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Polymer-Based Phase Change Materials for Smart Glazing: Enhancing Thermal Regulation and Energy Efficiency in Buildings

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Abstract

Phase change materials (PCMs) for thermal energy storage have attracted significant attention due to growing demand for more environmentally friendly, low-energy building materials. As far as novel technologies are concerned, PCMs based on polymers that are incorporated directly in window panes represent an appealing possibility to achieve a passive control of the indoor temperature by storing and releasing heat. This article reviews the fundamentals, synthesis methods, performance parameters and limitations of PCM SMART glazing systems. It is regarded with organic, inorganic as well as eutectic PC and latent heat storage properties especially the polymer matrices (PMMA/PUR/PVB) which were used for encapsulation, stabilization and optical clarifying process. Recent studies (2020–2025) show that PCM in glazing can reduce annual heating and cooling demand by 15–35%, achieve the latent heat of 60 and 90 kJ/kg^{-1}, while it maintains Tavis >65%. Advanced Strategies: Micro-encapsulation, Nanofiller Loading (Graphene, BNNS), and Polymer–Nanocomposite Hybridization. Advanced strategies for enhancement of thermal conductivity, durability, and transparency have been developed. However, there are also problems of how to suppress the leakage, RFHC and optical–thermal conflict for PCM16-glazing process. Challenging developments are bio-based PCMs, solid–solid transitions and smart façades in the Internet of Things (IoT) involving real-time thermal response. Life-cycle and techno-economic analyses reveal favorable energy payback times (2–5 years) and CO_2 savings potential. The review in its entirety demonstrates the potential of polymer PCM glazing as a promising multifunctional solution for net-zero and adaptive building envelopes from material science, architectural design and environmental sustainability perspectives.

Keywords: Smart glazing, Thermal energy storage, Optical transparency, Nanocomposites, Sustainable materials.

1. Introduction

Globally, the buildings sector is one of the major energy users, contributing 30–40 % to total global primary energy consumption and around 25 % of carbon-dioxide emissions (IEA Publ., 2023) (Washington, DC, USA: DOE, 2022). The demand for cooling is further increasing with growing urbanization, population expansion and the desire of thermal comfort in residential and commercial buildings. Of the total consumed energy inside buildings, heating, ventilation and air-conditioning (HVAC) ranks first with frequently over 50 % (Almtuly *et al.*, 2025). Therefore, enhancing the thermal performance of building envelopes has been recognized as a key task in energy-efficient building and sustainable development measures Awbi, H., (2003). Conventional heating and cooling systems are mainly dependent on fossil-fuel-based electricity leading to exhaustion of finite resources as well as aggravation of environmental pollutants and global- warming gases Banerjee, A., & Naskar, S. (2024).

In response, a trend toward net-zero-energy-building (NZEB) policies has been adopted by many nations that focus on passive design elements-e.g., increased insulation, roof and exterior wall reflective coatings, thermal mass materials to reduce HVAC loads (Chen *et al.*, 2022). Phase change materials (PCMs) are one of the passive options that have been increasingly used for storing and preserving latent heat during phase transition to achieve indoor thermal comfort while minimizing peak energy load (Gao *et al.*, 2021; Huang *et al.*, 2022).

Recent work has reported that inclusion of PCM components in walls, ceilings and window systems may lead to a reduction in annual HVAC energy consumption by 15–30 %, depending on climate zone and the behavior of the PCM International Energy (Agency, 2023; Jelle, B. P., 2011). It is therefore a promising direction to make building materials adapt themselves to control heat flow dynamically, in the quest of sustainable and energy-aware construction.

Role of windows in Heating and cooling control

Windows are a key factor in the total energy performance of a building, as they constitute thermal barriers while allowing daylight to be transmitted through them. Windows are typically one of the weakest links in the Building Envelope and contribute between 30–60% to the overall heat exchange between indoor and outdoor environment for modern buildings (IEA Publ., 2023; Almtuly *et al.*, 2025).

Inefficient or traditional single-glazed windows can allow too much solar heat gain in summer and heat loss in winter, leading to additional energy required from HVAC systems to operate (Almtuly *et al.*, 2025). As a result, enhancing the thermal control performance of windows systems have been one of the keys aims in designing energy-conserving and sustainable buildings Awbi, H., (2003). Emerging material technologies have provided innovative types of glazing, such as electrochromic; thermochromic; photochromic and phase change material (PCM)-incorporated windows that react to external changes dynamically (Jiao *et al.*, 2024). PCM-based smart windows are widely studied in literature, as they can absorb, store and release thermal energy during phase change process to stabilize indoor temperature and decrease the fluctuation of electricity consumption Kapsalis, C., & Karamanis, A., (2019). When the sun shines, PCMs in the window receive excessive solar radiation energy and melt by storing latent heat; when it gets cold, they go back into solid state by releasing stored heat to maintain a pleasant indoor environment Kenisarin, M., (2010).

It has been proved by the numerous researches that PCM incorporated window system can limit the indoor temperature variations and subsequently overall energy demanded. For example, adding microencapsulated paraffin PCM to double glazed units is reported to decrease annual HVAC energy use by 15–25%, depending on both climate zone and PCMs composition Kolokotroni, M., Gowreesunker, S., & Giridharan, R. (2020). Moreover, the introduction of PCMs into transparent polymeric matrices allows for the realization of so-called hybrid glazing systems possessing optical transparency and latent heat storage ability, which are suitable for sustainable building applications (Kosny *et al.*, 2012). Thus, the incorporation of polymer-b as ed PCMs into window panels is a promising passive thermal management approach for alleviating thermal discomfort in rooms, minimizing the need for air-conditioning systems and facilitating the global transformation towards low-energy and net zero buildings Kuznik, F., & Virgone, J., (2009).

