanotechnology to improve the PCM performance is discussed in the sixth section. The seventh section provides a summary of recent articles on the application of phase-change materials (PCM) in solar energy systems. The conclusions and recommendations for future research derived from the findings of the preceding sections are presented in Section 2. Thermal energy storage devices based on phase-transition materials have been the focus of extensive research over the past 2 decades.

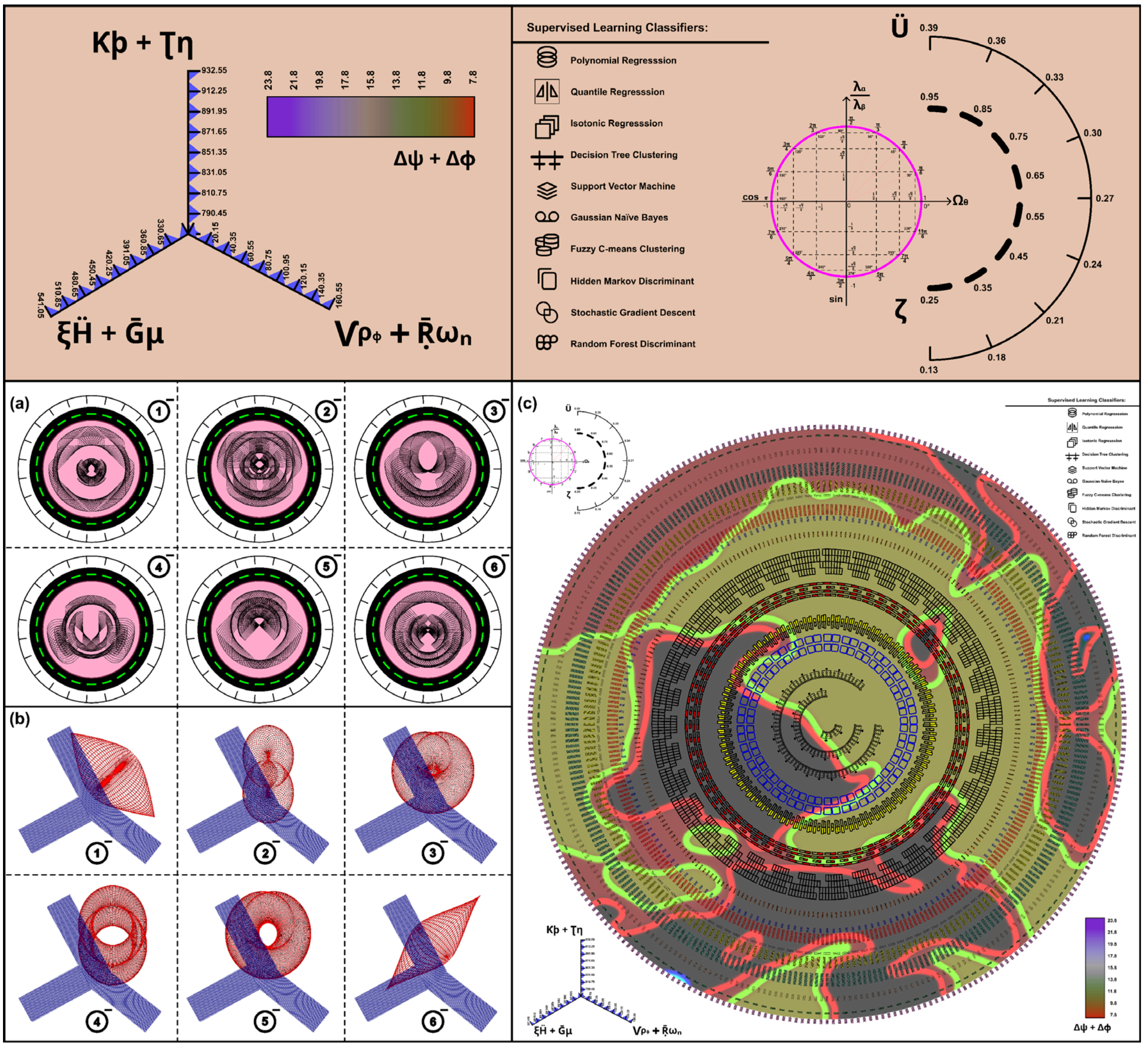

Figure 4 (a) Firm fix state test carried out on pure nitrates and nitrate/EG composite materials for a hybrid solar desalination system comprising solar stills and humidification-dehumidification (Note: The analysis used phase-change material (PCM) to enhance the performance of solar stills, resulting in the production of 754 L/m^2 day of freshwater, with curved cross segments, wickless heat pipes, a level plate solar system, indoor PCM heat capacity and a cooking unit to prepare various meals at noon, evening and night), with angular response-surface plots, estimated via the 6-set hierarchical bands of machine-learning classifiers pertaining to PCMs embedded in building envelopes in passive or active systems, as well as in air-conditioned energy storage facilities, comprising10 kW multi-phase heat energy storage system with 91 m^2 solar collector and a coefficient of performance 13 to 24 times higher than a single-phase system, based on corresponding stochastic response spectra of a 2D restricted volume thermal exchange model was employed to develop a PV/PCM system for enhanced efficiency, speed fields and vortex generation (Note: The PCMs were utilized for dynamic and passive cooling of electronics; specification: 0.04 m wide, 0.132 m high and 0.3 m long, with a leading group of thermal conductivity of 0.027 Wm^{-1} K^{-1}, with non-toxic, inert RT25 and GR40 paraffin waxes) illustrated as a dendrogram of stacked hierarchical bands of machine-learning classifiers.

However, there is a wealth of difficult-to-find information regarding this subject. PCMs exhibit 3 distinct states: Solidification, solidification, and gaseous. Their primary characteristics are solidification and solidification, respectively. These materials possess a substantial amount of energy that can be stored and discharged during operation. PCMs are used to store thermal energy in various practical applications owing to their properties. Samylingam *et al.* [187] studied the utility of TES systems. Urgent energy decisions, including those regarding thermal energy storage (TES), are required. A multiphase arrangement (PCM configuration) is a design for a thermal energy storage (TES) system that sequentially integrates multiple PCM types with distinct melting enthalpies and temperatures to improve the overall heat-transfer performance of the system. Owing to the low thermal conductivity of PCM, this configuration offers a modest energy storage capacity within a solitary PCM. The optimal configuration for a diversified phase-change material (PCM) system involves organising PCMs in a heat-transfer fluid (HTF) stream during the charging and releasing processes, in contrast to the trend of decreasing melting temperatures and increasing melting enthalpies. Therefore, to achieve optimal energy efficiency, specialists must perform an impartial evaluation of the characteristics of various materials and select the combination with the most appropriate dimensions for the intended application. The thermal behaviour of the PCM was achieved by employing 5 temperature sensors that were contained within the tank. The progression of the PCM through the HTF stream was monitored using these sensors, which were situated within the medium. A 20 kW thermal air heat exchanger and a 24 kWe electrical kettle were utilised in this office to refrigerate and heat the HTF, respectively, for energy consumption and the charging procedure, respectively. The heat transfer fluid (HTF) was produced using Therminol VP1, a thermal oil. A well-known configuration currently in use, the flat-plate phase-change thermal storage unit (PCTSU), has been the subject of extensive research. The (PCMs) (PCMs) inadequate heat conductivity of PCMs is a significant drawback that has prompted substantial effort to enhance their performance. By optimising the ratio of the PCM volume to the heat transfer surface area, the integration of the PCM in a thin layer decreases the thermal resistance between the heat transfer fluid (HTF) and PCM across the entire thickness of the section, in contrast to alternative geometries, such as circles. A plate PCTSU is comprised of numerous PCM plates encased in adiabatic rectangular separators. A gaseous or liquid heat-transfer fluid traverses the spaces between surfaces. One side of this plate heat exchanger was filled with PCM in accordance with development standards.1975 marked the beginning of research into the use of PCM for ventilation and heating in space. PCM products are available in various forms including polymers, granules and powders, and are commonly packaged in panels, cylinders, spheres and other types of containers.

There are several methods through which phase-change materials (PCMs) can be incorporated into conventional structural components. One such method involves the direct combination of PCM liquids or granules with the construction materials. Although this method does not require any additional apparatus, it has the potential for escape and decomposition. Another method, known as immersion, involves submerging the building material into the molten PCM and permitting permeation of the material through the pores of the object. Nevertheless, the study findings indicate that this method may not have a lasting effect on utilisation owing to potential leakage issues. Specific macro-encapsulated phase-change materials (PCMs) may be employed in buildings to mitigate adverse impacts on structural elements and prevent material leakage. It was suggested that 5 % microencapsulated PCMs in concrete could result in energy savings up to 12 %. Encapsulated phase-change materials (PCMs) may be incorporated into walls, floors, ceilings, and apertures via PVC panels, plastic sacks, aluminum foils, and other confinement materials. By integrating this, the thermal bulk effect of the building is enhanced. One benefit of utilising PCMs in building fabrics is their ability to transport energy directly to the intended destination without incurring additional cost or loss. The integration of phase-change materials (PCMs) into building structures has garnered significant attention owing to their potential to reduce energy consumption. A range of configurations has been the subject of research, including the use of PCM in wallboards and walls [115,138-

146]. The PCM was utilised beneath and on floors to satisfy the heating requirements [147,148]. PCM are frequently applied to the upper ceiling because it is the most exposed surface in a room and is typically hotter than walls and floors, which are frequently obscured by furnishings and fixtures. The sources consulted for their analysis of PCM integration into building ceilings were [149-151]. Adding a phase-change material (PCM) to windows and shutters to reduce direct and indirect solar gains and absorb surplus heat is an additional intriguing strategy [152-157]. PCM panels are used in ventilated double-skin facades to reduce the amount of energy required for heating and cooling spaces. Phase-change materials (PCM) can be incorporated into any region of the building envelope. Nevertheless, according to Yang *et al.* [211], wall installation is the prevailing method (80 %) described in the literature, owing to its straightforward configuration and integration.

Empirical validations

The use of PCM as a specialised storage unit positioned within the interior envelope of a space is an additional intriguing approach. Passive or active heating and cooling systems are integrated to store heat or frigid energy in the PCM and circulating heat-transfer fluid throughout the storage unit. In contrast to alternative implementation strategies, the concept possesses the benefit of being effortlessly assimilated into the interior environment. The framework of the establishment was unaffected by the installation, elimination or alteration of the PCM unit. The integration of a PCM storage medium with active systems for space heating and ventilation is discussed in [171-175]. Section 3 delves into specialised phase-change material (PCM) storage incorporated into free-cooling systems in conjunction with nocturnal ventilation or other natural cooling methods. Latent heat storage enables sustainable technologies such as phase-shift materials to store frigid energy from the night for daytime use. To induce freezing and heat dissipation, the charging procedure involves circulation of cold ambient air through PCM storage. This procedure was repeated until the ambient temperature decreased below the proper operating temperature of the PCM. Frigid energy is released when the interior temperature exceeds the upper comfort limit, and the heated air flows through the PCM storage. The phase-change material (PCM) undergoes melting owing to heat transfer facilitated by the airflow. Before being circulated throughout the structure, the departed air was cooled. Researchers have studied LHS systems for the free cooling of buildings for approximately 25 years. Various cooling and ventilation systems have been built using distinct phasechange materials (PCMs) and heat exchanger configurations. In general, a phase-change material (PCM) heat exchanger designed for free cooling comprises 3 primary components: A container that facilitates volume changes throughout the phase-change procedure; an efficient heat-exchange surface that transfers thermal energy from the energy source to the PCM and *vice versa*; and a suitable PCM material with the desired range of phase-change temperatures to store the absorbed heat as latent heat. Yang *et al.* [212] initiated the initial substantive dialogues regarding Latent Heat Storage (LHS) and alternative free cooling technologies in 2000. A system was constructed using heat ducts implanted in the PCM units to store the coolness overnight and discharge it during the day. Air was drawn over the visible portion of the heat ducts from the room by using a miniature fan positioned beneath the storage container. The experiment used $Na_2SO_4 \cdot 10H_2O$, a salt hydrate with a freezing/melting point of 21 °C. Additionally, borax nucleating agents were incorporated at a concentration of 1.5 % to mitigate the impact of supercooling. Heat pipelines featuring flutes facilitate enhanced heat transfer between the air and PCM, thereby streamlining the system retrofitting and obviating the necessity for complex heat exchange configurations on the exterior of the PCM. The design potential was evaluated through a combination of theoretical modelling and experimental investigations. A mean heat transfer rate of 40 W was recorded between the air and the phase-change material (PCM) during the 19-hour melting period, accompanied by a temperature differential of 5 K between the air and the PCM's melting point. To enhance the heat-transfer efficacy and reduce the duration of the transformation, the authors proposed a redesign of the fins connected to the heat pipelines inside the PCM unit. This approach reduces the number of PCM units required to chill a room, and the methodology was also utilised in an investigation by Yao *et al.* [213]. The authors evaluated the ability of a prototype cooling system operating at full scale to decrease the temperature of a chamber during the summer season in the United Kingdom. Circular PCM units featuring the incorporated heat ducts were positioned above a ceiling fan with a sweep diameter of 1.20 m. At night, the heat ducts are utilised to draw chilly outdoor air that is warmed by the ceiling fan prior to its outdoor release. To augment air convection in the vicinity of the PCM storage, the apertures were consistently sealed during the day, while the ceiling fan remained operational. The authors stated that the analysis revealed that the combined operation of the innovative storage system and night ventilation resulted in a heat transfer rate of 200 W, which adequately met the cooling demands under typical summer conditions in the United Kingdom.

Compared to alternative solutions such as refrigerated beams and conventional air-conditioning systems, this technology has the potential to generate significant energy and cost savings. A substantial reduction in CO_2 emissions can be achieved by substituting air-conditioning equipment with free cooling systems. It is estimated that the installation of the recommended free cooling system in 2000 office buildings in the United Kingdom could reduce annual CO_2 emissions by approximately 430 tons, given that HVAC systems currently consume approximately 10 % of all fossil fuels. Tofani and Tiari [214] established a mathematical framework for evaluating the thermal efficiency of a night ventilation system utilising PCM-packed bed storage (NVP). This study makes a significant contribution to the literature. The mathematical results were verified through an experimental study conducted in an actual test chamber in Beijing, China over the course of the entire summer. The PCM used in this study was composed of fatty acid molecules created by the authors. The material exhibited a melting temperature range of 22 - 26 °C and latent heat capacity of 190 kJ/kg. A bulk weight of 150 kg was used in the experiment. During the testing period, which spanned 24 June to 4 July 2019 the interior temperature was effectively reduced to a comfortable level, in contrast to the chamber lacking a conditioning system. The maximum cooling discharge rates of 1000 W and 300 W were achieved at night and during the day, respectively. Coefficient of performance (COP) for experimental configurations. Yu *et al.* [215] undertaken the construction and evaluation of an experimental prototype designed for free cooling applications. The researchers utilised commercially available flat-plate PCM packs with a melting temperature range of 20 - 25 °C to minimise heat loss. The packets were encased within a carapace composed of space between 2 polystyrene plates. A parametric investigation is conducted to assess the performance of the empirical model under various conditions. Next, a functional free-cooling system was devised using the most favourable outcomes. According to the statistical analysis, the PCM solidifies more rapidly when thinner encapsulation, higher flow rates, and a greater temperature differential between the phase-change temperature and the input air are combined. Among the various factors that affect the PCM melting process, intake temperature has the most significant influence on the encapsulation thickness. The melting rate was significantly reduced by the augmentation of the airflow. To cool an industrial area, the authors constructed a cooling system with a mean loading capacity of 3,000 W using 8 tested modules (RT25 and C22 PCMs) based on the most optimistic results from the parametric analysis. A comparison of the proposed system with more traditional cooling methods demonstrates that it is technically and economically viable. In contrast to the experimental configurations utilised by Zeinelabdein *et al.* [216]; Zhai *et al.* [217], the impact of incorporating graphite matrices into a PCM in a flat-plate container to improve heat transmission was investigated. A computational model was employed to evaluate the system, supplemented by experimental validation, to increase the confidence. The results were compared to those of a system without a graphite matrix. A 30 %

reduction in the PCM thickness incorporating graphite components resulted in an equivalent solidification/melting reaction time to that of the pure PCM, despite consuming only half the fan power. While the energy storage decreased marginally by 12 - 20 %, the enhanced design effectively decreased the PCM phase transition time by 50 %. The apparatus comprised a rectangular duct measuring 900×140×140 mm^3, which was designed to facilitate direct heat transfer between the ventilation air and densely packed bed. Rubitherm GR is the name given to the PCM granules, which consist of 65 % ceramic materials and 35 % paraffinic hydrocarbon by weight. These particles are available for commercial purchase and range in diameter from 1 to 3 mm. The PCM has a phase transition temperature between 22.5 - 25 °C. To replicate the fluctuations in ambient air temperature, the output air temperature of the storage system was examined across a range of input temperatures. The findings indicate that the departure air temperature was consistently maintained within the PCM phase-change limit during the discharging phase. Furthermore, the suggested chilling apparatus was incorporated into a residential ventilation system while the ambient temperature was maintained at 26 °C. To determine the effect of air temperature on the system efficiency, the summertime ventilation burden for 8 Japanese municipalities was calculated using a simulation tool. A reduction in ventilation burden from 62.8 to 42.8 % was achieved. The authors asserted that the benefits of this approach are predominantly ascertained from diurnal temperature variations rather than the mean temperature.