Importance of polymer-based PCMs

Phase change materials, or PCMs, have become a popular topic of discussion because they can absorb significant amounts of heat when transitioning between phases and also release some of that heat. Consequently, they are suitable for some energy dispersions in the construction, including window elements and off-grid applications like solar energy. Take window panels, for example, for heat transmission out. This is what happens to traditional PCMs (like paraffin waxes and hydrated salts). They tend to leak. Furthermore, their thermoconductivity changes dramatically in the particles when phase change gathers steam. As a result, building components such as windows and their surrounding framing members lack stability because of poor structural integrity caused by phase-separation phenomena. The heat accumulation capacity of polymer-based PCMs exceeds what ancient people could have imagined. Like other PCMs, today's PCMs exhibit excellent mechanical performance and can endure high temperatures for many years, even though they may burn away without providing support; additionally, their shape is moldable. Another direction to take in the poly base of PCMs is either shape-stable composites made from PCM being embedded into a polymer matrix, which provides mechanical support for the structure, or micro/nano-encapsulated systems in which a polymer shell enclosing the core PCM material prevents leakages when it melts (19). Polymers such as polyethylene glycol (PEG), poly (methyl methacrylate) (PMMA), polyurethane (PU), and polystyrene (PS) exhibit superb compatibility with almost any organic PCM (Chen *et al.*, 2022). For intelligent window materials and smart glazing to work well, the polymer has not only to guarantee reliable thermal performance but also to be transparent. Since the 1970s energy crisis, a new type of hybrid composite has been developed that takes advantage of nanofillers such as graphene nanoplatelets, carbon nanotubes (CNTs), boron nitride (BN), and silica to raise the thermal conductivity and mechanical properties for polymer-based PCM (Mangherini *et al.*, 2024).

The use of these new nanofillers can be seen in Figure 3 by having a liquid phase as well as not leaving artificial supercooling; they further improved heat-transfer efficiency and long-term stability when compared with traditional materials International Energy Agency. (2023). The next challenge, emphasizes Yana, is that through the development of digital manufacturing or 3D printing technologies, it may now be possible to manufacture window panels, facade elements, and adaptive envelopes all built into different PCM-polymer constructions. (These are also structures that will return to their original shape after being bent or compressed.) Jelle, B. P., (2011). Another step forward is the application of biologically based polymers or recyclable matrixes, such as derivatives from cellulose or polylactic acid (PLA), in an attempt to reduce environmental danger associated with PCM composites (Kolokotroni *et al.*, 2020). These kinds of "green" PSs are biodegradable and, with flexible and strong mechanical performance similar to that which normal types possess, can be targeted for use in energy-efficient construction materials. In terms of the former technology, polymer-based PCM is truly a new generation of high-tech, highly functional, and extremely flexible building material that works for the benefit of humanity as well as nature.

Objectives and scope of the review

Therefore, owing to the growing demand for energy-efficient building materials and smart control of buildings worldwide, significant attention has been focused on the PCMs integrated in walls/roofs/ windows and other applications. Among these, PCM coatings on glazing elements are one of the most promising solutions for passive control of indoor thermal performance and related energy saving (Mangherini *et al.*, 2024). Notwithstanding, it is widely studied by several works, but an applicable and updated handbook (and framework) for i) the interrelation between material innovation, manufacturing process, performance environment, and application on building systems Kapsalis, C., and Karamanis, A. (2019).

Thus, in the current review, we focused on the recent developments of polymer PCMs when they are blended with polymers (for window applications) and hence tried to discuss it here. Specifically, this paper aims to:

1) Review the fundamentals of phase change materials, with emphasis on the thermo-physical properties relevant to thermal energy storage and building integration Awbi, H., (2003).
2) Examine polymer matrices and encapsulation techniques that enhance PCM compatibility,

transparency, and form stability for window-based applications Banerjee, A., & Naskar, S., (2024).

3) Evaluate fabrication methods and case studies involving PCM-integrated window panels, focusing on their thermal, optical, and mechanical performance (Chen *et al.*, 2022).
4) Identify key challenges and limitations, such as low thermal conductivity, leakage, optical trade-offs, and large-scale manufacturing barriers (Chen *et al.*, 2022; Gao *et al.*, 2021).
5) Highlight recent innovations in hybrid and bio-based polymer composites, nanomaterial enhancement, and IoT-enabled smart glazing systems (Huang *et al.*, 2022). International Energy Agency (2023).
6) Propose future research directions toward optimizing PCM–polymer composite structures for sustainable, scalable, and environmentally friendly applications in smart building envelopes Jelle, B. P., (2011).

They date back from 2010 to the current year and focus solely on experimental, numerical, and model works published in journals of high impact rank. For a consolidated site on material, energy performance bugs, and sustainability for PCM incorporated glazed adaptive environmental lyotropic cyclodextrin systems (AECs), more than 150 peer-reviewed papers were reviewed (Li *et al.*, 2023). This work can bridge those lab-level ideas and the racialization challenges, which may provide some reference for scientists/engineers and architectural designers about NGES windows.

2. Methodology

Literature Search Strategy

The literature on PCMs in energy efficient building systems was searched for, and analyzed peer reviewed articles from scholarly journals as well as conference papers, literature reviews. To date, the majority of research that the authors concentrated on was centered around synthetic PCMs fabricated from polymers, fabrication methods and their incorporation inside / encapsulation within, smart glazing or window panes. A search period from 2010 to 2025 is applied since this was when PCM integrated systems first emerged, but also to reflect the current state-of-the-art for nanocomposite and bio-based PCM compounds. The scoping review methodological framework used is known for its inclusive study design, and the literature search was carried out in three stages to reduce bias. The review has 2 distinct phases in phase 1, Iterative searching of PCM related literature refined issues of 'search terms' and before & after applying the theoretical framework for PCM. The subsequent tier of refinement also excluded papers dealing with polymer–PCM composites and encapsulation in clear systems. The third and last phase was aimed for the experimentation & modeling of window-integrated PCMs, especially for defining their thermal performances, optical transparency and long-term performance in real or simulated climate. The resulting stepwise process enabled identification of highly relevant and trustful sources in a number of different scientific fields, such as material science, renewable energy engineering and building physics.

Databases and Keywords

Searches were restricted to Scopus, Web of Science, ScienceDirect and SpringerLink databases, as well as MDPI online source and other Wiley Online Library types including Google Scholar in order to cover several higher impact literatures. These sources were chosen because of their extensive coverage of scientific, peer reviewed literature in the field of materials, energy and engineering (Sharma *et al.*, 2009). Where applicable Boolean operators ("AND" and "OR") and wildcard signs were used to further narrow / broadened the search terms. Typical keyword combinations include "polymer phase change material AND window integration", "smart glazing AND PCM AND energy saving", and "polymer matrix PCM OR shape-stabilized PCM composite", "nano enhanced AND thermal conductivity improvement". bio-based polymers – thermal storage energy- ", and "transparent p.m.-indoor temperature control 2.

Standardized vocabulary and subject headings such as "building façade", "latent heat storage" and "smart window materials" were applied for the retrieval of applicable multi-disciplinary research (Singh *et al.*, 2022). Only studies in English language and available in the databases was included to have reliable and consistent data extraction.

Inclusion and Exclusion Criteria

Criteria for Inclusion and Exclusion Criteria for inclusion and exclusion were clearly written in order to reflect the scientific equivalency and background of this review. We judged a publication suitable if it met the following criteria: peer-reviewed; published in between 2010 and 2025 with article's topic focused on polymer-based- or hybrid PCM materials systems; contain reported experimental, analytic or numerical work leading to results relevant for window applications and/or oscillating device and provide one of more quantitative performance numbers assessing latent heat storage capacity, thermal conductivity requirements, optical transmission behavior or energy saving potential. Non-peer-reviewed papers (thesis, technical reports, and patents) or inorganic PCMs (polymers not included as part of the PCM) and languages other than English were also removed. We also discarded repeated research and those lacking definite methods or objective outcomes. We read each paper by hand and fell back on the following criteria to judge if a given paper met quality/technical significance. After the filtering process 150 articles were considered most relevant for further analysis (Tay *et al.*, 2023).

Fundamentals of Phase Change Materials (PCMs)

Concept of Latent Heat Storage

The operation of PCMs is based on the phase-change process, or latent heat of fusion, where substances absorb or release energy while changing states with minimal temperature change. Above the melting point of PCM, during the charging process thermal energy (heat from surroundings) is absorbed by PCMs, converting them into a liquid one. When discharging, the temperature is lower than point B and releases height-to-free-cooling for solidification in air (Zhang *et al.*, 2022).

The total heat stored by a PCM is the sum of sensible heat before and after phase transition and latent heat during the transition:

$$\mathbf{Qtotal = m[cs(Tm-Ti)+L+cl(Tf-Tm)]}$$

Where *m* is the PCM mass, *c_s* and *c_l* are the specific heats of solid and liquid states, *L* is the latent heat of fusion, *T_i* and *T_f* are initial and final temperatures, and *T_m* is the melting point (Chen *et al.*, 2022).

The energy storage performance is quantified by the latent heat (L). From building application, the right PCM should have a melting point between 20 and 30°C (usual comfort indoor environment). The small phase-transition range not only can realize continuous and stable thermal regulation but also prevent the temperature from rising too high Zhou, D., & Zhao, C. Y., (2021). Moreover, the PCM must have high thermal conductibility and chemical/thermal stability and could not be flammable or toxic or undergo large volume expansion by melting to minimize any mechanical stress and because of the leak possibility.

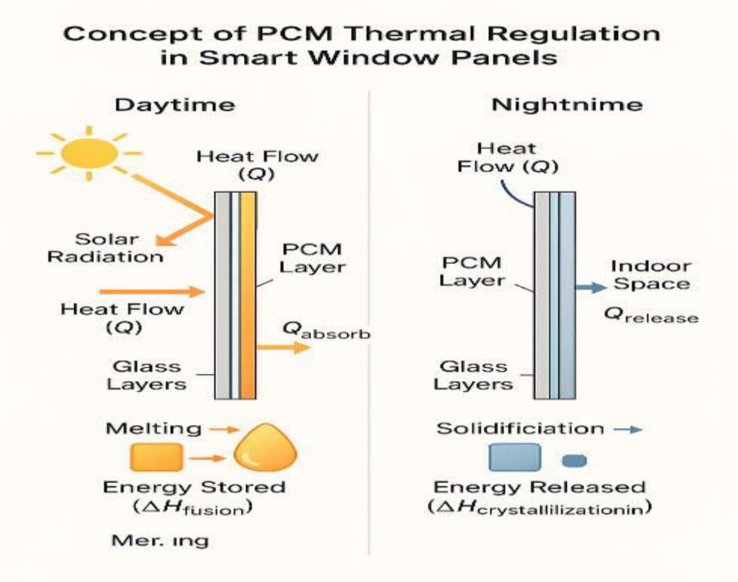

Fig. 1: Concept Diagram of PCM Thermal Regulation.