To facilitate the installation of a floor supply airconditioning system, Zhang *et al.* [218] suggested incorporating a packed-bed latent heat storage system into the mass of a building to increase its thermal storage capacity. An experimental model was constructed for the study, featuring a floor area of 0.5 m^2. A layer of PCM granules measuring 30 mm in depth was deposited directly on the floor. The PCM was composed of foamed glass beads and paraffin wax, both of which had solidification and melting points of ~20 °C. Through nighttime circulation of chilly air from an air conditioner, the concrete slab, PCM-packed bed, and floorboard can store frigid energy. The discharge of frigid energy accumulated throughout the day occurs through pores in the floorboards. Maintaining the interior temperature at 28 °C, it was charged and discharged in accordance with a schedule resembling that of an office building's air conditioning system over the course of 24 h. By implementing this approach, the daily cooling burden was reduced by 89 %, and the estimated 1.79 MJ/m^2 of cooling energy was night. Consequently, the AC system can operate for a mere 3 h throughout the day. The authors hypothesised that by adding more PCM, the office space under consideration might be able to meet its daytime cooling needs. To assess the heat transfer characteristics of the proposed PCM cold storage system that utilises free chilling, Zhang *et al.* [219] devised an experimental configuration. Approximately 3.6 kg of paraffin Rubitherm RT20, a commercially available phase-change material with a melting temperature of 22 °C, was placed in an ergonomically designed metal container for seamless integration into the building ceiling. External insulation was applied to the metal conduit to prevent movement of cold air from the environment. To enhance the thermal efficiency, aluminum fins were affixed to the upper and lower borders of the metal box both inside and outside. A numerical model was employed to calculate air temperature and heat transfer over time for a specified range of air and intake temperatures. A strong correlation was observed between the outcomes predicted by the model and the empirical observations. The interior air temperature decreased from 27 to 24 °C at a rate of 7.8 L/s for duration exceeding 2.5 h. The predictions generated by the selected parameters indicated potential energy reductions ranging from 14 to 87 %. Zhang *et al.* [220] introduced a free cooling method as a means to reduce the utilization of traditional air conditioning systems in buildings. As an integral component of this technology, cylindrical latent heat thermal energy storage (LHTES) devices were filled with paraffin PCM spheres. The numerical model presented by the authors accounts for fluctuations in the fluid velocity and sphere-to-sphere distances resulting from the small diameter ratio between the tube and sphere. This was assessed by integrating an LHTES device into the mechanical ventilation system of the existing Slovenian residence. The TRNSYS simulation tool was employed to assess and validate the concept in comparison with the alternative cooling systems. The research demonstrated that by utilising a free-cooling device, the capacity of the mechanical system can be reduced substantially while the comfort levels are increased. To achieve thermal comfort in the examined residence, 6.4 kg phase-change material per square meter of floor space can be utilised. The developed LHTES device can be used for winter heating in conjunction with a vented façade or an air solar collector. Zhao *et al.* [221] conducted a significant investigation to assess the capacity for free refrigeration in 6 European cities under various weather conditions. The cylindrical LHTES device, previously documented in certain studies [148,159], was utilised in the mechanical ventilation system of a building. The PCM used was RT20 paraffin, which is readily available in the market and has a broad phase-change temperature range of 12 K. Cooling degree hours (CDH), denoting the highest possible unrestricted cooling potential, was calculated using **Figure 2(d)** datasets to optimise the size of the LHTES system. The airflow was modified by the control unit in accordance with the intake ambient air temperature (TA) and egress air temperature (TAE). When the ambient temperature exceeded the interior temperature, which frequently occurs in the selected cities, the interior space was ventilated with ambient air within the thermal comfort range. An independent air circulation system is implemented to reinforce the PCM. The PCM unit was utilised to ventilate the room in the afternoon when the ambient temperature surpassed the interior temperature, thereby expelling the stored cold. For continental locations, it is more advantageous to utilise a phase-change material with a wider temperature range of 12 K, as opposed to one with a smaller range of 4 K. For optimal performance, the optimum PCM melting temperature should differ by 2 °C from the mean temperature during the warmest month. Between 1.0 and 1.5 kg/m^3/h is the optimal PCM mass-to-air flow rate ratio for achieving 85 - 95 % of the maximal CDH. To investigate the thermal characteristics of 2 prototypes of large-scale PCM-air heat exchangers designed for unrestricted cooling, Zhao *et al.* [222] designed an experiment. One prototype, according to the research by Zhao *et al.* [223], utilised aluminum containers containing inorganic PCM, whereas the other utilised organic PCM containing aluminum panels. An air conditioner was used to represent the different modes of operation. A feasibility study was conducted to investigate various airflow rates and inlet air-temperature combinations. The findings of this study revealed that aluminum panels incorporating organic PCM exhibited reduced conductivity and energy retention compared to aluminum containers. However, owing to the consistent thickness of the panels, they demonstrated higher melting rates and more effective chilling capabilities. In contrast, the pouches encountered issues, such as PCM leakage and container expansion throughout the phase transition. The authors demonstrated that it is more cost-effective to enhance the conductivity rather than the heat exchanger design to attain the intended results, as the latter approach often incurs greater expenses. Zolfagharroshan and Khamehchi [224] made the decision to proceed with the second prototype, an aluminum panel incorporating organic PCM, on the basis of its excellent performance, as documented in a study by Moradi and Cioccolanti [225]. An empirical model comprising 18 PCM modules is constructed to assess the technological feasibility of the proposed cooling system. The authors found that the modular design approach was advantageous for evaluating the technical viability of the tested configuration for various applications. By employing this approach, it is possible to modify the number of PCM modules, average phase-change temperature, and cooling power necessary to achieve the intended interior temperature as well as the time required to maintain it. In addition, the PCM melting-temperature selection parameters were assessed in relation to the cooling burden. It was ascertained that a PCM with a melting point lower than the desired interior temperature was more appropriate for high cooling demands. Conversely, a PCM with a melting point closer to the target indoor temperature is more suitable for low-cooling demands. To examine the entire thermal cycle of a PCM-air heat exchanger operating at a full scale, Amiri *et al.* [226] devised an experimental configuration.

The rigid aluminum slabs were manufactured using RT27, a commercially available macro-encapsulated paraffin. The primary findings indicated that the properties of the PCM remained unchanged and that the continuous heat cycling of the intended storage unit was a recurring process [227,228]. By maintaining a temperature differential of 8 K between the incoming air and the typical temperature of the phase-change material (PCM), the complete solidification of the PCM was achieved within 3 h. The air mass flow fluctuated between 0.4 and 0.5 kg/s. The mean power input was 4.5 kW for a duration of 1 h during the solidification phase and 3.5 kW for the melting phase. Using 3 PCM containers, a prototype storage unit was constructed and evaluated in a room with controlled climate. The phase-change material (PCM) employed was a commercial salt hydrate (SP29, Rubitherm GmbH) with a temperature range of 28 - 29 °C. A 0.5×0.5×0.01 m^3 galvanized steel container was utilised to store it. In the PCM charging procedure, 3 discrete input air temperatures (20, 22 and 24 °C) were utilised. Conversely, during the discharge phase, 3 distinct temperatures (36, 38 and 40 °C) were utilised. The main conclusions suggest that the investigated PCM storage could potentially be used to regulate indoor daytime temperatures by discharging the stored cold energy at night. There was a 55 % increase in the time required for the PCM to solidify completely as the intake charge temperature increased from 22 to 24 °C. Conversely, a 33 % decrease in the time required for full solidification was observed when the inlet temperature was reduced from 22 to 20 °C. An increase in the air flow rate from 4.0 to 5.0 m^3/h resulted in a reduction in the solidification time by nearly 16 %.

Researchers have observed that high flow rates and low inlet air temperatures are effective for rapid PCM solidification during the charging phase [167-188]. Conversely, lower flow rates enable frigid energy discharge during the day. Using a numerical method, Zhang *et al.* [229] investigated a flat-plate air-based PCM storage system for free refrigeration in Islamabad, Pakistan, during summer. The modelling results were validated using data from a recent experimental study conducted by Wieland *et al.* [230] that utilised identical input temperature data and simulation times. The results demonstrate that both methodologies aligned reasonably well. The numerical model predicted higher outflow air temperatures at the onset of the melting phase simulation and the temperatures remained lower for the duration of the simulation. It was concluded that the solidification process was more rapid than that observed experimentally, as predicted by computer calculations. The authors determined that the cooling system effectively reduced the daytime temperature in the scorching and arid regions under investigation to a level suitable for human comfort. The cooling capacity was optimised by selecting a PCM whose melting point was aligned with the maximum comfortable temperature during the summer month. The melting temperature appears to exert a greater influence on the system than the airflow rate. The modular heat exchanger devised by Singh *et al.* [231] facilitated free cooling in zones with minimal diurnal temperature fluctuations. Thermal storage is composed of a substantial number of vertically layered modules, with spacers positioned both above and below each module. The module was conceptualised as a 750 mm diameter shell containing a PCM and multiple air circulation passages. A computational fluid dynamics (CFD) simulation was performed on a solitary module featuring 2 air separators to analyse the temperature distribution, airflow patterns, and heat transfer mechanisms of the intended heat exchanger. The temperature contours demonstrate a more pronounced increase in temperature at a reduced velocity of 0.1 m/s in comparison to 2.0 m/s. This can be attributed to the enhanced air mass flow, which maintained a consistent temperature of 299 K along the PCM walls of the inner tube, and 295 K at the spacer inlet. A steady-state study was conducted to ascertain the pressure drop between the module and spacers and to comprehend the flow and temperature variations of the air passing through the module. By employing this methodology, it is possible to determine the appropriate geometrical and flow parameters in accordance with inflow conditions and surface temperature. In a transient investigation, the solidification properties of the PCM and geometrical dimensions of the modular design were assessed. Based on the results obtained from the CFD simulation and experimental data, it can be concluded that for the selected PCM to exhibit a suitable phase-change temperature range, the scanning rate used in the DSC analysis must correspond to the cooling and heating rates of the application. Neglecting to do so could lead to discrepancies in the phase-change temperature between theory and practice. The separators facilitated extended periods of air retention, resulting in heightened heat transfer, particularly when air velocity was reduced. Subcooling of the phase-change material (PCM) in proximity to the interior ring of the tubes was observed when the temperature between the 2 tubes exceeded the solidus temperature. This was due to the reduced heat transfer surface area of the PCM module. Consequently, a recommendation is made to decrease the distance between cylinders. Additionally, a marginal phase transition was observed at the periphery of the PCM module. The authors proposed to reduce the external diameter of the module design. Samaan *et al.* [232] suggested the implementation of free chilling as an additional use for air conditioners.

A feasibility study was conducted in Istanbul, Turkey, utilising hourly dry-bulb temperature data spanning 16 years, to examine the effectiveness of free conditioning in an all-air HVAC system. As stated by the authors, the HVAC system may employ an economiser cycle, also known as free cooling, to conserve energy and maintain comfortable temperatures while decreasing operational expenses. This can be achieved by utilising natural ventilation to satisfy a portion of the energy requirements when the weather is favourable. The seasonality and temperature of the supply air influences the unrestricted cooling capacity at a given location. A substantial amount of energy is conserved throughout the transitional months. With the exception of circumstances where the ambient temperature is at least equal to or lower than the elevated supply air temperature, the free-cooling method may be ineffective during summer. Saadeh *et al.* [233] devised and enhanced an Indirect Evaporative and Storage Unit (IESU), an innovative phase-change material (PCM)-based refrigeration system intended for residential use in Amman, Jordan. An indirect air chiller and a PCM heat exchanger are components of the recommended cooling system. Two PCM layers were contained within a flat, rectangular, corrugated tube that served as a heat exchanger. The PCM used was a commercial salt hydrate with a phasetransition temperature of 20 °C. A parametric investigation was conducted to analyse the effects of different PCM storage configurations and operating condition parameters on the thermal behaviour of the IESU. It was determined that the effect of the heat exchanger length was more significant than that of the breadth. Moreover, as the distance between the plates increased, the cooling burden increased owing to the reduced number of PCM modules.