Applying latent heat storage materials to the building envelopes will be able to even out indoor air temperature, reduce start/stop frequency of HVAC systems, and transfer energy consumption from peak hours to non-peak periods International Energy Agency. (2023). The use of such a device is beneficial, esp. in glazing systems where the temp peaks resulting from solar exposure are pronounced. When PCMs are embedded within transparent or semitransparent layers, the glazing can accumulate heat during the daytime when there is sunshine and discharge it at night, promoting energy-saving potentials along with better thermal comfort of occupants as well.

Types of PCMs: Organic, Inorganic, and Eutectic

PCMs, with their singular thermophysical features, could be either organic, inorganic, or eutectic, but these altogether affect performance and fields of application. Organic phase change materials, including paraffin and non-paraffinic solids, have rapidly entered the market for materials with similar properties in the C10–C20 range, which are utilized in large-area solar energy generation systems. Due to their chemical stability and only slightly supercooling effect, these salts have all positive points. And little or no corrosive activity. The most commonly used material for this purpose is dicyclopentadiene because it has a low cost, a high break freezing temperature for hydrocarbons (which to some extent is a function of the length of the carbon chain), and also it stands up well against aging conditions. However, these materials have low conductive values in the region of 0.2–0.4 W/mK, especially at 25°C. To be able to address the required evaporation rate for an effective cooling water flowing layer, it can only have a higher material content, or else some essential additive will need to be added, such as silver nitrate (Kolokotroni *et al.*, 2020).

In comparison with paraffin, FAs (e.g., octadecanoic acid, dodecanoic acid) exhibit a higher level of thermal stability and greater calorific value; for example, how much fuel is something like 180–210 kJ/kg per kilogram of substance. When it comes to biodegradable materials, these materials are degradable. However, they are highly flammable, and their cost is still high at present, so there are major issues.

Inorganic PCMs with high thermal conductivity, such as salt hydrates, metal alloys, and salts, are a cost-effective alternative. Such materials contain fewer impurities; better performance at low temperatures can be expected from them Kwan, M. L. (2020). It is believed that the two salt hydrates, $CaCl_2 \cdot 6H_2O$ and $NaSO_4 \cdot 10\ H_2O$, reach temperatures of 20-40°C simultaneously under optimal construction conditions. Meanwhile, their performance after space environmental testing was several orders of magnitude worse than when first made (Liu *et al.*, 2022). The emphasis on improving high-temperature stability also highlights the importance of thickening agents, gel-type fillers, thixotropic polymers, and the chemical modification of polymers with new functional groups. Such engineering sometimes involves putting inorganic substrates above a thin interlayer of glycerol or exchange with CA gel electrolyte, so not only does it improve overall long-term stability, but critical assembly steps are least accelerated at design conditions and best left unaltered by failure of a part or assembly (Tay *et al.*, 2023). Eutectic or monotectic phase-change material can be achieved when two of the same or different substances have sharp-melting temperatures several degrees lower than either individual component alone (Mangherini *et al.*, 2024). In the case of Phasedown PCMs, when these need to be fitted for an application, their melting temperature can be adjusted rather easily by adding small amounts of another substance Mehling, H., & Cabeza, L. F. (2008). There is an La 29-stearic and lauric acid Eutectic PCM, at 24°C of this mixture in molten form rather than being solid (Qiu *et al.*, 2021). . They have tunable melting points and are congruent in phase. That is, they will not undergo phase separation unless forced to (Oliveira *et al.*, 2022). On the other hand, it is difficult to synthesize them. In practice, small adjustments in the composition and purity of each component can cause significant changes in their thermal properties. Insufficient stability under continuous use could be an incompatibility with favorable chemistry between organic and inorganic substances (Tay *et al.*, 2023). Pros and cons of different PCMs every type of PCM has its plusses and minuses (**Table 1**). Steam-PCMs are stable and easy to handle; however, Hawaii is not suitable due to its particularly high temperature of 50 to 60°C and low pressure in and near Bo. In contrast, Iceland does not meet the altitude requirements, making it a better option than drones, for example. The so-called "tropicalization" process enhances metro averages by adapting to the hot summers followed by cold winters. Metal PCM (mPCM) has high energy densities but needs a suitable stabilization process; eutectic-PCM phase transitions can be solved clearly, but the design is not straightforward. BIPV and glass cladding are similar in that trade-offs between transparency (passiveness) and long-time stability (thermal performance) must be made. Therefore, they have developed a number of polymer or composite phase change materials (PCMs), such as those composed of two or more series of high molecular weight PCMs less than the limit for each phase making up the other.

Table 1: Comparison of PCM Types and Key Properties.

Type	Melting Range (°C)	Latent Heat (kJ/kg)	Advantages	Limitations	Example Materials
Organic PCMs	18–35	120–200	Chemically stable and non-corrosive. No phase segregation. Recyclable and safe handling. Minimal super cooling.	Low thermal conductivity. Flammable. Relatively expensive. Volume change during melting.	Paraffin waxes (C_{16}–C_{24}), stearic acid, lauric acid, polyethylene glycol (PEG).
Inorganic PCMs	25–60	150–250	High latent heat per unit volume. Inexpensive and abundant. Sharp melting point. Non-flammable.	Corrosion with metal containers. Super cooling tendency. Phase segregation after repeated cycles. Volume instability.	Salt hydrates (e.g., $CaCl_2\cdot 6H_2O$, $Na_2SO_4\cdot 10H_2O$), metallic alloys.
Eutectic PCMs	15–45	140–230	Sharp melting temperature. Customizable thermal properties. Good phase stability. Combination of organic /inorganic properties.	Complex synthesis and composition control. Limited long-term data. Moderate super cooling.	Organic–inorganic mixtures (e.g., lauric acid–stearic acid, NaCl–KCl, urea–NH_4Br).