An optimal design has been identified, which has a repayment period of 7.8 years and has the potential to reduce annual cooling demand by 80 %. For free-cooling applications, Razman *et al.* [234] investigated the thermal properties of various phase-change materials (PCMs) by utilising a variety of PCMs to store and release heat. The storage medium is composed of numerous PCM slab units with multiple PCMs contained within each unit. Rectangular air passage tunnels can be produced by aligning components parallel to each other. Air circulation occurred on the side of the PCM with the lowest phase-change temperature relative to the higher phase-change temperature when it was being charged. When discharging to improve the heat transfer from the PCM to the airflow, a reverse flow occurs. The thermal efficacy of the cooling system was evaluated using a 2-dimensional mathematical analysis utilising the effective heat capacity method. After empirical examination, the computed outcomes demonstrated a satisfactory degree of concurrence. In Tabriz, Iran, and Eindhoven, Netherlands, technological advancements significantly surpassed those of traditional air-conditioning systems, attaining optimal thermal comfort with a Coefficient of Performance (COP) of 7.0. Researchers determined that a PCM slab with a reduced length

and thickness exhibited the maximum coefficient of performance (COP). The optimal design parameters for sustaining an outflow air temperature below 20 °C for approximately 8 h were a PCM slab thickness of 9 mm, an air channel length of 1.30 m, and an air channel height of 3.2 mm. Oyekale and Adetona [235] devised a thermal energy storage (TES) system utilising rectangular cylinders filled with commercial RT28HC PCM for free-cooling applications in structures. The effect of the PCM tube configuration on the efficacy of the system is numerically examined. A feasibility study found that horizontally oriented tubes performed marginally worse than vertically oriented tubes did. In addition, the authors delineated the necessity of heat-exchange enhancement strategies to augment the chilling capacity of the system. Nguyen *et al.* [236] analysed a variety of interior temperatures (specific Stefan numbers) to examine the effects of plate thickness and mass flow rate on free-cooling applications in structures. The product used was a commercially available Rubitherm's salt hydrate PCM (SP22A17). Owing to the inherent challenges associated with the experimental monitoring of these parameters, numerical modelling was employed to track the temporal evolution of the temperature distribution and melt percentage within the PCM plates (**Table 3**). The heat flux (Q) at each time step (j) was computed utilizing the subsequent formula: m represents the air mass flow rate, V_p represents the air specific heat, ρ signifies the air density, v represents the air velocity, A represents the area of the inlet side, and T_i and T_o represent the inlet and exhaust air temperatures, respectively. The results of this study revealed that, as the Stefan number (*St*) increased, the discharge air temperature and refrigeration capacity of the storage unit increased. Additionally, increasing the mass flow rate optimises the chilling capacity and accelerates the melting process. The thermal behaviour of the heat exchanger was significantly influenced by the linear relationship between the thickness of the PCM plates and PCM melting duration for the given configuration. The values of T_m, T_i, and L_p represent the average melting temperature, inlet temperature, and latent heat of fusion, respectively, of the PCM. When the same PCM is utilised, the Stefan number depends solely on the input temperature.
To evaluate the feasibility of free cooling technology in Asia, Moncayo-Riascos *et al.* [237] analysed climatic data for a year and the cooling requirements of a ten-story commercial structure. The primary aim was to generate recommendations for enhancing the free-cooling methodology. According to the findings of this study, free cooling can maintain year-round thermal comfort in a building or location, without the need for additional mechanical systems. To allow the PCM heat exchanger to operate for both summer cooling and winter heating in buildings situated in the hot dry and cold dry climates of Islamabad, Pakistan, a study published in 2015 by Menberg *et al.* [238] combined a freestanding solar-air collector with the free cooling system. The phase-change range of the commercial phase-change material (PCM), which is composed of a paraffin mixture and a salt, was 23 - 27 °C. Solar energy was harnessed using a flat-plate glass solar-air collector to meet the heating requirements during the winter season. The collector warms the air prior to forcing it through the PCM storage via a compressor for extraction on a chilly night. For year-round comfort in the specified region, the authors discovered that a PCM with an approximate 27.5 °C summertime transition point was the optimal option. In the summer, employing a phase-change material with a melting point of 29 °C yields a 15 % increase in chilling capacity and a mere 3 % reduction in heating capacity when compared to a PCM with a 27.5 °C melting point. It has been demonstrated that a with a melting point of 21 °C can be utilised to improve system performance under winter conditions. The winter application of PCM is unfeasible because an optimum melting point of 29 °C is established for summer chilling purposes. However, usage in the opposite direction is feasible. Medina *et al.* [239] conducted a numerical simulation to examine the thermal performance of a ventilation system integrating flat-plate PCM storage for summer comfort in a retrofitted house located in 4 French cities (Trappes, Lyon, Nice, and Carpentras). A phase-change material composed of paraffin with a latent heat of fusion of 170 J/g was subjected to testing at temperatures ranging from 21 to 25 °C during melting. The home was modelled using

the TRNSYS software, which was integrated with MATLAB simulations to represent the PCM/air system. In the majority of instances, overnight crystallisation of the phase-change material was found to be partial, indicating suboptimal system performance. As a result, an increase in airflow is hypothesised to enhance performance. By employing 700 kg of phase-change material (PCM) and reducing the comfort temperature to 26 °C, the number of disagreeable summer hours can be reduced to 2.6 % in Trappes and below 8 % in Lyon. Despite significant improvements in summer comfort in Carpentras, additional PCM are necessary. Therefore, a system feasibility study is necessary. Medina *et al.* [240] conducted an experimental investigation on PCM storage incorporated into a ventilation system to improve the comfort of buildings during summer in Mediterranean countries, specifically Portugal. Three rectangular metallic modules containing the R25 PCM and a climate-controlled cooling/heating device were placed within an insulated wooden conduit. Throughout both phases of the transformation, the effects of the temperature and velocity of the incoming air were assessed. In every scenario examined, the input air velocity was found to have a significant effect on both the phases. As the input air velocity increased, the solidification time decreased linearly, whereas the melting time decreased non-linearly. The influence of the incoming air temperature on the melting process was readily discernible. The temperature and velocity of the air input must be meticulously adjusted throughout the operating cycle, including the charging and discharging phases.

Table 3 Eutectic PCMs with phase-change temperatures between 19 and 30 °C [213-239].

PCM Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)
65.5 % Capric + 34.5 % Lauric acid	18.5 - 19.5	141.8
61.5 % Capric acid + 38.5 % Lauric acid	19.6	133
45 % Capric + 55 % Lauric acid	22	144
75.2 % Capric acid + 24.8 % Palmitic acid	23.4	154
26.5 % Myristic acid + 73.5 % Capric acid	24.6	156
34 % $C_{14}H_{28}O_2$ + 66 % $C_{10}H_{20}O_2$	25	148.7
50 % $CaCl_2$ + 50 % $MgCl_2.6H_2O$	26	96
66.6 % $CaCl_2 \cdot 6H_2O$ + 33.3 % $MgCl_2 \cdot 6H_2O$	27	128
Octadecane + docosane	24.8 - 27.6	204.9
Octadecane + heneicosane	23.8 - 27	174.97
13.4 % Stearic acid + 86.6 % Capric acid	26.8	166
48 % $CaCl_2$ + 4.3 % NaCl + 0.4 % KCl + 47.3 % H_2O	27.9	189
50 % CH_3CONH_2 + 50 % NH_2CONH_2	28	167
Triethylolethane + urea	30.8	219
47 % $Ca(NO_3)_2 \cdot 4H_2O$ + 53 % $Mg(NO_3)_2 \cdot 6H_2O$	32	137
60 % $Na(CH_3COO) \cdot 3H_2O$ + 40 % $CO(NH_2)_2$	33	207.8

Medina *et al.* [241] conducted a parametric study to assess the heat transfer characteristics of a phase-change material (PCM) storage system designed to alleviate the cooling demands of buildings during the summer. A solar collector was used to assess the efficiency of the system during winter heating. Compact storage module (CSM) plates containing paraffin RT 22HC phase-change material (PCM) from Rubitherm were used in this study. During the investigation of both the horizontal and vertical PCM module configurations, a perforated plate was positioned in front of the modules to ensure continuous flow of air. Numerical investigations of the TES system were conducted using the Fluent software, and the outcomes were substantiated through a comparison with empirical data. An anemometer was used to measure the airflow, which was visually observed by tracking the movement of smoke between the modules. The results validate the effectiveness of the flow-control design implemented in a perforated plate. The observed reduction in the pressure varied between 2.1 and 13.3 mbar, indicating that the distance between the modules did not significantly affect the power consumption of the fan. Based on the data, the authors proposed that the thickness of the module be reduced to lengthen the duration of phase transition. Mirahamad *et al.* [212] conducted a theoretical and practical investigation into a small-scale phase-change material heat exchanger unit designed to regulate interior temperature fluctuations in a prototype greenhouse. The latent heat storage system under consideration consists of a flat slab structure encased in aluminum pouches of varying sizes, which were inserted into a PVC conduit featuring a circular cross-section. Each pouch contained 200 g of PEG1000 PCM. A greater temperature differential between the PCM and the input air may, according to research, abbreviate phase termination and increase the efficiency. However, increased air velocities may result in a decrease in both the efficacy and phase length. The interior temperature of the greenhouse was reduced by approximately 10 K during the height of the day owing to the installation of the LHS conditioning system. Muthuvelan *et al.* [67] conducted an experimental study in Pune, India, with the objective of assessing the thermal efficacy of a free cooling flat plate modular PCM heat exchanger. A commercial HS 29 phase-change material (PCM) with a phase-change temperature range of 17 - 29 °C was used in the heat exchanger. It consists of 10 PCM modules and weighs 76 kg each. Polystyrene (25 mm) is used to insulate the outer casing. The system design incorporated a natural cooling capacity of 0.5 kW. A 2.5-meter-wide, 2.5-meter-tall container was fabricated to measure the interior temperature using the air supplied by the system. The airflow rate ($\dot{m}_{air}$) necessary to fill the PCM was determined using **Figure 3(b)** dataset. The dataset incorporates the following variables: (m_{PCM}) represents the mass of the PCM; (L) denotes the PCM's latent heat of fusion; (C_p) signifies the specific heat of the air; (ΔT) signifies the temperature difference between the PCM and the ambient air; and (dt') signifies the expected charge time. The results indicate that it is possible to achieve a temperature reduction of 2.5 K in the cabin. The design is most effective in locations where the ambient temperature remains 5 K above the user's comfortable threshold throughout the discharge period. However, air conditioning is mandatory in designated areas. To enhance efficacy, the professionals recommended reducing the thermal losses. It is possible that when coupled with evaporative or radiant chilling at night, this method can eliminate the need for air conditioning. Ma *et al.* [242] utilized a 1.20 ×0.415×0.410 m^3 manufactured PCM heat exchanger system comprised of eleven PCM modules for free cooling purposes in Bangalore, India. They investigated the thermal parameters of the system and found that the refrigeration requirements of a commercial building are satisfied by the system. A commercial RT27 paraffin PCM with a melting temperature range of 25 - 28 °C was selected based on daily temperature fluctuations at the site. Various intake temperatures (19, 20, 21 and 22 °C) and inlet air velocities (3.0, 4.0 and 5.0 m/s) were assessed within an environmental chamber throughout the charge phase. A spectrum of internal loads ranging from 0.5 to 3.0 kW was assessed throughout the discharge phase to alter the temperature of the interior air utilised for cold extraction. The system was experimentally and computationally evaluated using the CFD model. No variations in air velocity were observed when the input temperature as increased from 19 to 22 °C, resulting in a 60 % increase in charging time, according to the study. Instead of relying exclusively on elevated air velocity settings, which inevitably result in diminished efficiency, it is recommended to expedite the charging procedure during periods of lower temperatures. Consequently, less electricity is consumed by the fan. By applying the free cooling device at internal heat discharge levels of 0.5 and 3.0 kW, the space experienced a temperature reduction of 2.0 - 3.5 K. Minimal internal heat burden has a significant impact on performance and should be avoided. López *et al.* [243] conducted a comparative study to assess the effectiveness of 2 methods for implementing phase-change materials (PCM) in buildings: An integrated PCM ceiling designed for passive cooling and a distinct PCM storage unit intended for free cooling purposes. Energy-Plus and CFD modelling tools were used, and pertinent experimental data were employed to authenticate the results. The research findings indicated that the implementation of phase-change material (PCM) for free ventilation in a residential structure located in Melbourne, Australia, resulted in a more substantial reduction of interior temperature by 1.8 °C compared to its use on the ceiling, which achieved a mere 0.5 °C temperature reduction. In this experiment, an excessive amount of PCM was used as stated by the authors.

Modelling studies

This section examines the potential cleaning of water using the heat storage derived from a concentrated solar heater. Paraffin wax was selected as the phase-change material to facilitate heat dissipation in 2 separate insulated energy sources. As a result of the elevated turbulence rate, paraffin wax absorbed scalding water. The subsequent substances were permeable and safeguarded by the SAHs.

PCTSU system characterization

The developed model accounted for 36 % of the combined efficacy of the steam generator and power block. It was employed to predict the thermal performance of a PCTSU for an 840 MW solar tower power station with a discharge duration of 6 h and a capacity of 50 MWel. When phase-change materials are utilised in lieu of the intended storage capacity, an atypical energy storage system comprising a solitary tank is vital. To achieve the equivalent energy square transformation efficacy during the release phase, PCM storage requires an appropriate phase-change temperature. **Figure 2(a)** shows the thermophysical properties of the selected eutectic PCM (PCM580), which had a phase transition temperature of 580 °C. As is customary for PCMs derived from salts, the thermal conductivity of the robust PCM is anticipated to be 0.5 W/m K, despite the fact that this value is not specified in the reference. To charge the PCTSU, the source temperature from the focused collector must be sufficient to transmit the thermal power capacity to the energy storage site. The SunShot program uses liquid sodium to increase the operating temperature above 650 °C. The liquid salt and various HTFs were charged to a supply temperature of 630 °C. Once the temperature of the output matches that of the channel (630 °C), the device is considered completely charged. A moderate reduction in the thermal efficacy of the recipient resulted from an increase in supply temperature. The permitted source temperature in the energy capacity reservoir, which was linked to each HTF throughout the release process, was 290 °C. The release ceased when the output temperature was decreased to 565 °C. The HTF characteristics provide information on the density, specific heat capacity, thermal conductivity, and dynamic viscosity over a temperature range of 290 - 630 °C. The 'physical and substance information' section of Perry's Chemical Engineers' Handbook [244] details the characteristics of supercritical carbon dioxide (s-CO_2), compressed air, steam and ambient air. Theoretically, the vaporous heat-transfer fluids discussed here do not possess any upper limit for their maximum temperature. The sun-salt properties, which are suitable for temperatures as high as 585 °C, were provided by the sun Guide Model [245]. The characteristics of sodium were extracted from the study by Li *et al.* [246]. Each HTF analysed was a Newtonian fluid. Solar salts have a higher density than sodium (twice its density). Compressed air has an approximately 1.5-times greater density than steam and a 10-times greater density than ambient air at 10 bar. The thickness of the supercritical carbon dioxide in the gaseous heat transfer fluids under consideration was approximately 15 times greater than that of compressed air. The specific heat of steam was significantly greater than that of the alternative vaporised heat transfer fluids. The specific heat capacity of solar salt remains constant at 1.5 kJ/kg K throughout the current temperature range. The volumetric heat capacity was calculated by multiplying the specific heat and thickness. Analogous to the thickness chart, Lai *et al.* [247] provided data on the volumetric heat capacities of different HTFs. Compared to other heat transfer fluids that have been investigated, the volumetric heat capacity of solar salt was the highest. To exchange the same quantity of energy at proportional operating temperatures, a heat-transfer fluid (HTF) with higher specific heat requires a reduced mass flow rate. Conversely, an HTF with higher volumetric heat capacity can be exchanged at a lower volumetric flow rate. The data presented in all figures in this paper indicate that regardless of their mass, the low thermal conductivity and viscosity of gaseous Heat Transfer Fluids (HTFs) are remarkably consistent and comparable. Fluid sodium, which has a conductivity 100 - 150 times greater than that of other thermal energy storage media, is currently the most investigated heat-transfer fluid in terms of conductivity. Owing to its increased energy storage capacity and more resource-efficient operation compared to the traditional 2-tank system, the MLSPCM concept has been demonstrated to be a feasible alternative to current TES designs. Kowthaman *et al.* [248] conducted a study examining the implementation of different PVCM storage designs in a 50 MWe CSP power facility that utilized heat exchangers. The utilisation of Standby Transformer Equipment (STE) can be enhanced by a Transformer Emergency System (TES) that provides reliable power during periods of high demand or as a reserve service. Inactive energy storage performs well as a direct steam generator in STE systems owing to the isothermal nature of phase-change materials during melting and consolidation. This reduces the exergy losses that occur during fuelling and unleashing. The efficient charge and discharge of these energy storage devices necessitates an innovative heat exchanger design owing to the limited thermal conductivity of the PCMs. An inventive energy storage method, phase-change material (PCM), can be transferred between a heated and frigid tank via a screw heat exchanger during the phase-change procedure. In contrast to other designs, this method effectively segregates the energy storage and thermal exchange containers. The utilisation of this heat exchanger in a Thermal Energy Storage system for a 50 MW electric direct steam solar thermal power plant was assessed through annual yield calculations. Using the Levelised Cost of Electricity (LCOE), 2 energy storage systems with distinct designs were compared to develop a cost structure. A schematic of a 50 MWel DSG power plant featuring a 2-tank TES is shown in the image. The solar field consists of direct Fresnel collector assemblies organised in a section dedicated to dispersion and superheating. At a pressure of 106.9 bar, the steam expanded and was heated to a specified output temperature of 550 °C. Compared to steam turbine units, dry-cooled condensers, feedwater heaters, pumps, and auxiliary equipment, the square force (PB) has a rated capacity of 50 MW. The energy storage system consists of the following components: A sensible heat exchanger for energy transfer, heat exchanger to elevate the temperature of the salt during charging, chilly granular tank, and heated tank filled with liquid PCM. **Figure 2(b)** illustrates a system that employs energy storage and release mechanisms to facilitate elevated vapour temperatures within the power block. The vapour was heated to 550 °C using a fossil gas burner. In a 3-tank system, heat is stored as follows: Solid granular PCM is contained in a tank labelled ‘solid’, a chilly tank containing liquid PCM that is close to its melting point, and a third hot tank containing superheated PCM. A high steam outlet temperature during discharge can be achieved without the need for fossil fuel co-firing by manipulating the salt mass stream in conjunction with the steam mass stream to facilitate superheating and evaporation. The range of the thermal exchanger was modified in the basic design instance to provide the necessary release force for an optimal turbine operation (m = 38 kg/s). In this diagram, 24 % of the overall quantity of salt is superheated and stored in a hot energy reservoir throughout the day. The energy reservoir was maintained at a moderate temperature to accommodate the residual PCM.

Solar air heaters with TESs

This capability underpins the prospective future applications of solar energy. Obtaining materials with the necessary thermophysical properties to store solar energy as heat is a primary obstacle. The materials in question can be categorised into 2 main groups: Those that store energy in the form of sensible heat and those that undergo a phase or physical substance change at a specific temperature within the temperature range supplied by the solar heat collectors. The thermal heat reserves that solar-powered thermal applications can be directly utilised include (i) sensible heat storage (SHS), which refers to the retention of sensible heat in solid substances such as water or powders (which is a viable option for solar-powered thermal applications and heatstorage mediums that can undergo thermal elevation while maintaining its phase stability); and (ii) latent heat storage (LHS), which is the inactive heat of fusion in suitable material mixtures (paraffin wax and inorganic ions). The implementation of these heat-retaining materials not only enhances the thermal efficiency of an SAH, but also prolongs the progression of the heating-up phase. In addition, the substantial heat-storage capacity of these materials renders them exceptionally advantageous for solar thermal systems operating during periods of low light or adverse weather conditions. Solar thermal system (TES) materials have been used in various applications. A subset of these varieties is presented in **Figure 2(c)**, and they are regularly implemented in the SAHs. To develop a resilient transient TES system utilising PCM, Jiménez-García *et al.* [249] investigated a widely used technique. The primary function of the system is to determine the type of heat exchanger and materials used in its operation. It was discovered that the identification of PCMs is a crucial element in any TES that requires a reexamination of its inherent characteristics. An additional critical requirement is the early identification of cold and hot heat energy sources as well as the air heat energy exchanger framed by the PCM during the TES development process. Jello and Baser [250] investigated the regular convection within the channel between the sine-wave protection and FP spread in a cross-folded SAH. Javaherian *et al.* [251] conducted research on a method for inserting a retaining plate composed of aluminum canisters into the 2-fold pass divert of an FP-SAH. Intelligent concentrated solar heat collectors are refractive and capable of producing energy at temperatures above those of the FPCs. The primary task is to monitor the solar trajectory and reorient or focus the beams of the sun to illuminate a designated region. Photovoltaic cells and solar collectors are the most common technologies used for space heating and scalding hot water heating in residential settings. Increasing the efficacy of a solar thermal system through power reinforcement is not a straightforward process unless the system maintains its optimal performance for a prolonged duration despite adverse climatic conditions. The pertinent system presently operates on 2 distinct forms of data (fuel): Electricity generated by PV and solar energy and other (alternative) fuels, including electricity, oil and LPG. Several recommendations for using half-to-half SAHs have been examined in relation to this entity. To facilitate drying and space heating with heated air, 2 solar air heaters (s1 and s2) of identical dimensions were conceptualised and constructed. Caution was exercised to evaluate the thermal performance of both air radiators under a variety of conditions; the plywood utilised in the construction of the 2 solar air warmers had a thickness of 1 cm. The 151×53 cm^2 specific area of the safety plate was manufactured from a 0.5 mm thick 22 SWG Al sheet. The separation between the protective plate and the coating on both radiators was measured to be 10 cm. S2 secured a safety plate, which was coated with a granular powder layer measuring 1 mm in thickness with a 2 mm buoy glass. The side dividers of the SAH were angled at 115 ° to maximise solar radiation through the exposed surface.

Air-PCM heat energy exchanger

phase-change materials (PCM) have the potential to be used for heat storage and peakload reduction. Isik *et al.* [252] conducted an investigation into the optimization of load removal arrangements and the streamlining of a PCM-Air heat energy exchanger with the aim of enhancing indoor air quality and thermal comfort. To facilitate the incorporation of microencapsulated paraffin PCM (PCM) into the ventilation system, an exchanger was specifically designed. The objective was to transition the energy consumption of space heating from the peak to off-peak hours. Nguyen *et al.* [236] conceptualised and produced a PCM-air heat exchanger with paraffin as a heat-accumulating medium. It is possible for the heat exchanger to be installed in a ventilation plenum, roof above a corridor or artificial ceiling as part of an HVAC system. The dimensions of the heat exchanger ought to be 1.05×0.80×0.25 m^3. The selection of the Paraffin Microtek 37D was based on its notable attributes, which included a fusion latent heat of 230 kJ/kg, 10 % expansion observed during phase transitions, and an approximate melting/solidifying temperature range of 37 °C. Following the thermal expansion, substantial quantities of paraffin were stored in metal containers that were parallel to each other and spaced sufficiently apart. Three compartments were further perforated to accommodate the temperature sensors positioned at varying depths within the PCM at 3 distinct locations on the plates: The channel, centre, and outlet. The PCM chambers were thermally isolated from their environs by using polystyrene boards. The timber panels were then utilised to provide a sturdy foundation and harness available solar energy. During the initial exploratory phase, the unit was connected to a system that measured the various wind flow rates. In addition to the original paraffin values, several phase-change material (PCM) characteristics, 3 rising coefficients and 3 novel values were utilised in the second optimisation study. The modified parameters are displayed in **Figure 2(d)**. The model was approved based on the results of this study. It was subsequently utilised to replicate an initial control plan, as described in the previous section. The objective of the system was to accurately and efficiently replicate the functioning of the heat exchanger unit under various conditions such as fluctuating circulation rates. To enhance the thermal conductivity, mass fractions of graphite (EG) of 5, 10 or 20 % were employed. To determine the thermal conductivities of the pure nitrates and nitrate/EG shape-settled composites, an initial fixed-state test was conducted. The pure phase transition materials used were potassium and sodium nitrate, both of which are recommended by Beijing Kangpu Huiwei Innovation Co., Ltd., China, with a purity of 99.0 %. Following the combination of pulverised potassium and sodium nitrate, ethylene glycol (EG) was introduced to generate a nitrate blend with mass fractions of 5, 10 or 20 %. Previous studies have indicated that cold-pressed composites outperform warm compression and infiltration composites [253]. These composites were expected to exhibit discernible isotropic characteristics. Approximately 10.0 - 40.0 mm thick specimens measuring 50.0 mm in width were used for the fabrication of each sample. **Figure 3(a)** shows the meticulously documented parameters of the specimens. Hebbar *et al.* [254] investigated a hybrid solar desalination system that employed solar stills to perform both humidification and dehumidification. This hybrid system effectively mitigated water loss during desalination by generating power from solar stills using the residual heat from humidification and dehumidification. The efficiency of a solitary solar still is approximately 90 %, whereas the system's efficacy in increasing the output ratio through heat-water drainage is merely 50 %. The daily water output of several types of solar still systems varies: a conventional system yields 3.2 kg, a single solar still produces 10.5 kg, a 4-solar still produces 42 kg, a humidification-dehumidification system produces 24.3 kg, and a hybrid system generates 66.3 kg. The costs per litre of distillate for the standard, humidification-dehumidification, and hybrid systems are approximately 0.049, 0.058 and 0.034 $, respectively. The potential application of phase-change material (PCM) in Egyptian contexts has been devoted to the development and testing of solar stills in solar desalination systems [172-191]. Compared to the conventional sun still, which yielded 4.51 L/m^2 day of freshwater per day, the solar still with PCM produced approximately 7.54 L/m^2 day. According to the data, a solar still utilising PCM generates 67.18 % more freshwater daily than a standard solar still. In a pilot-scale experiment conducted between June and July 2018, the PCM-equipped solar still in Egypt exhibited superior performance compared to the conventional solar still in terms of daily freshwater output, demonstrating an enhancement of 67 - 68.8 %. Phase-transition material-based indirect solar desalination is commonly employed in technologies such as solar air/water heating, buildings, and desalination to efficiently harness and manage variable solar energy. Zeinelabdein *et al.* [216] examined the temperature history curves of specific phase-transition materials using a modified enhanced temperature-history method (THM). Two phase-change materials (RT82 and RT90HC) were used in this study. RT82 and RT90HC have melting and solidification temperatures of 70 - 87 and 80 - 95 °C, respectively. Hassan *et al.* [255] examined solar desalination in a subsequent evaluation. PCM or paraffin wax was utilised in the analysis of solar desalination energy as a heat storage method. An assortment of media and PCM charge and discharge parameters was employed in our experiments. According to the analysis, the selected PCMs can store thermal energy in a non-membrane-based indirect solar desalination system. The findings of their research demonstrated that the storage method significantly influences the exergy degradation of both the PCM medium and passive solar still. At times, the solar still achieves an instantaneous energy efficiency surpassing 80 % at night, whereas during the day it maintains an efficiency below 5 %.

Solar cooker

A circular solar cooker featuring a curved cross segment, wickless heat pipelines, level plate solar system, indoor PCM heat capacity, and a culinary unit was conceptualised, constructed, and evaluated to assess its efficacy in preserving food temperature throughout the night and preparing various meals at different times of the day. The circular solar cooker comprises 3 fundamental elements: An interior PCM culinary unit, exterior flat-plate solar collector, and network of closed-loop wickless heat pipelines. The outdoor cooker contained the evaporator component of the wickless heatpipe system, whereas the domestic PCM culinary unit contained a condenser component. The evaporator segment of the wickless heat pipe network necessitated sectioning of 15 copper tubes measuring 0.75 m in a length and 16 mm in diameter. Fifteen copper tubes were twisted using an innovative method, yielding curved cross-sections featuring major and minor radii of 14 mm each and angles of 22 °. The tubes were arranged in the form of risers, with a pitch spacing of 0.13 m and vertical alignment. To assemble the evaporator, the receptacles were brazed to 2 flat headers composed of copper and measuring 25.4 mm in diameter. To establish a connection between the evaporator and condenser segments of the closed-loop wickless heat pipe network, the headers of the evaporator were affixed to 2 copper receptacles, each with a diameter of 12.7 mm. The interior surface of the evaporator assembly was cleaned and washed using a method described by Hasan *et al.* [256]. Based on the findings of this study, it is possible to effectively utilise the solar cooker to prepare a diverse range of meals on 2 separate occasions per day: Lunch at midday and supper and breakfast the following evening in secluded regions of Upper Egypt, including Toshka, Owaynat and Lake Nasser. These results indicate that the current cooker is capable of preparing beans, a popular breakfast and dinner option in Egypt, which requires low temperatures and lengthy preparation periods. Overnight, preheated or warm meals in a cooker can be reheated the following morning for breakfast. The material used to construct the accumulation covering plate of the cooker was designed to conceal or reduce the heat radiation loss.

The thermal conductivity of energy storage materials can be enhanced by augmenting the volume of the steel fleece within the PCM. This, in turn, facilitates faster rates of thermal exchange throughout the charging and discharging processes and has been an indispensable human need throughout history. It embodies a significant concept regarding energy utilisation methods in developing countries. Establishing logical, appropriate, and discretionary culinary practices is essential to the general population. Additional solar panels are necessary for push-button solar cookers, which increases their costs. A solar cooker requires a heat-storage medium to enable storage of thermal energy during periods of low solar intensity. The cycling process was regulated using an electrical circuit, which promptly commenced the solidification test after the melting test. To solidify the PCM, frigid air was supplied via a refrigeration fan. To provide the necessary quantity of water for the subsequent analysis, 463 g of $MgCl_2 \cdot 6H_2O$ was transferred to a Pyrex glass container with a detachable glass cover (DSC estimation). The temperatures of the PCM were monitored using K-type thermocouple wires that were aligned and had an accuracy of ± 0.5 °C. The thermocouples were connected to a personal computer and a Cassy Module (serial number 524010) over time, and the temperatures of the PCM were monitored as it began to dissolve and then solidified. The range of dissolution temperatures for the sample was determined by measuring the minimum to maximum temperatures on the DSC curve. Optimal supercoiling occurs within a temperature range of 0.1 - 3.5 °C. Hasan *et al.* [257] examined significant obstacles associated with solar cookeries to evaluate the innovative configuration of a compact solar cooker that utilises concentrating technology, which is commonly employed for daily heat capacity implementation. This implementation serves 2 distinct purposes by incorporating a standard coaxial cylindrical culinary vessel into another vessel. A phase-change material (PCM) was injected into the voids between the 2 coaxial containers to produce a coating matrix. By implementing 1-D limited variations, thermal consolidation was achieved in the heating set. Lumped components that are convective, thermally connected, and exposed to external radiation are utilised to simulate the interior mechanisms of the utensil. The application of the numerical model to analyse the transient characteristics of Madrid’s climate was predicted using validated test data. Two alternatives, the specialist assessment of paraffin and erythritol, were exhaustively investigated for subsequent PCMs. Solar energy is available in a range of designs, from rudimentary and affordable priced models to advanced and expensive contracts that may not be suitable for economically disadvantaged communities. Although it may not rank among the most cost-effective models, the ‘illustrative cooker’ could potentially enhance accessibility for economically disadvantaged regions, owing to its reasonable price and satisfactory performance. Designated between 1950 and 1960, the appliance model remains under development. The utensil was disassembled into isothermal coaxial elements that conformed to the geometry of the 2 coaxial vessels, emulating the cargo and its protective box as chambers of equal volumes. Convection, radiation or 1-dimensional heat conduction may be employed when required to achieve heat equilibrium in individual components. After breakfast, 1 h is typically available for housekeeping or other errands. Given that some heat remained, the initial temperature of the utensil was set at 70 °C. With the aforementioned types of implements, 3 meals can be arranged for a family on sunny days during the summer and winter. It appears that winter, approximately 2 h earlier than summer, is a more favourable season for transporting items indoors for heat preservation. In contrast to phase-change materials (PCM), such as erythritol, paraffin seems more suitable for its designated application because of its phase transition occurring at 100 °C. Increasing the energy conductivity of a PCM does not result in an increase in its energy-storage capacity. To facilitate rapid indoor cooking, a PCM with greater dissolving heat conductivity, such as erythritol, is advantageous. By substituting water for a high-temperature heating medium such as culinary oil, the storage and preservation of thermal energy can be enhanced. By working outdoors and utilising heat storage, the amount of sunlight reaching a food item can be reduced. The thermal efficacy of a prototype solar cooker incorporating an evacuated-tube solar collector and a phase-change material (PCM) energy storage system was investigated. A PCM energy-storage unit connects the distinct energy-gathering and heating components of an appliance. Solar energy is stored in a PCM energy storage unit during the day and subsequently utilised for culinary purposes at night. The energy transfer and storage system (ETSC) with PCM energy storage unit components includes a closed-circuit circulating line with water serving as the Heat Transfer Fluid (HTF), an ETSC, a PCM energy storage unit, a culinary unit, a pump, a safety valve, a flow meter, and a stainless-steel tube heat exchanger. The ETSC was acquired from Nippon Electric Glass

Co., Japan (**Figure 3(b)**). To function as a phase-change material (PCM), 45 kg erythritol was positioned between the cylinders of the apparatus. Phase-change materials (PCMs) undergo expansion when they dissolve; therefore, to account for the expansion during the PCM disintegration phase, the energy storage unit was not filled to capacity. The culinary dish fits snugly inside the PCM energy-storage unit because it is 297 mm wide and 300 mm tall. Owing to the high frictional resistance of the solar collector and conduit system, a pump with a sufficient force was chosen. During the course of the day, the heated water transfers its thermal energy to phase-change material (PCM), and the heat is stored as latent heat in the stainless-steel tube heat exchanger. The cost-effectiveness of the PCM thermal energy storage unit was validated, notwithstanding its elevated price when employed for group applications. The device can efficiently achieve PCM temperatures up to 130 °C, allowing structures to store and discharge a greater amount of energy.