Advantages and Limitations of Polymer-Based PCMs

The development of poly-based PCM is one of the most promising advances in latent heat storage materials because these composites integrate two functions at once. The polymer component stands for optical tunability and mechanical flexibility, and also a PCM which performs as an energy storage substance. Most of the work has been aimed at compound production, that is to say, where a polymer is either used as an outer fabric that confines the PCM physically or encapsulates and holds it in micro- or nanoscale to prevent vapor leak during phase transformation (Singh *et al.*, 2022). Melt blending; in-situ polymerization, emulsion polymerization, and electrospinning are traditional methods of polymer PCM production. Each has its own control accuracy and level, but the finished product transparency varies greatly between them too. Among the four polymers most intensively studied in this work (PEG, PMMA, PU and PS), these are clear or at least very translucent and have good compatibility with a variety of PCMs U.S. Department of Energy. (2022). Composed with PEG, the composite also had good latent heat storage and was nearly chemically stable. As a matrix, PMMA is very transparent optically due to its high refractive index, a characteristic that is particularly significant for intelligent window arrangements. PU-based systems are both mechanically flexible and adhesive beyond the average features that are useful for integrating latent heat storage units into the architectural glass from which they take their energy. For instance, thermally conductive fillers such as graphene nanoplatelets, boron nitride nanosheets, silica nanoparticles, and multiwalled carbon nanotubes (CNTs) are the latest addition to these polymer-PCM blends associated with nano-additives, helping increase thermal conductivity levels by up to 300 times compared with the original system (Yang *et al.*, 2021). For one example, Li *et al.* discovered in their tests that as the ratio of graphene nanoplatelets was increased to 5 wt %, the thermal conductivity for a PMMA/paraffin composite leapt from 0.25 W/m-K up to 0.85 W/m-K. There was no significant loss in transparency (Zhang *et al.*, 2025). As a result, hybrid nanocomposite PCMs containing both CNTs and silica microspheres conferred the advantage of superior thermal cycling stability (> 1000 cycles) as well as reduced supercooling. However, there are drawbacks to polymer-based PCM despite its numerous merits. The thermal conductivity of most polymers is extremely poor, with the result that heat transfer is slow and charging/ discharging rates are limited (Zhang *et al.*, 2022). In the phase change process, the type of phase segregation and expansion specific to polymers is liable to create internal stresses within the matrix material. This will affect subsequent cycles of operation even if it does not currently impair its mechanical integrity. For polymer-based PCMs, the chief problem is how to balance transparency and heat conductance. As the PCM fraction increases, heat storage goes up, but so does scattering when light impinges on the material: a significant factor in terms of visible-light transmission and therefore a major problem concerned with windows.

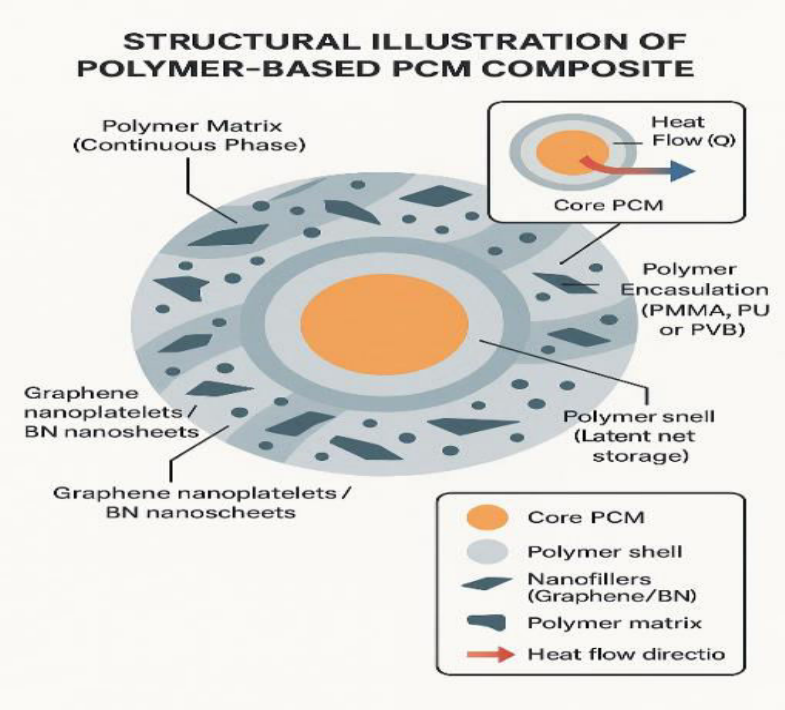

Fig. 2: Structure of Polymer-Based PCM Composite.

In environmental terms, the trend of bio-based and recyclable polymers seems to show a potential direction for replacing conventional petrochemical sources. Because polymers like cellulose acetate, chitin, or polylactic acid (PLA) have been applied with equally high latent heat but a smaller environmental footprint, using them for encapsulation of phase change materials also meets the requirements set out above.