In recent decades, PCMs and other building materials have been used to increase the thermal mass. PCM provide the ticing energy storage capacity for a variety of heating applications in structures, including wallboards, underfloor heating, and other components. This section focuses on the recent implementation of PCM-based heating systems in the constructed structures. Giraldo *et al.* [258] conducted experimental investigations on brick masonry walls by employing PCM microcapsules. In conjunction with insulating layers, PCM has a promising future as a thermal energy regulator for interior space conditions, according to the findings. Utilising phase-change materials (PCMs) can substantially increase energy efficiency and decrease the need for air conditioning. The 3 model wall specimens used were as follows: a reference masonry wall (M1) devoid of PCM, a masonry wall with PCM (M2), and a masonry wall with PCM and insulating material (M3). Ten millimeter-thick M3 insulation was used to insulate the exterior face of the wall. Each wall specimen had an identical external dimension. The liquid paraffin PCM was introduced into the steel microcapsules through a plastic conduit. Once each wall was prepared, a test-ring structure was installed. Giraldo *et al.* [259] conducted research on the application of PCM wallboards in the direction of subsurface heating and space heating. Several experiments were conducted in 2 identical test houses as a part of this investigation. The application of the PCM in the design of an underfloor heating system illustrated efficient peak load shifting. An interior wallboard system based on PCM was constructed for energy storage in the area. The results demonstrated that the combination of a PCM wallboard and underfloor heating system could result in exceptionally efficient energy consumption. Expenses were reduced by 28.7 % and energy usage was conserved by 18.8 %. Franco *et al.* [260] conducted an experimental evaluation of PCM-based TES devices for structural use. To analyse thermal energy transmission in a PCM-based energy storage system, they utilised a large number of PCMs. Furthermore, he devised a PCM configuration that regulates the thermal energy throughout the charging process in specific building contexts. Five parameters were assessed throughout the PCM discharge process: Phase-change temperature subsequent to subcooling, solidification time in the mid-plane, crystallisation initiation time and temperature difference between the solidified and cooled surfaces induced by subcooling. To provide a comprehensive description of the energy-charging process, the results indicated that organic convection must be incorporated into the free-form PCM in any simulation. Therefore, subcooling must be considered during discharge. A study conducted by Day *et al.* [261] investigated the feasibility of utilising PCM-based TES devices for solar air heating. The feasibility of integrating phase-change materials (PCMs) into an energy storage system in conjunction with a solar air heater was assessed. At high mass flow rates, the collector efficiency and thermal energy-transfer coefficient were higher. Without incurring any additional energy consumption, the 200 kg/h mass flow rate efficiently facilitated a homogenous thermal energy exchange throughout the charging and discharging processes. To enhance the capacity of the energy storage system and ensure an extended period of uninterrupted thermal energy provision following sunset, the airflow rate was reduced during discharge. Chen *et al.* [262] evaluated a phase-change material (PCM) used for energy storage in building envelopes that is economical. High-density polyethylene (HDPE) granules composed of glycerides and fatty acids were used to fabricate building envelopes. A test structure located in a heated and humid environment underwent a coating process involving PCM/HDPE granules with cellulose insulation on the exterior wall. The trial duration was several months. The researchers analysed a numerical model to ascertain the efficacy of the PCM-HDPE granules on the wall and their impact on reducing heating and cooling burdens while considering power consumption. Agarwal *et al.* [263] employed a shell-and-tube configuration to investigate a system for storing latent thermal energy. Air was utilised as the heat energy transfer fluid (HTF), and paraffin wax was used as the heat energy storage medium. The thermal energy efficacy of the system was assessed by utilising the charging and discharging of stored energy. These results illustrate the capability of the system to provide heated air for the dehydration of food products, even in the absence of sunlight or with low solar energy intensity. This suggests that a system that operates on latent heat-energy storage is practical. Cedeño *et al.* [264] evaluated a novel and enticing PCM-based technology intended for use as a thermal energy storage medium for building envelopes in a concrete core structure. He implemented the notion that an interior slab could function as a Thermal Energy Storage (TES) system to fulfil a portion of the country's ventilation and heating energy requirements. To store thermal energy, the initial approach relied on the melting of the phase-change material (PCM), whereas the subsequent procedure employed free chilling over the course of the night. By injecting ambient air into the monolith, the phase transition material (PCM) undergoes solidification at temperatures below 21 °C. The author incorporated a PCM that had been macro-encapsulated in small tubes and inserted it into the vacant areas of the precast concrete slabs. Testing the prototype device in a 2-story residence that replicated real-world conditions was his approach. The results obtained from both theoretical and experimental assessments suggest that the concept was prepared for implementation.

Cooling applications

Numerous analyses on the demand for solar energy have revealed that the demand for calm living spaces in residential and commercial structures is escalating dramatically, particularly in developing and impoverished countries. Among the factors cited are the expansion of the nation's gross domestic product, increase in the use of internal thermal energy in buildings, demand for comfort among residents, and advancement of cost-effective refrigeration technology. Owing to the necessity of chilling in the industrial and building sectors, research on cooling techniques based on renewable energy sources has become a top priority. Recent discussions on global climate change in France have placed a significant emphasis on the advancement of renewable energy technologies. Commercial and residential buildings require more refrigeration because of the nation's rising energy demand, which has led to an increase in the quantity of cooling energy produced, necessitating the installation of energy-storage devices. Efficient enhancement of building thermal energy performance can be achieved through the integration of phase-change materials (PCMs) into cold energy storage systems. By storing frigid energy as latent heat storage and releasing it when necessary, phase-change materials (PCMs) have the potential to reduce the amount of energy consumed by many businesses that utilise cooling equipment. The PCM-based technology has the potential to prevent the temperature of buildings from exceeding a specified threshold. An additional significant benefit is that PCMs can be implemented in both the active and passive systems. Active mechanical mechanisms and additional energy are not required for passive systems. In response to temperature fluctuations within a building, phase-change materials (PCMs) either retain or discharge thermal or adrenergic energy when the air temperature exceeds its melting point. Passive systems, including gypsum, wallboards, and ceilings, were confined within the building envelope. A mechanical cooling mechanism is required to charge or discharge the PCM thermal energy. By combining this phase-change material (PCM) with air conditioners in energy storage systems, frigid energy can be stored using free-energy cooling devices or solar-energy-based absorption cooling systems. Night ventilation systems often reduce a room's cooling requirements by 30 - 50 %, which can result in significant energy savings. A proficiently engineered night ventilation system can decrease the peak operating temperatures by 2 - 5 °C the following day. Numerous studies have examined the potential of free-cooling and absorption-cooling systems powered by solar energy. The climate, solar heat gain, heat energy transfer coefficient, and thermal bulk of a building are the primary determinants of the efficiency of these systems. This section provides an overview of PCM-based cooling technologies and their potential for sustainable cooling of structural buildings.

A phase-change material (PCM)-based free-energy cooling system absorbs frigid energy from the environment at night and returns it to the structure during the day to supply the essential cooling. A distinct energy storage component was positioned beneath the target temperature zone to facilitate the energy transfer in the free-energy cooling system. During nocturnal hours, mechanical blowers were employed to introduce ambient air into the energy-storage unit. Maintaining a temperature range of 15 - 20 °C is essential for the effective operation of PCM-based free-energy conditioning systems in buildings. Additional factors to be considered when assessing the efficiency of a free-energy cooling system include the selection of a suitable phase-change material (PCM) that is adequately encapsulated within building structural components, such as walls, roofs and floors, while also considering the local environment. For climatic zones in Asia and Europe, some authors have suggested the use of PCM-based free-energy refrigeration systems as efficient means of storing chilly energy. To decrease the reliance on air conditioning in structures, Cao *et al.* [265] investigated and evaluated a heat-pipe-based free-energy cooling system. He devised a mathematical model to compute the thermal energy transmission from air to the PCM as well as the dimensions of the test unit. A latent heat storage unit was integrated with a heat pipe-based PCM system to store frigid energy overnight and regulate the temperature of the building during the day. The research discovered that for the PCM to undergo thawing and freezing within feasible time periods of 7 - 10 h, a significant temperature difference of 15 °C between air and PCM was required. Bu *et al.* [266] developed and evaluated a PCM-based TES system for providing buildings with free ventilation and heating. They used 30 plates coated with the RT22 HC paraffin wax. Researchers discovered that individuals conserved the most energy in March of winter using a model developed with the Fluent software. The most substantial accumulation of cold occurred during the summer months of July and August because of significant variations in day-to-night temperatures. When the heating and cooling demands were compared, they discovered that the total amount of heat or frigid energy in the workplace was negligible. The annual energy consumption of an office can potentially decrease by approximately 142 kWh. Bozgeyik *et al.* [267] developed a free-cooling energy system utilising a cylindrical Thermal Energy Storage (TES) unit. The RT-20 PCM was utilised in a spherically enclosed system that was incorporated into the ventilation system. To optimise its efficacy, the interior temperature was maintained at 26 °C, while adjusting the melting temperature to within ±2 °C of the operating temperature. The optimal system performance was achieved when the charge airflow rate exceeded the discharge flow rate. Ashena *et al.* [268] proposed a conceptual approach for floor-based air conditioning that incorporates latent heat storage materials within the bulk of the building. The foam glass beads were submerged in paraffin wax to produce a granular latent thermal energy storage medium. He continuously operated the system throughout the day and night, generating 1.79 MJ/m^2 of heat a night. The findings indicate that the utilisation of air conditioning was restricted to 3 h during the day, commencing at 13:00, which led to an 89 % night shift ratio. Future advancements could potentially increase the latent heat storage capacity of granular PCM, enabling the utilisation of energy storage to satisfy the complete daytime air-conditioning demand. Zhou *et al.* [269] conducted a feasibility study on the practical implementation of phase-change material (PCM) in free-cooling systems to store chilly air outside during the night and transfer it indoors during the day. The experimental system he devised effectively regulated the temperature, intake, and exhaust airflow by utilising a PCM energy-storage unit. By employing frigid energy that is conserved during the night, this method may potentially reduce the amount of refrigeration required during the day according to a series of experiments. Zhao *et al.* [270] devised an experimental methodology that cools structures by utilizing the frigid energy storage of a PCM at night. A passive energy cooling system and theoretical framework for free-energy cooling are presented. To maintain the temperature of the heated air during the summer, paraffin, which has a melting point of 22 °C, was stored. The competitive outcomes of implementing this conceptual framework in a region characterised by both low and high temperatures were deliberated. Zhang *et al.* [271] conducted an assessment of the energy and exergy potential of a multiple-PCM TES unit designed for use in free energy cooling applications. To evaluate the efficacy of the system, he investigated the effects of airflow rate and input air temperature on the energy and exergy during the day. Theoretical research has demonstrated that increasing the intake air temperature and airflow rate increases the rate of thermal energy transfer and decreases charging time. Nevertheless, they also result in elevated output air temperatures and greater absorption of thermal energy by the PCMs. Increased temperatures of the intake air led to increased Coefficients of Performance (COPs), whereas decreased temperatures of the inlet air resulted in greater overall exergy efficiency. Zapata *et al.* [272] performed a mathematical analysis of the thermoelectric system having a PCM energy storage unit. They proposed and experimentally validated a design guideline for an integrated thermoelectric energy-cooling system. After conducting an exhaustive investigation, they concluded that the Coefficient of Performance (COP), cost, and cooling capacity were the 3 most influential factors in determining materials for thermal energy storage.

Solar refrigeration and air conditioning

Considerable research is currently being devoted to the application of solar energy to refrigeration systems. Buildings situated in heated regions may have reduced cooling requirements because of solar energy cooling systems. Additionally, they can reduce peak power demand, thereby mitigating the environmental contamination caused by excessive coal-based energy generation. Recently, solar-powered refrigeration systems for a variety of cold energy storage applications have become commercially available and demonstrated tremendous potential. Diverse cooling methods employed in solar-powered cooling systems include photovoltaic-based electrical cooling systems and solar-collector-based thermally propelled cycles. Solar energy is sporadic because of fluctuating weather patterns and topographical features that may impede the quantity of usable solar radiation. The integration of an energy storage unit is imperative to maximise the efficiency of solar energy conditioning systems. Single-effect solar absorption chillers operate using a solitary absorber and generator, in accordance with a fundamental absorption cycle. One potential method for regulating the temperature of the generator is to employ an inexpensive, non-concentrating flat-plate or evacuated-tube solar collector. A single-effect absorption system has a lower Coefficient of Performance (COP) than double- or triple-effect systems do. To enhance the COP, concentrated solar collectors are combined with multi-effect chillers, including double- and triple-effect absorption chillers. Although dual-and triple-effect chillers are expensive, they consume less energy than conventional ones. By capitalising on the isothermal nature of the energy storage process and the high energy storage capacity of phase-change materials (PCMs), a latent heat storage system stores thermal energy efficiently. phase-change materials (PCMs) possess a significant capacity to retain thermal energy within a specified temperature range in solarenergy cooling systems. PCMs are used under an extensive range of temperatures. The schematic design indicates that the TES-based solar cooling system approach can effectively provide cooling energy throughout the day. In their study, Yang *et al.* [273] successfully incorporated a 10 kW cooling capacity heat energy pump solar energy absorption refrigeration system with a multi-phase heat energy storage system comprising phase-change materials (PCMs) characterised by distinct melting points. The individual utilised a solitary flat-plate collector comprising 91 m^2 of solar collector area to fulfil daily cooling energy requirements. The compound parabolic tube collector, heat pipe-based evacuated tube collector, vacuum tube collector, and flat-plate collector were the 4 types of collectors used in this system. The coefficient of performance of the single-phase thermal energy storage system was observed to be 2.4 to 1.3 times lower in this particular climate zone than that of the proposed system. They concluded that the use of phase-change materials (PCMs) in thermal energy storage systems created an optimal operating environment during periods of minimal solar radiation intensity. Wohlgemuth and Littlechild [274] enhanced the solar energy cooling system through the optimization of the latent heat energy storage system. He modelled the developed system from an energy and financial perspective for a typical office building using a system software. The simulation was executed for various scenarios, including (i) sensible (water) storage for both tanks, (ii) PCM energy storage for heated side tanks, and (iii) cool-side tank sensible energy storage. According to the results obtained from the system, the most energy-efficient approach is to utilise containers with capacities ranging from 300 to 2000 liters. Water should be stored in a larger tank and PCM S44 should be added to a smaller tank. phase-change materials (PCMs) outperform water thermal energy storage in solar-powered heating and cooling systems. However, this is only the case when the average temperature of the energy storage system is close to the melting point of the conventional moist cooling towers. Wang *et al.* [275] implemented a solar-powered absorption cooling system that makes use of phase-change materials (PCMs) and a dry air chiller. With only a marginal increase in the overall electricity consumption of the absorption energy cooling system, he discovered that by incorporating a phase-change material (PCM) into the chiller's heat-energy rejection circuit, a portion of the necessary power could be transferred to off-peak hours.

Tiktas *et al.* [276] developed a high-temperature phase-change material (PCMs) system for solar-powered refrigeration and chilling at the University of Lleida in Seville, Spain. Phase-change materials (PCMs) with an enthalpy of 225 kJ/kg were employed within a temperature range of 166 - 173 °C. Prior to finalising the energy-storage tank design, they conducted preliminary assessments of 2 energy-storage configurations using identical PCM. In the initial stages of the charging process, fins are used to enhance the thermal energy transfer rates, thereby facilitating rapid energy storage. During the discharging process, the solidified PCM in proximity to the tubes hinders the heat transmission to the PCM, which is dissolved in the corners owing to its low thermal conductivity. Tian *et al.* [277] introduced a strategy for storing refrigerant energy within an assimilation chiller system in order to regulate fluctuations in solar energy availability and maintain a constant supply of cool energy with minimal reliance on an external thermal energy source. Consequently, the energy contained in the PCM cannot be released. Rizza devised a volumetric efficiency lithium bromide-water system to facilitate the development of a water-ice thermal energy storage (TES) system, Rizza devised a volumetric efficiency lithium bromide-water ($LiBr/H_2O$) system. It was determined that this system exhibited greater efficiency than a system that lacked an energy storage system. The National Institute of Solar Energy in India is equipped with a triple-effect absorption chiller manufactured by Thermax that operates on trough collectors. In the absence of solar radiation, phase-change materials (PCMs) were employed within this system to store thermal energy and supply the absorption chiller with heating requirements. Despite ongoing research, the literature on this system is extremely limited. Tan *et al.* [278] constructed a dynamic model of an innovative household refrigerator featuring a heat energy storage condenser by employing shape-stabilized PCM (SSPCM). The simulation illustrated that the implementation of latent heat energy storage in the SSPCM facilitated uninterrupted heat energy transmission from the energy condenser, resulting in an enhancement of approximately 19 % in the coefficient of performance. By incorporating SSPCM into the insulating layer, the energy consumption of the system was reduced by 12 %. The decrease in the freezer temperature and subsequent increase in the ambient air pressure were attributed to energy conservation. The energy consumption of the new refrigerator decreased after the temperature transition in the second stage, which peaked at approximately 49 °C using the SSPCM. The application of phase-change materials in photovoltaic systems can increase the operational temperature of a photovoltaic (PV) system to 80 °C, causing the integrated transporter to concentrate on crystalline silicon PV cells. Consequently, the efficiency of the PV cells increases, whereas the voltage decreases. The solar system experienced a decline in net power generation owing to the delayed occurrence of a voltage drop resulting from the increase in temperature. By measuring the voltage and force characteristics of the PV cell at various temperatures, a temperature-dependent power loss coefficient can be derived. Temperature dependence of the power output of crystalline silicon photovoltaic systems operating above 25 °C is common, with coefficients ranging from 0.4 to 0.65 %/K. The implementation of PV in buildings resulted in an increase in the operating temperature of the panels, subsequently impeding power generation by 9.3 %. Appropriate temperature control for building integrated photovoltaics (BIPV) is required for this purpose. Numerous heat removal techniques used to maintain the minimum temperature are shown in **Figure 3(c)**. Robust liquid phasechange materials (PCMs) have been utilised as temperature regulators in specific applications. A 1-dimensional thermal energy exchange model was developed [279], with a specific focus on the cooling effect generated by an integrated phase-change material (PCM) contained within an electronic package.

Photovoltaic PCM systems

Combining photovoltaic technology with a change material to create a PV/PCM system is an effective method for increasing the efficacy of a photovoltaic system. To predict the conduction of heat and liquid elements within a PV/PCM system, a 2-dimensional restricted-volume thermal exchange model was developed. The model prioritises the mathematical statements of the Navier-Stokes energy equations. Using the experimental data, a 2-dimensional restricted volume heat transfer method was validated. Furthermore, a comprehensive analysis of the application units is conducted. The preliminary numerical model can forecast the temperature, velocity fields and vortex formation within the system for a variety of system configurations. At an ambient temperature of 23 °C and an insolation of 750 W/m^2, the temperature of the PV cell may reach 45 °C. Conventional air-cooling systems are incapable of maintaining optimal photovoltaic performance when the ambient temperature exceeds 23 °C and the solar radiation exceeds 400 W/m^2. In contrast to alternative systems, concentrating solar photovoltaic systems offers additional benefits in terms of cooling. phase-change materials (PCMs) can withstand or emit significant amounts of energy within a specific temperature range. PCMs, or change materials, are extensively utilised in numerous applications including heat storage, heat management in systems, and active and passive cooling of electronic devices. The ability of a PCM to regulate temperature and store energy is contingent on its properties, heat-exchange mechanisms, and system configuration. To accurately predict the thermal performance of PCM temperature control systems and develop fundamental system designs, a comprehensive understanding of the heat exchange mechanisms occurring within the PCM is essential. The phase-change properties of the PCMs were evaluated using differential thermal energy investigation, calorimetry, and differential scanning calorimetry (DSC). Sujith *et al.* [279] delineated the standard operating procedures (SOPs) utilised in to examine PCM attributes in their audit. They emphasised that external observation and study of the phase-change were not feasible and that the logical apparatus utilised was both complex and expensive. The efficacy of 3 PV/PCM systems with distinct internal configurations - designated 'EA', 'EB' and 'EC'- evaluated after their construction. The front and rear elements of each PV/PCM system were constructed using aluminum. The PCM from the front divider was coupled with an aluminum straight blade, a wire lattice and strip grid balances to enhance the rate of heat exchange. The internal system dimensions were as follows: 0.3 m in length, 0.132 m; height and 0.04 m; width. The vertical end surfaces and translucent Perspex sections comprise the top and bottom of the PCM compartments. Phase movement could be discerned because of the varying thicknesses of the Perspex in the systems (EB and EC) compared to the system EA (0.008 vs. 0.012 m). To insulate the top, bottom and sides of the system, a 0.050 m-thick layer of 0.027 $Wm^{-1}K^{-1}$ thermally conductive polystyrene foam was utilised. A solar-holding coating was applied to the front surfaces of the device to impart specific radiative properties and efficiently retain the solar energy.

Partially accessible PCMs must possess a specific phase-change melting temperature, such as a PV characterisation temperature of 25 °C. Although RT26 and RT27 exhibit similar characteristics, RT25 is currently not available. GR40 paraffin waxes comprised the majority of the straight-chain hydrocarbons identified in these experiments. RT25 is paraffin wax, which belongs to the saturated hydrocarbon group and is denoted by the general chemical formula C_nH2_{n+2}. GR40 is a phase-changing material, in which 89.5 % of the particles fall within the range of 1 - 3 mm. Paraffin wax ($C_{20}H_{42}$) was bonded to an inorganic base material (SiO_2) to form this combination. The absence of toxicity and inertness of RT25 and GR40 towards the vast majority of substances renders them safe for both human health and the environment. The thermophysical characteristics of aluminum, GR40 and RT25 are shown in **Figure 1(a)**. Phase-change materials (PCMs) were employed in research endeavours in accordance with the manufacturer's data. It is anticipated that their properties will remain consistent throughout multiple phase-change cycles and the modified equilibrium plans for the temporal temperature increase at the front surfaces of each system were investigated. **Figure 1(b)** shows that the EC system was equipped with a strip aluminum network, whereas the EA and EB feature blades protruded 36 mm into the PCM. This balance was consistently reconciled on every occasion. The ambient temperature was recorded to be 23 ± 1 °C, accompanied by an insolation level of 750 W/m^2. The front surface temperatures of test systems EA, EB and EC were compared to those of PCM RT25 in the absence of PCM. At 140 min, the temperature increase of the PV/PCM system was reduced by over 30 °C for each system featuring internal blades (EA, EB and EC) compared with that of a single-level aluminum plate. By utilising systems EB and EC, which had a greater capacity than system EA, the 'PV' system achieved a reduction in the temperature. This was owing to the increased surface area of the enlarged metal, which enabled heat transfer into the PCM in the EB and EC. As the working fluid, PVT systems utilise air or water to elevate the temperature of PV panels. Energy production, including that of a PVT system, is impossible without the use of solar radiation. Utilising phase-change materials (PCMs) in PVT systems can optimise their use, increase their efficiency, and boost the system dependability. The thermal storage capacity of the new technology is 33 % to a maximum of 50 % greater than that of the previous PVT method. A PVT-PCM system is more effective at reducing the temperature than a standard PVT system, and a combination of phase-change materials and solar cells can increase the power efficiency in humid climates. An assessment of the energy-saving capabilities of a PV/PCM system was conducted in the United Arab Emirates (UAE) over 1 year. A paraffin-based phase-change material (PCM) with a melting temperature range of 38 - 43 °C was placed at the rear of the PV panel. The chilling of Phase increased the PV output. Santos *et al.* [280] examined the thermal and electrical performance of a hybrid PV/PCM system incorporating double-skin facades (DSF). A numerical model was utilised to simulate the optical, thermal and electrical properties of the PCM, PV, and DSF by incorporating validated codes. The monthly cooling energy requirement was reduced by 20 - 30 % through the incorporation of a PCM layer and a semitransparent PV layer into the DSF cavity. The application of a phase-change material (PCM) and ZnO/water nanofluid blend in photovoltaic thermal systems was investigated. PCM/nanofluids predominantly focus on the fundamental concepts of PCMs, their classification, and their expanding applications in solar technology. This study provides a comprehensive categorisation of phase-change materials (PCMs), including their names and characteristics. The principal conclusions of this study are as follows. Energy recovery and other significant results suggest that photovoltaic materials (PCMs) have considerable potential for efficiently transforming solar energy into usable electrical and thermal energy. Globally, PCM technology has enormous potential for widespread adoption as a means of fostering sustainable economic growth in several countries. The findings of this study indicate that phase-change materials (PCMs) could potentially be implemented in solar thermal and photovoltaic (PV) systems to ensure consistent energy provision for various human needs and to test sophisticated control systems for these energies.

PCMs are utilised in solar energy systems to store thermal energy for subsequent use, even in the absence of solar radiation. Solar thermal power plants, air purifiers, water heaters and solar cookers use these. Solar-powered heating, culinary refrigeration and air conditioning systems have been developed using cutting-edge technologies. The implementation of 0-energy building designs can be significantly facilitated through the use of phase-change materials in residential and commercial solar refrigeration and air conditioning systems. In numerous instances, the application of PCM in solar thermal systems is limited. Anxiety-related issues in this extremely prospective new high-tech industry are being investigated by scientists from around the globe. PCMs have considerable application potential in solar thermal power facilities including parabolic troughs, dishes and power towers. PCMs are commercially viable owing to their cost-effectiveness. phase-change materials (PCMs) increase the efficiency and effectiveness of solar thermal systems, including air conditioners, water heaters and solar appliances. Solar energy systems are initially restricted to operation only when solar energy is present owing to the intermittent nature of solar energy and its daytime availability. By utilising phase-change materials (PCMs), these systems can operate even in the absence of solar radiation, thereby significantly increasing their dependability and efficiency. Phase-change materials (PCMs) are utilised in solar photovoltaic (PV) systems in novel and innovative ways. They have enormous economic potential and require further investigation. The utilisation of phase-change materials (PCMs) in photovoltaic (PV) and PV-thermal (PVT) systems provides a sustainable alternative to the thermal energy provision of PV systems in situations where solar energy is not accessible. The possibility that nanotechnology could enhance PCM performance in PVT applications is promising for the future of humanity. Building heating, specifically for ventilation and heating, is an important and intricate application of phase-change materials (PCMs). This paper states that a great deal of research is being conducted on the use of phase-change materials (PCMs) to store thermal energy in various building applications, such as floor tiles, shutters and wall boards. A PCM-based building energy management system can potentially reduce peak energy consumption significantly.

Sensitivity assessment

This section provides essential insights into the factors that significantly influence the thermal performance and implementation of free-cooling methods as per the most recent review. The following factors were considered: Climate, PCM transformation temperature, PCM encapsulation, heat transfer issues (resulting from incongruent melting, supercooling and limited thermal conductivity of PCMs) and PCM stability. We considered the financial viability of implementing complementary cooling systems. Researchers can identify recommendations for new research areas, gain a better understanding of opportunities to address problems and devise strategies to improve technological performance by examining these factors. Free cooling is a concept that is dependent on weather and environmental conditions. The magnitude of daily temperature fluctuations influences nocturnal ventilation more significantly than the mean outdoor temperature, regardless of location. Latent heat retention: It is widely recognised that free cooling is effective in arid environments, where daily temperature fluctuations range from 12 to 15 K. To meet this threshold, meticulous design deliberations and an exact selection of PCM properties are required for diurnal temperature variations. Further research is required in the critical area of integrating PCM storage with natural cooling methods, such as evaporative cooling and earth cooling, in addition to passive ventilation systems, such as wind collectors. The literature has documented a multitude of methods for determining the PCM transition temperature selection criteria for free-cooling technologies. A phase-change material (PCM) utilised in the free cooling system must have a phase transition temperature that is close to the interior design temperature and lies within a certain range to ensure rapid crystallisation during overnight charging. As stated by Roshani *et al.* [281], certain locations, particularly those that experience high temperatures, may not have the capacity to withstand PCM phase-change temperatures throughout the year. Resch *et al.* [282] recommended the use of a phase-change material (PCM) that can endure a wide range of outdoor temperatures for an extended duration owing to its ability to absorb heat from diverse input air temperatures. Higher melting and solidification temperatures render PCMs more suitable for augmenting the cooling of structures in swelling climates. An algorithm was developed to ascertain the optimal phase-transition temperature (TOT) by utilising the peak melting temperature (TMT) of the PCM and average ambient temperature (TOT). However, for warmer climates, Qyyum *et al.* [283] recommended employing PCM between 19 and 24 °C. The specified range yields an egress air temperature from the storage medium ranging from 23 to 27 °C during the discharge period. This temperature range was considered suitable for the summer height. Qiu *et al.* [284] stated that phase-change materials (PCMs) utilised for thermal energy storage in buildings should have phase-change temperatures ranging from 20 to 32 °C to provide comfort in a variety of climates. The temperature setting of the PCM transformation should be coordinated with suitable active or passive heating and cooling systems, and it is challenging to select a singular phase-change material (PCM) capable of meeting year-round comfort requirements owing to the substantial seasonal fluctuations expected in numerous locations.

For various climates, it may be optimal to set the switching temperature within the comfort limit of the overheating period. Alternatively, one could expand the operational temperature range by utilising a composite of phase-transition materials, which is a method by which a PCM can be incorporated into structures while undergoing protection against external influences and leakage, thereby ensuring sustained viability. Specific limitations of PCM, such as the combustibility of paraffin, can be mitigated by utilising PCM container, and the functioning of the storage system is contingent upon the characteristics of the PCM container. Because of PCM encapsulation, the duration of the freezing/melting process is influenced by the heat conductivity. In addition to the thermal and structural stability, simplicity of handling, and optimal surface area for heat transmission, the PCM container must possess strength and resistance to corrosion. Diverse PCM encapsulation methods have been developed and implemented by businesses and researchers, each utilising a unique design and set of manufacturing materials. PVC panels, shells, granules, metal or plastic spheres, flat plates, plastic bags, various types of plastic tubing, cylindrical pipelines and additional examples are few. The categorisation of encapsulation into microencapsulation or macroencapsulation is determined by the container size, as exemplified by phase-change materials (PCMs). Through microencapsulation, particles 1 - 1,000 µm in size were encased in thin, rigid shells. Microcomponents can be incorporated into any matrix that is compatible with the surrounding exterior. When macro-encapsulation is utilised, phase-change materials ranging in volume from millilitres to several litres are encased in a variety of container designs, including pouches and aluminum panels. Typically, the heat exchanger surface is a container, and microencapsulation can expand the range of potential applications in structures by managing volume fluctuations, increasing the heat transfer via a larger heat exchange surface, and decreasing the exposure of the PCM to the external environment. Certain microencapsulations may affect the mechanical strength of building materials, and microencapsulated PCMs are more expensive than their macroencapsulated counterparts, making it acceptable to employ macroencapsulation in building walls and partitions to prevent PCM leakage. The rate of heat transmission may be impeded during the solidification process owing to specific macro-encapsulations. Buildings utilise phase-change materials (PCMs) for heating and cooling; however, their application presents a number of obstacles, such as supercooling issues, incongruent melting, and the low thermal conductivity of commonly used PCMs. Numerous academic institutions and PCM companies are currently engaged in comprehensive research to overcome these limitations and to improve their thermal properties.