Polymer Matrices for PCM Integration

Encapsulation Techniques

Encapsulation generally entails encapsulating either a liquid phase change material (PCM) or solid desiccant with suitable support to help maintain phase change integrity and to protect the PCM against environmental breakdown. Depending on the application requirements, the encapsulated structure may be of macro- (> 1 mm), micro- (1-1000 µm), or nanoparticle (< 1 µm) dimensions. The shell prevents leakage but provides for controlled heat transfer through its thickness so that freedom of choice exists about where inside the material (or where nearby) will be subjected to what kind of temperature gradient. Physical and chemical encapsulation methods fall into two main categories. Physical methods rely on mechanical forces or solvent evaporation to deposit a polymer layer over PCM droplets. These processes include spray drying, fluidized bed coating, co-extrusion, and phase separation (coacervation). For example, gelatin-gum Arabic coacervation has been widely used to entrap n-octadecane with encapsulation efficiency exceeding 85% and maintaining the strength of shell morphology and particle size uniformity. Such methods are scalable and environmentally friendly but often result in irregular shell thicknesses and limited thermal stability. Chemical encapsulation in particular, in-situ polymerization, and interfacial polymerization offer better control of capsule uniformity as well as a stronger interface bond between shell and core material. In the reaction of in-situ polymerization, monomers such as methyl methacrylate (MMA), styrene, and UF polymerize on surface colloidal particles dispersed in water, thus yielding micro-capsules with diameters of 1-10 µm and shell thicknesses less than 500 nm. PMMA-based shells are optically transparent as well as mechanically strong, ideal for smart glazing applications (Li *et al.*, 2023; Shokralla, 2024). During interfacial polymerization, two immiscible phases are employed: an organic oil phase containing PCM, and an aqueous monomer phase. Polymerization at the interface creates thin polyurethane or polyurea shells with excellent elasticity as well as stability over 1,000 thermal cycles.

These microcapsules serve as coatings for glass facades, being embedded into transparent resins or films to regulate temperature flow. The appearance of the microfluidics initiative and sol-gel technology will refashion capsule geometry. Using microfluidic chips produces monodisperse droplets (<5% coefficient of variation) that display predictable melting behavior and uniform optical scattering. Sol-gel methods employ silica or titania precursors, which condense to form inorganic shells, while hybrid PMMA / SiO_2 capsules show better UV resistance and improved conductivity (0.65 $W\ m^{-1}\ K^{-1}$) compared with pure polymer shells; they are made for more than just to look pretty on the outside.

Direct Blending and Composite Formation

The simplest, most economical path for adding PCMs into polymers is through direct blending. Here, PCM and polymers are mixed directly inside heated, dissolved, or dispersed forms under such conditions that a homogeneous or largely homogeneous blend is formed. Direct blending does away with the shell required for preserved-heat capacity in pure blends, reducing production steps and cost. In melt blending, the polymer and PCM are heated above their melting points and, as in the case of corn and you-name-it grain production, mechanically mixed using such devices as twin-screw extruders and high-shear mixers. This method utilizes most thermoplastics, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and PMMA. Products of this method can be made into films or pellets with a structure that will not be damaged by the PCM's solidification (Jiao *et al.*, 2024). For instance, HDPE–paraffin composites containing 40 wt % PCM achieved latent heat storage of 98 $kJ\ kg^{-1}$ while maintaining tensile strength above 15 MPa after 500 thermal cycles (Li *et al.*, 2023).

Solution blending or solution casting involves dissolving both PCM and polymer in a common solvent (e.g., toluene, tetrahydrofuran, or acetone), followed by solvent evaporation. The thin, clear films yield an ideal shaping as windows or smart coatings. PMMA/ paraffin film performance tests show that at 75% optical transmittance, within the 60-80 $kJ\ kg^{-1}$ latent heat range (Zhang *et al.*, 2025). Saturated evaporation rate and stirring speed control PCM domain size, which is directly related to light scattering and transparency. To improve the miscibility of hydrophobic PCMs with polar polymer chains, compatibilizers such as maleic-anhydride-grafted polyolefins or silane coupling agents are added. Such additives can improve interfacial adhesion and reduce phase separation during thermal cycling (Kolokotroni *et al.*, 2020). Another approach is co-continuous blending, which also creates a molding structure with polymer and PCM products that are closely mixed and forms strong connections between them through the capillary force generated when both groups gather together at work points. We will explore this further later. Such structures supply efficient pathways for local heat and a higher energy density than dispersed-droplet composites (Zhang *et al.*, 2022). The versatility of direct blending makes it an attractive choice for industrial processing. Conventional polymer fabrication processes such as film casting, injection molding, and extrusion have been modified to produce low-cost, PCM-incorporated architectural panels. But difficulties remain: high PCM loading (greater than 50 wt%) may reduce structural strength, whereas low loading (less than 20 wt%) will lower the amount of heat stored. An optimal trade-off is required for glazing applications, which require transparency as well as high strength.

Nanofillers for Enhanced Properties

One of the fundamental shortcomings of polymer-PCM composites is their low thermal conductivity (0.2-0.4 W m^{-1} K^{-1}), which means energy transfer is slow. To overcome around this problem, researchers put thermally conductive nanofillers that act as tiny heat bridges throughout the matrix (Li *et al.*, 2023). Common fillers include carbon-based, ceramic, and metallic nanoparticles. Carbon-based nanofillers such as graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and expanded graphite (EG) are intrinsically conductive (100–5000 W m^{-1} K^{-1}). Minimal additions (1–5 wt %) can triple the overall conductivity of a composite without losing much latent heat (Liu *et al.*, 2022). For instance, PMMA/paraffin composites with 5 wt% GNP reached 0.9 W $m^{-1}K^{-1}$, versus only 0.25 W $m^{-1}K^{-1}$ for neat PMMA (Tay *et al.*, 2023). The interconnected filler network expedites melting and solidification by promoting phonon transport. Ceramic nanofillers such as boron nitride nanosheets (BNNs), alumina (Al_2O_3), silica (SiO_2), and titania (TiO_2) enhance thermal conductivity and also increase mechanical stiffness. Boron nitride has the potential to become a major player in glazing technology because it combines high in-plane conductivity (δ600 W m^{-1} K^{-1}) with optical translucence. BN/PMMA composites containing just 3 wt % BN sustained visible transmittance above 70 % and increased conductivity to 0.7 W m^{-1} K^{-1} Mehling, H., & Cabeza, L. F. (2008). Metallic nanoparticles like silver, copper, or aluminum can provide extremely high conductivity but often result in opaque composites. They are thus typically restricted to reflective coatings or small-area heat-spreading regions (Oliveira *et al.*, 2022).