Most research on phase-transition materials has identified low thermal conductivities, resulting in inadequate heat-transfer capabilities for free cooling. Conductivity enhancement has been the subject of considerable scholarly investigation in an effort to optimise melting and crystallisation processes during charging and discharging. Qian *et al.* [285] presented a comprehensive summary of theoretical and experimental investigations aimed at enhancing the conductivity of PCM. Utilising materials with high thermal conductivities, such as carbon fibre, copper, aluminum, nickel, stainless steel and honeycomb, arranged in various configurations (fin, honeycomb, wool, brush, etc.), is an efficient method for accelerating heat transmission. Pratama and Babadagli [286] enhanced the heat transfer between the air and PCM unit by implementing a series of axial metal planes positioned perpendicular to the longitudinal conduit. The use of tubes with fins has been documented by Pokhrel *et al.* [287], who inspected aluminum fins situated externally and internally on a metal receptacle filled with a PCM. phase-change materials (PCMs) are utilised in metal-matrix topologies to maximise the conductivity and minimise the loss of stored energy. This approach has the potential to mitigate volume fluctuations of paraffin and reduce the supercooling of salt hydrates. Incorporating multiple phase-change materials (PCMs) into configurations is an effective approach for augmenting the heat transfer. The temperature differential between the melting point of the PCM and circulating air is critical for this method. The variation in airflow direction was reduced when a solitary PCM was implemented. To sustain a consistent temperature differential in the flow direction, it was possible to arrange multiple PCMs with a lower melting point during discharging and an increase in temperature during charging. This concept increases the efficacy of the storage system by generating constant heat flux. According to Pan *et al.* [288], the heat transfer rate was significantly enhanced when multiple PCMs were utilised, as opposed to a single PCM. In spite of the fact that these strategies have ultimately enhanced the heat transfer of the storage system, the PCM's overall weight and system cost tend to increase. Stability is a significant factor influencing the long-term performance of PCM materials in buildings. This instability may be primarily caused by temperature cycling or corrosion between the material and container, which compromises the stability of PCM properties. The heat stability of phase-change materials (PCMs) can be evaluated by examining their thermophysical properties over multiple heat cycles. To prevent system degradation, this issue must be considered when selecting PCM for a specific application. Pan *et al.* [289] conducted thermal cycling investigations in order to evaluate the stability of particular inorganic and organic phase-change materials (PCMs). Research findings indicate that organic phase-change materials (PCMs) retain their robust thermal characteristics for a duration of 1,000 cycles, whereas inorganic PCMs exhibit suboptimal performance following a significant number of cycles.

Error estimation and optimization protocols

Thermal energy storage (TES) is used in thermodynamic systems to address unpredictable and fluctuating characteristics of solar radiation. To reduce energy wastage and increase the system performance and thermal dependability, TES bridges the gap between supply and demand. Therefore, it is imperative to develop cost-effective TES systems that can operate efficiently. Limited solar thermal facilities worldwide have implemented Thermal Energy Storage (TES) on a large scale. Currently, investigations are underway regarding the implementation of Thermal Energy Storage (TES) systems in a variety of residential solar applications. Utilising computational fluid dynamics in design is a prevalent method of cost reduction, and Fluent® software serves as a practical instrument in numerous engineering contexts; the 2 classifications of thermal energy storage are sensible and latent energy storage. Inert storage refers to substances that persist in a solid or liquid state without undergoing physical changes. Latent heat storage frequently involves phase transitions from solid to liquid or from liquid to vapour. Latent heat-storage materials possess the capacity to store 5 - 14 times more heat per volume than alternative materials. Latent heat-storage system (LHSS) materials must exhibit specific chemical and thermophysical characteristics. Owing to its favourable thermal properties, water is the most prevalent medium for storing sensible heat. Latent heat-storing materials have experienced a surge in popularity because of their capacity, adaptability, and efficacy in thermal applications. Sensible heat storage devices store thermal energy using the heat capacity of a solid or a liquid. This occurs when a storage system is depleted and charged. When selecting a sensible heat storage medium, it is critical to consider the 3 most significant thermophysical properties of the material: specific heat, volume and temperature change. The most frequently employed sensible heat-storage materials and their corresponding properties are shown in **Figure 1(c)**. Phase-change materials, also known as latent heat storage materials, undergo energy transfer or absorption as they transition between the solid and liquid states. A significant benefit of employing an LHS instead of an SHS is its ability to retain heat within an almost equivalent temperature range. Initially, these substances operated as sensible heat-storage materials, permitting the temperature to increase in direct correlation with the enthalpy of the system. However, after the material undergoes a physical transformation, heat is either absorbed or released at a virtually constant temperature. Thus, properties such as thermophysical, kinetic and chemical characteristics are meticulously considered when selecting materials for various applications and the materials used for latent heat storage are distinguished by their physical, chemical, thermal, kinetic and economic properties.

Heat transfer enhancements

Practical methods for increasing the heat transfer rate during charging and discharging include PCM enhancement. Numerous methods exist for attaining desired outcomes, such as modifying the physical composition of the PCM or the design of the heat exchanger. However, these alterations are not without drawbacks, as the rate of heat transfer is inversely proportional to cost, time required, and energy consumed. The design modification of the PCM container to enhance heat transmission is discussed in the previous section. A limited selection of scholarly publications within this domain were scrutinised in this segment. Okoroafor *et al.* [290] investigated the impact of natural convection, heat pipe spacing, fin length and fin count on a thermal energy storage device comprising numerous fins linked to both single and multiple heat pipes. A heat flux of 40 kW/m^2 was applied to the heat pipe evaporator, which had a thermal conductivity of 0.5, to increase the PCM (KNO_3) temperature to its melting point of 608 K. The performance was evaluated by employing the enthalpy-porosity method on a transient finite volume model in 2 dimensions. The natural convection decreased the time required to charge the system by 30 % and ensured a more uniform temperature distribution. A decrease in the spacing between the heat pipes accelerated PCM melting. Although the number of fins does not affect the system performance, the temperature differential within the PCM decreases as the fin length increases. Godson *et al.* [291] compared 2 shell-and-tube PCM tanks, 1 with fins and 1 without fins, and identified a comparable effect of fins. Fins are advantageous in processes that entail only partial charging and discharging, and are not indispensable for complete melting. They argued that increasing the number of fins decreases the amount of PCM in the container owing to the additional cost, labour, and space required to do so. Nematian and Rahimi [292] found that the number of PCM in a dual-pipe heat exchanger decreases when the fins are longer along the longitudinal axis, which results in an increase in the weight and a decline in the overall performance. An increase in the Stefan number facilitates the obstruction of vortex mergers and spurs the formation of vortices in fins of greater height. Naito *et al.* [293] conducted an experimental investigation into the impacts of longitudinal fins in a double conduit containing PCM. At an inlet temperature of 85 °C, a reduction of 24.5 % in the melting process and of 43.6 % in the solidification process was detected. Nadkarni *et al.* [294] conducted an experiment on annular and longitudinal fins within a twin pipe. They discovered that longitudinal fins performed better than annular fins at the same volume percentage. The fin width affects heat transmission and must be modified according to the intended use. Tao and He (126) conducting research on the improvement of a shell-and-tube double pipe latent heat storage unit was as well. An outer tube featuring a helical fin and various phase-change materials (PCMs) substantially enhances the melting fraction and heat-storage capacity in 4 distinct scenarios, as determined by researchers. Finned tubes are commonly employed to charge and discharge phase-change materials (PCMs), thereby augmenting the heat transfer. Mechanical conductivity enhancers (TCEs) consisting of a metal matrix and metal foams are commonly employed to facilitate temperature dispersion. Further details regarding the configuration of thermal energy storage and heat transport under specific operational conditions can be found in a study by Moussa and Dehghanpour [295]. This study also examined the impact of porosity on the maximum thermal diffusivity of the metal foams. Although a reduced pore size can result in an imperceptible temperature gradient during charging and discharging of the thermal storage device, it can also occupy a greater volume within the matrix, thereby increasing the overall latent heat capacity. Although multitubes encased in circular concentric tubes accelerate the melting rate, they result in subcooling. In contrast, the longitudinal fins provide consistent heat transfer and prevent subcooling.

Nano-fluids

Considerable research efforts have been devoted to investigating the potential of nanofluids to improve the absorption capacity of solar collectors and induce phasechanges. Mikkelsen *et al.* [296] combined Al_2O_3 and TiO_2 nanoparticles with oleic acid ($C_{17}H_{35}COOH$) as a solvent in paraffin wax (59.2 °C melting point). The melting time decreased by 6 % with the addition of 0.05 % TiO_2. It was demonstrated that the quantity of nanoparticles and positioning of the encapsulated PCM spheres within the storage vessel are 2 crucial aspects of the improvement. A study conducted by Meng *et al.* [297] investigated the effects of various mass fractions (1, 2, 3, 4 and 5 %) of nanoparticles (Al_2O_3 and TiO_2) on the same base substance, paraffin wax. It was found that the incorporation of 5 % Al_2O_3 and TiO_2 resulted in a 65 and 40 % increase in mass fraction, respectively, and a comparable reduction in melting time. One notable advantage compared to traditional collectors is the ability to precisely optimise volumetric absorption by manipulating nanoparticle size and shape distribution. In the PCM-integrated solar collector, Medina *et al.* [298] meticulously designed paraffin wax mixed with 80 µm aluminum powder particles of varying mass fractions. The substitution of pure wax with aluminum additives substantially enhanced the usable heat gain and reduced the charging time by 60 %. Medina *et al.* [299] measured the effective latent heat of nanofluids in water. The researchers made the unexpected finding that the latent heat of vaporisation can be significantly influenced by the type of nanoparticle employed (graphite or silver) by as much as ± 30 %. In certain instances, graphite nanoparticles enhance thermal storage capacity and photothermal performance [247-277]. Carbon-based nanostructures featuring high aspect ratios exhibit the greatest potential as nanoadditives owing to their superior thermophysical characteristics compared to those of metal and metal oxide nanomaterials. The remarkable capacity retention exhibited by the nanocomposite PCM can be ascribed to its swift charging and slow discharging characteristics. Medina *et al.* [300] investigated and evaluated the thermal properties of a composite material consisting of a nitrate mixture and SiC ceramic honeycomb (KNO_3/$NaNO_3$; 50:50 mol %) for the purpose of thermal energy storage. It was discovered that the latent heat of melting and freezing temperatures in the composite phase-change material (PCM) were significantly lower than those in the pure PCM, whose melting and freezing temperatures were recorded as 222.6 and 223.4 °C, respectively. It was demonstrated that the mass percentage of SCH in the nitrate mixture/SCH composite PCM is directly proportional to the heat storage and release rates of the PCM, suggesting that the PCM is appropriate for latent heat thermal storage systems. Massarweh and Abushaikha [301] conducted a numerical survey on nanoparticle dispersion in a vertical cage with sinusoidal surface waviness ranging from 0 to 0.4. Geometry influences and regulates the thermal processes. Solidification can be accelerated by the addition of nanoparticles, but the ability of PCM to store and release energy is diminished. Solidification can be delayed by a low Grashof number and an increased waviness. Mascetti *et al.* [302] recently published a study examining the heat transfer properties of PCM ($Mg(NO_3)_2 \cdot 6H_2O$) in conjunction with carbon nanotubes (CNT) and nanographites using conventional heating and solar radiation. The researchers noted a 77 % increase in the rate of ultrafast melting and solidification within seconds for a CNT-PCM composite with a concentration of 0.2 wt%.

The superior heat transmission performance of carbon nanotubes (CNT) in absorbing and retaining solar energy has been observed in thermal energy storage systems [278-289]. Carbon nanotubes (CNTs) are widely recognised to have the ability to increase thermal conductivity with minimal compatibility concerns. Liu and Mauter [303] enhanced the heat transfer efficiency and thermal stability of the composite phase-change material paraffin wax by incorporating extended graphite (EG 300 µm), with no discernible impact on the latent heat of fusion. Lin *et al.* [304] report that nanofluids have optical characteristics that allow them to absorb approximately 95 % of solar radiation. The analysis focused on nanofluids produced using a fundamental model and an estimated effective extinction coefficient, which included graphite, aluminum, copper, silver, and gold. The obtained results were consistent with the experimental values. Potential direct absorption solar collectors can be enhanced through the application of graphite and aluminum nanofluids, and they discovered that the utilisation of nanofluids enhances the efficiency of solar thermal applications. Direct absorption collectors (DAC) are optical configurations that enhance the output temperature and thermal efficiency without compromising other properties. Alternative varieties of solar collectors enhance the specific heat and convective heat transfer coefficients with a reduced environmental impact. The conversion of light to heat was enhanced in nanofluids with particular nanoparticle concentrations, and certain hybrid nanofluids exhibited even higher conversion efficiencies. Efficiency is occasionally compromised in the pursuit of stability, necessitating further investigation. Nanoparticles that have been the subject of most scientific investigations include titanium dioxide (TiO_2), aluminum oxide (Al_2O_3) and copper oxide (CuO). The absorptivity of carbon nanotubes (CNT) across the solar spectrum is the highest, reaching cent percent. Further investigation is necessary regarding the application of nano-refrigerants in generators, given the infrequent utilisation of direct absorption in solar absorption cooling.

A DAC offers 2 advantages: More compact design and enhanced efficiency. However, its longer repayment period may render it less economically viable in developing nations. A viable alternative could involve the utilisation of water-based carbon black nanofluids, which possess a moderate sunlight concentration of 10 suns and operate at an economical efficiency of 70 %. The most recent assessment by Li *et al.* [305] provides additional information regarding the various categories of enhancements and their impact on thermal energy storage systems. The referenced source presents a comprehensive examination of the thermophysical properties of phase-change materials (PCM) that have been enhanced with nanoparticles.

Future prospects and challenges

This study provides an exhaustive synopsis of several studies on thermal storage systems. The techniques used to increase the heat transport of phase-change materials and the energy efficiency of thermal storage systems were investigated. Numerous published studies have attested to the extensive experimental and analytical research conducted on packed beds and encapsulation technologies. A variety of parameters, including design, setting, PCM materials and heat transfer enhancement methodologies, have been utilised to compare diverse research projects. Limited research has been devoted to the assessment of pressure reductions in packed-bed thermal storage systems and calculation of the friction factor, which is contingent on the dimensions, configuration and geometry of the packed-bed system. Extensive research has been conducted on various forms and configurations of fins and other extended surfaces, porous media, metal foams, matrix materials and graphite materials to enhance the heat transfer in thermal storage systems by increasing the effective thermal conductivity in a mixture of phase-change materials and additives. An intrinsic drawback of these approaches is the requirement to augment the capacity of the system to maintain an equivalent quantity of stored energy. Numerous studies have examined the impact of nanoparticles, nanofluids and microencapsulation on the thermal efficiency of LHTSs. In phase-transition materials, including additives, the increased heat-transfer rates are attributed to the enhanced thermal conductivity of the PCM, as shown by the trial results. A review of the relevant literature emphasised the critical role of natural convection in the solidification and dissolution of PCMs. In addition to the density, viscosity, and thermal conductivity of phase transition materials, the shape and dimensions of the enclosure have a substantial effect on natural convection fluxes. Therefore, it is critical for storage system design to conduct a thorough analysis of natural convection within storage systems that incorporate liquid phase-change materials (PCMs). Several recommendations for further research on the use of PCM in solar absorption cooling and other applications were provided. Considering the wide range of topics addressed, high-temperature heat-transfer fluids (HTF) are currently in use, whereas high-temperature latent heat storage remains an area of research. Although the compatibility of materials at high temperatures has been acknowledged, their dependable construction and seamless integration into the system remain infrequently observed. Investigations on the economic viability of prototype storage systems are limited. Little attention has been paid to the application of nanotechnology to improve the Heat Transfer Fluid (HTF) in high-temperature applications, and further research is required on energy-exergy analysis and empirical formulation in the context of system design and integration. Limited scholarly research is currently being published on the migration of melting/freezing layers in materials that undergo phase transitions. Thus, the functionality of the PCM storage device is enhanced. Although the optimal operating temperatures for generators in single-and multi-effect absorption cycles have been determined in several studies, integrated storage units are yet to be investigated.

The heat transfer from an external LHTSS requires energy. The energy required for pumping can be decreased by integrating the generator and LHTS units. To date, only 2 endeavours have been initiated with this intention. It is anticipated that the implementation of such an integration will result in a more efficient system; the most efficient configuration for a cylindrical PCM storage unit is the multitube variant. The performance could potentially be enhanced through the incorporation of longitudinal fins with multiple tubes to reduce the subcooling. Therefore, a storage unit combination is required for a unique design, and the operating temperatures of the absorber and the condenser are nearly identical. No effort has been made to integrate them into a solitary device that incorporates PCM. Owing to the significant impact of the thermal conductivity of the PCM on the energy dissipation during operation, its use at the condenser must be strictly regulated. In particular, studies examining the impact of PCM with a condenser operating at temperatures above 40 °C on compressor runtime, particularly in regions where refrigeration is prevalent, have utilised cold storage to identify substances that exist at subzero temperatures; however, their thermal stability, phase separation, and subcooling concerns remain poorly understood. Industrial-scale research on phase-transition materials for large-scale thermal cold storage is uncommon, and nanoparticles, when combined with a variety of phase-change materials (PCMs), provide an array of opportunities and experiments that result in enhanced PCM synthesis. Customising the attributes of application-based PCM is an effective method for adjusting them to the operational conditions of the system. However, studies on phase segregation and high-temperature cycling are scarce owing to the considerable time required to investigate this phenomenon. This aspect establishes the dependability of the product and merits further investigation. Although many salt hydrates possess advantageous thermal properties, additional methods are required to optimise their advantages and mitigate the challenges they present. phase-change materials (PCMs) can be readily incorporated into solar energy systems through various means. Following an analysis of the utilisation of phase-change materials (PCMs) in solar energy applications, the following suggestions are believed to be necessary to enhance the quality of the current technology: Phase-change materials' restricted thermal conductivity and heat transfer may be enhanced by aluminum foam; by utilising a complex compact apparatus, PCM properties can be ascertained, and thermal energy storage devices are anticipated to be recognised as indispensable assets for energy systems in the future. The development of efficient conversion technologies is critical given that TES is indispensable for heating and cooling energy transmission. The advancement of energy storage systems in the future could impede the progress of chemical fuels intended for energy storage, irrespective of their carbon content, and batteries can be utilised to store photovoltaic energy generated by solar panels. Voltage variations between anodes generate rapid response times and high-power outputs, making batteries an attractive option for energy storage. These batteries provide indispensable and highly desirable functions in future energy systems. Thermal energy harvesting and phase-change materials (PCMs) are primary subjects of future research. By implementing state-of-the-art technology to enhance the current system, it may become evident that an improved energy storage mechanism is required for the energy system. Further research will be incentivised by these findings to devise comprehensive approaches that delineate the fundamental prerequisites for ensuring the practical dependability of data when utilising phase-change materials (PCMs) to model solar energy systems.

This study provides an overview of recent advancements in various techniques aimed at improving the heat transfer in LHTES systems. Two potential strategies for enhancing heat transmission, as indicated in this study, are to augment the heat transfer area of the storage system or enhance the thermal conductivity of the storage material (PCM). High-conductivity materials or particulates are used to enhance the thermal conductivity of phase-change materials (PCM). In addition, extended surfaces such as fins and heat pipelines are commonly employed to augment the heat-transfer area. Combined heat transfer enhancement is an essential method for improving the heat transmission in LHTES. The methodology involved augmenting the thermal conductivity of the PCM and enlarging the heat-transfer area. An extensive synthesis of research pertaining to the combined boosting technique was examined in this study. According to this review, very few studies have investigated how PCM can simultaneously increase their heat-transfer area and thermal conductivity. It is advisable that future enquiries incorporate enlarged surfaces, such as fins and heat pipelines, in conjunction with high-conductivity materials to enhance the heat transfer in LHTES systems. However, research publications dedicated to solar cookers are scarce. A decline in publications has been observed in the domains of solar refrigeration and air conditioning following a similar pattern. The primary determinants influencing the economic viability of solar cooling alternatives are system performance and sun collection technology. An absorption refrigeration system that incorporates solar assistance is a feasible alternative to the conventional solar-powered cooling systems. Elements such as temperature, system performance, component costs, and refrigeration requirements significantly influence techno-economic feasibility. The estimation of the total burden is significantly affected by various factors such as the number of occupants, orientation, predominant use, glass type, and composite wall materials and layers. Incorporating suitable photovoltaic modules and thermal storage containers has the potential to hasten the period of return on investment. Although extensive economic research has been conducted on conventional systems and systems employing sensible storage containers, comparative cost studies on the incorporation of PCM as latent heat thermal storage in solar absorption cooling systems are scarce. Li *et al.* [306] employed a genetic algorithm and exergoeconomic analysis to devise a phase-change material (PCM) storage system for a 45.4 kW LiBr-H_2O system. Their analysis revealed a return period of 1.13 years when PCM storage was utilised, and 0.61 years when it was not. The thermo-economic optimisation method and the concept of exergetic cost were employed by Li *et al.* [307] to optimise a single-effect absorption system utilising LiBr-H_2O. They suggest that the enhancements provided by these strategies were reasonably priced. Despite an increase of 12.58 % in investment costs, the production expenses decreased by 3.5 %. Subsequently, they implemented an identical methodology to increase the COP and energy efficacy of the system by 10.419 and 10.423 %, respectively, at the cost of an additional 3.14 % investment. The COP and exergetic efficacy of the NH_3-H_2O absorption system were enhanced by 44.2 and 44.6 %, respectively, using the same method. This objective was achieved through cost reductions of 64.4, 30.4 and 70.5 % for the generator, SHX and rectifier, respectively. Investments in the evaporator assembly and the RHX increased by 19.1 and 100 %, respectively. Resch *et al.* [282] conducted computer research on a LiBr-H_2O system by employing thermo-economic and optimisation techniques. The efforts resulted in a substantial reduction of 64 % in primary energy consumption and a repayment period of 12 years. Subsequently, Laazaar and Boutammachte [308] improved their approach to determine the annual total cost and repayment period. Three types of repayment periods were calculated: 1 incorporating public funds into the capital cost (14.8 years) had the shortest payback period. Kurnia *et al.* [309] modelled and adjusted the proportions of an entire LiBr-H_2O system for Greek hospital construction. Four scenarios were simulated using chiller units with 2 capacities (70 kW and 121 kW), each employing a different collector area and solar percentage for heating and cooling, respectively. The return period for the fourth scenario, which combined a 70 kW absorption system with a 50 kW compression vapor pressure system, was the shortest at 11.5 years. The collector surface had an area of 500 m^2 in area, and the hot water storage reservoir contained 15 m^3 of water. According to Khan *et al.* [310], the repayment period for a 70 kW LiBr-H_2O absorption system that cools a medical facility in Greece is 24 years. Khan *et al.* [311] assessed the viability of implementing solar absorption systems in 3 locations spanning numerous countries, focusing on single-family residences, hotels and offices. Hotels and single-family residences were the most economically feasible options. A reduction of 5-50 % in the required collector area can be achieved through the utilisation of evacuated tube collectors as opposed to flat plate collectors. Kabeyi and Olanrewaju [312] evaluated a

150 kW lithium bromide-water system installed in a medium-sized office building in California, USA. The anticipated repayment period for a 40 % government subsidy was 13.8 years. Jiang and Bu [313] incorporated the climate of Abu Dhabi, United Arab Emirates into a model of a 10 kW NH_3-H_2O system. A significant reduction of 47 % in the energy consumption was observed when the existing system was replaced with a conventional vapour-compression vaporisation system. Although they disclosed a negative correlation with the electricity costs, the repayment period was not specified. Izam *et al.* [314] estimate that it would take 18.5 years for a 1,500 kW LiBr-H_2O solar absorption system operating for 10 h per day to generate a profit. With a 50 % government subsidy, this period was reduced to 9 years in the Kingdom of Saudi Arabia. One potential approach to reducing the COP from 18.5 to 16 years is to increase it to 0.7644. Despite research findings on the practical implementation of free cooling in constructed storage systems demonstrating their advantageous energy efficiency and results, insufficient emphasis has been placed on assessing their economic viability. Huang [315] asserts that the initial investment in a PCM-based free cooling system is approximately 10 % higher than that of a conventional air conditioning system with an equivalent capacity, notwithstanding the technology's incomplete commercialization.

Operational expenses can be significantly reduced by correctly sizing the system [295-302]. He and Bu [316] assessed the technical and financial viability of a free cooling system in contrast to a conventional air-conditioning system. To fulfil the yearly cooling needs of a standard residential structure in Jordan, which is located in a Mediterranean climate, a cost-effective cooling system (€5671) was devised. The economic feasibility of the system was compromised owing to its operational expenses, which surpassed the annual energy savings owing to its extensive scope. Following the parametric analysis, an enhanced design was developed which reduced the initial expenditure to approximately €1195 and accounted for approximately 80 % of the total cooling burden. The Payback Period (PB) for the enhanced system was calculated to be 7.8 years. The initial investment in indirect evaporative conditioning was substantial because of the requirement of 2 blowers. Because of the omission of a cost breakdown by the authors, the initial percentage of the PCM share incurred is unknown. According to an economic analysis of the free-cooling system devised by Hatte *et al.* [317], the storage phase-change material (PCM) accounts for approximately 17 % of the total cost. Reports indicate that the free cooling system consumes approximately 94 % less electricity than conventional air-conditioning systems with comparable capacities. The storage facility will require an additional 9 % of the total cost, payable over a period of 3 - 4 years, as shown in **Figure 1(a)**. Haris *et al.* [318] published a cost breakdown of the Thermal Energy Storage (TES) technology developed by Hannan *et al.* [319] for heating and cooling buildings. The office structure had a length of 4 m, width of 3 m and height of 2.8 m. Experts have estimated that the total initial cost would be €1140, which is approximately double the price of a standard air conditioner. Fifty kilograms of paraffin RT22HC PCM are contained in the metal receptacles that comprise the PCM panels; these panels represent 50 % of the total cost. If the system is exclusively employed for cooling purposes, its initial cost may be approximately 20 % lower than that of the solar collector. Based on Han *et al.* [320], phase-change materials (PCM) and their encapsulation constitute the primary source of capital expenses. Diverse factors, such as fluctuations in system dimensions and the specific phase-change material employed, may contribute to the discrepancies observed in the percentages. Free-cooling systems may become more affordable if PCM production becomes widespread [321,322]. Mass production of thermal energy storage (TES) systems could potentially lead to a reduction in the cost of phase-change material (PCM).

Conclusions

This paper presents a comprehensive review of significant research on phase-change material (PCM)-based thermal energy storage techniques. This review focuses on the strategies employed to enhance the efficiency of thermal storage systems and the methodologies used to analyse heat transfer issues in phase-change materials (PCMs). This study examines the published results and provides an analysis of various methodologies employed to enhance heat transfer, such as additives, fins, nanofluids, nanoparticles, microencapsulation and thermal conductivity techniques. This book provides a summary of the experimental and analytical techniques used to increase the thermal conductivities of PCMs. In addition, the methods employed in contemporary investigations to evaluate the dynamic viscosity of nanofluids are discussed. The objective of this analysis is to establish a firm foundation for selecting the optimal design for diverse heat transfer applications, including PCM. This study provides a comprehensive assessment of state-of-the-art techniques utilised to improve the heat transfer in latent heat thermal energy storage (LHTES) systems. Heat transfer in LHTES systems can be enhanced by modifying the system geometry or increasing the thermal conductivity. In this study, the application of expanded surfaces, such as heat ducts or fins, to improve the heat transmission in LHTES systems was investigated in depth. Following this, we examined methods for increasing the thermal conductivity, including the use of porous materials, high-thermal-conductivity nanoparticles, and low-density materials. Research on maximising the heat transfer through the use of combination strategies has been conducted. This study makes recommendations and examines gaps in the literature regarding heat-transfer enhancement methodologies for LHTES systems. Energy storage is an essential component of systems that operate using renewable energy technologies. In contrast to photovoltaic systems, solar thermal systems have achieved widespread acceptance and efficiently harnessed a substantial amount of the sun's diurnal thermal energy. However, they lack sufficient thermal reserves to ensure operation in situations of minimal or no solar radiation. were selected and evaluated, and their thermophysical characteristics were improved to facilitate continuous operation for 24 h within a functional thermal energy storage system (TESS). Constant operation is required for solar absorption refrigeration systems used for space conditioning and food storage. To accomplish this, a thermal energy storage (TES) system that is efficient and employs materials with high heat of fusion, such as phase-change materials (PCMs), is imperative. This study thoroughly examines the challenges and benefits associated with the operational temperatures of each component in a single-effect solar absorption system, which affects its efficiency, as well as the appropriate phase-change materials (PCMs), integration strategies and enhancements. The results of the investigation, the benefits and drawbacks of PCMs, the potential avenues for PCM enhancement, and the evaluation of energy, cost and labour are utilised to formulate suggestions regarding the trajectory of subsequent research. The extended thermal energy storage capabilities of solar energy systems can be achieved using phase-change materials (PCMs), which take advantage of the intermittent nature of solar energy and its nighttime unavailability. phase-change materials (PCMs) enable the utilisation of solar energy in systems that are not reliant on ambient solar radiation. Hence, the use of phase-change materials (PCMs) in solar energy systems can mitigate the imbalance between the energy supply and demand, which is inherent in traditional electrical sources. Therefore, this study investigates the latest developments in the utilisation of phase-change materials (PCMs) in a variety of solar energy systems and highlights the expanding sectors that require immediate application.

Recent advancements in phase-change materials (PCMs) for solar thermal energy systems, including solar thermal power plants, solar air heaters, solar water heaters and solar appliances, have been thoroughly examined. The text also discusses the application of phase-change materials (PCMs) in solar photovoltaic systems to improve PCM performance, as well as the heating and cooling functions of PCMs in buildings.

Although PCMs are indispensable in solar energy systems, their disadvantages and general unavailability in the market are environmental and financial concerns. The objective of this study is to showcase novel and innovative ideas contributed by authors from around the globe regarding the extensively researched application of phase-change materials (PCMs) in the field of solar energy. These findings provide recommendations for future research that will aid the investigator in refining the study subjects to enhance the system. The construction industry is a major contributor to global energy consumption. HVAC systems (heating, ventilation and air conditioning) consume the most energy within structures. It is possible to decrease the capacity and operating hours of traditional heating and cooling systems by implementing sustainable and environmentally friendly alternatives such as free-building conditioning. Free refrigeration can be achieved by adopting a suitable thermal storage system to capture and store natural cold energy that occurs at night. Researchers have utilised phase-change materials as storage media in free-cooling systems because of their capacity to absorb and release heat within a specific temperature range and their high energy densities. This enables the systems to maintain comfortable temperatures throughout the day and night. The purpose of this study is to present an exhaustive analysis of recent advancements in free-cooling systems that utilise latent heat storage. In addition, we seek to highlight the critical factors that influence the performance of these materials in applications involving unrestricted cooling. The results of this evaluation provide valuable information for ascertaining possible enhancements that can be implemented in storage materials. The use of PCMs for nocturnal cooling effectively regulates interior temperatures and substantially reduces cooling burdens in a variety of locations, according to each analysed study.

Conflicts of interest

No financial or institutional support was involved in the preparation of this paper. The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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