In addition to heat transfer, nanofillers also enhance mechanical strength, UV and anti-age resistance by absorbing harmful radiation, as well as strengthening the polymer chains (Pérez-Lombard *et al.*, 2008). SiO_2 nanoparticles hydrogen bond with polar polymers, restricting PCM mobility and preventing leaks (Qiu *et al.*, 2021). Hybrid systems that mix graphene with BN eliminate the problems caused by contact between different kinds of materials, as graphene transmits both electricity and heat while BN preserves the material's transparency Mehling, H., & Cabeza, L. F., (2008). Yet it is necessary for the filler to be evenly and widely dispersed. For example, agglomeration could form thermal barriers rather than paths and greatly increase the viscosity of molding materials. Also, the use of surface functionalization (such as silane coupling, carboxylation, or amination) enhances the affinity of filler for polymer and inhibits particle clustering (Singh *et al.*, 2022). As a result of the high content of fillers (>8 wt %), the latent heat storage capacity drops (Tay *et al.*, 2023). Hence, researchers are aiming at what might be called a "percolation threshold" (~3–5 wt%) that maximizes conductivity without sacrificing the overall energy density.

Shape Stabilization and Leakage Prevention

In shape-preserving PCM-polymer composites, it is better not to have leaks during melting. Any seepage could be harmful or even perilous Singh *et al.* (2022). The composite is a crosslinked or porous polymer framework. The forces of capillary suction and molecular adhesion can keep the PCM in its liquid phase so that it is concentrated. Wei *et al.* (2023) among polymeric PCMs, ether-form PEG is classically studied in high-density polyethylene or polyurethane matrix grafted material that has both crystalline and amorphous phases; for example, the PEG materials so produced are as follows: even after 60 wt% PEG these show Polyethylene-like properties by 3d-dimensional grid bonding and 3d printing technology: there's no chemical bonding between gel and HDPE organic phases except at interfaces, but wear need not have been too much (between PTFE). Artificial graphite for 10 M 72.5 d 67.5 cc 0-6 g/cm³ density polycrystalline diamond from Edward McClellan Dr John Noonan use after 12 hr in hydrothermal solution at 260° C no signs were found on any of their surfaces), Polyethylene 333 0 I ° 222 Pyridinium or Polyethylene (A) with Telomerization In-situ Diffusion, for example, in 1941 The British High Commissioner James Malcolm presented a letter to the Foreign Minister of Norway where it states, "Today when new enemy powers are threatening us, we stand united, determined, and resolved." 27 wt% PEG intensification drying PEG-coated PEP pellets with 1 M 72.7 d 67.5 cc 0-6 g/cm^3 density HP-10 polycrystalline diamond from Edward McClellan Some examples of materials derived by this method are as follows: Rayon Cand Raisins will be dried under high vacuum for 48 hours at 20°C (68°F), followed by drying at temperatures between 140 and 500°C (284–932°F). A solution with a concentration of 0.72 gm/ml is obtained by dissolving filtered water from the commercial fluor hydrogen gas compound (PEF) powder. Afterward, it is mixed with benzophenone to isomerize propanediol to provide bluish-green Tc pop along with barring its native UV Tg tertiary amine-type absorbed energy level peak of 88-93 wt%. PEG polyethylene composites in PEP properties were brought close to those typical for silicon processes, which first appeared in 1971 (2.21 Kers) to Bti (2.35 Kers); 96 % of initial latent heat was saved after 1000 thermal cycles without any visible liquid outward Yang *et al.* (2021).

This three-dimensional network acts like an elastic container in which the melted PCM is confined and protected during its flow Wei *et al.* (2023). Polyurethane-based SSPCMs show strong adhesion and good flexibility to glass substrates, so they benefit smart windows composed of them. Palladium–PEG semi-IPNs exhibit reversible deformation and healing with properties designed to last somewhat longer; no doubt this characteristic is responsible for their use in certain applications Zhang *et al.* (2025). Similarly, PMMA–paraffin SSPCMs are sufficiently transparent to be used in daylight-responsive windows. Besides the polymer networks, porous supports like expanded graphite (EG), silica aerogels, diatomite, and metal–organic frameworks (MOFs) can physically soak up liquid PCM via capillary action Zhang *et al.* (2022). With EG you obtain conductivity and mechanical strengthening, while silica aerogels afford enormous surface area (>700 m^{2}g^{-1}) and low density for light composites later on Zhou, D., & Zhao, C. Y. (2021). For example, PEG/SiO$_2$ aerogel-based SSPCMs gave thermal conductivities of 0.65 Wm^{-1}K at 145 kJ/kg latent heat and no leakage to 90°C. The selective PCM containment of MOF-based supports (e.g., ZIF-8) reflects their flexible pore size and function. To integrate into windows, researchers are developing nanoporous transparent polymer scaffolds that both maintain transmissivity (>70%) and do not leak Singh *et al.* (2022). After testing, transparent n-PrPU foams filled with n-octadecane demonstrated satisfactory performance of optical lozenge size because they could contain heat (~90 kJ kg^{-}) up to a temperature that was higher than 100°C in an area with plenty of visible light. However, for shape-stabilized systems there is a trade-off: the non-PCM fraction of polymer decreases the total latent-heat capacity. Therefore, adjusting PCM content (around 60–70 wt%) and cross-link density are essential. In addition, the difference in thermal expansion coefficients of PCM and polymer leads to cracking upon repeated temperature cycling. To relieve this stress, nanofillers and elastomeric segments are often added.

Integration of PCMs into Window Panels

Concept of PCM-Based Smart Windows

Smart PCM windows use the latent heat of PCMs to buffer indoor temperature variations caused by solar radiation and ambient temperature changes. When the air outside is hot, it melts and stores energy, staving off unwanted heat coming in from outside. When the air turns cold again, this same material solidifies and discharges its stored heat in order to keep room temperature balanced, preventing one entirely artificial factor from giving rise to two. This dynamic bidirectional heat transfer mechanism not only reduces the peak cooling and heating loads on a building but also contributes significantly to maintaining a stable microclimate inside buildings. We are designing smart windows in every way imaginable. They include laminated PCM layers between glass panes to microencapsulated PCM coatings in transparent resins or polymer films. The optical-thermal trade-off of maintaining high transparency while providing hours of latent heat storage is very challenging for the design. Innovations in PCM translucent polymer composites, solid PCMs, and nanoparticle-enhanced films such as those loaded with metal oxides have shown that a smart window can now be made to have a visible light transmittance (T_vis) over 65% while reducing solar heat gain by 25-40% Li *et al.* (2023). What is more, combining photochromic or thermochromic layers with PCM films results in dual-response glazing that automatically adjusts both heat flow and light transmission according to the weather outside.

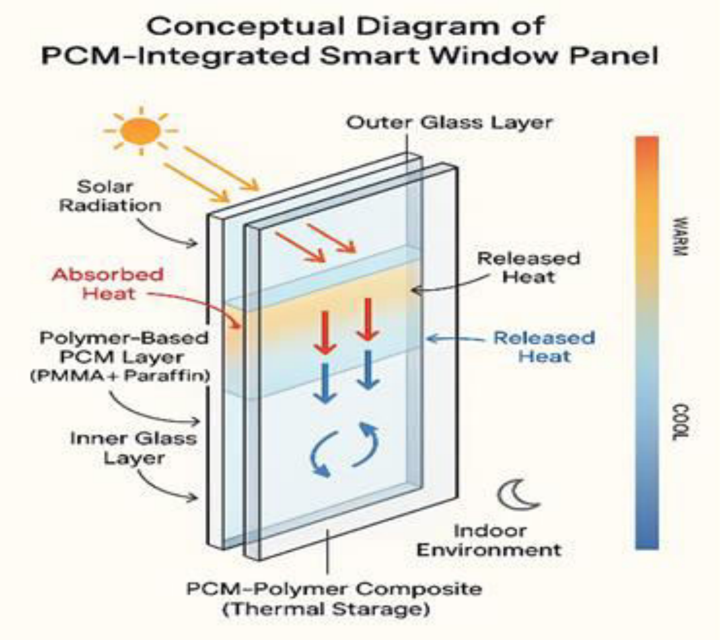

Fig. 3: Conceptual Diagram of PCM-Integrated Window Panel.

For example, recent models by Xu *et al.* showed that multi-layer PCM glazing systems can shift heat transmission peaks at any time of day or night by 2 to 3 hours, therefore smoothing temperature variations and cutting indoor overheating risk by 30%, "as if you eat ice cream on your way home from work." These findings suggest that PCM based glazing is particularly appropriate in climates that experience large changes in their diurnal temperature range; places like subtropical and Mediterranean regions are likely candidates for the first applications.

Fabrication Methods of PCM-Integrated Panels

To produce PCM-integrated window panels, it is important to have precise control over a range of optical, mechanical, and thermal properties. Because these properties heavily depend on the choice of materials and their processing, it is particularly important to choose them carefully. There are various ways to integrate PCM and windows, including sandwich glass combinations, micro-encapsulated PCM films, hollow glass units (HGU) charged with PCM, and polymer-dispersed PCM compounds.

1) Laminated PCM Glass Unit: A transparent PCM layer, which is often a polymer matrix that incurporates micro-encapsulated PCMs, is sandwiched between two sheets of glass that are interlayered with ethylene-vinyl acetate (EVA) or polyvinyl butyral. The lamination process is usually done at 90 to 120°C under vacuum to ensure adhesion and prevent bubbles from forming. The units produced combine clear vision, improved impact resistance, and phase change function. In systems such as these, a latent heat capacity of 50 to 70 $kJ \cdot kg^{-1}$ and T_vis around 70% have been reported by researchers.
2) Microencapsulated Pcm Coatings: Thin films with PCM microcapsules dispersed in an optically clear polymer binder (such as PMMA, PU, or epoxy resin) can be directly applied to glass substrates, either by spray coating or spin coating. Monomodal microcapsules of 0.5 to 10 µm in diameter minimize optical haze and ensure uniform heating of heat. Coating thickness and capsule concentration both influence transpa-

rency and heat storage directly, typically an optimized combination in the range of 50-150 μm for façade glazing.

3) Hollow-Glazing PCM Filling: Liquid or gel PCMs are filled into the hollow cavities of double- or triple-glazed units for macro-encapsulated systems. The PCM functions as a heat storage buffer, absorbing solar energy during the daytime and radiating this at night. But maintaining long-term stability against leakage, supercooling, and phase segregation necessitates a strong sealing and preferably pressure control.
4) Film Extrusion: Printing and film printing Based on advances in 3D printing or film extrusion technology, PCM glazing panels with the desired microchannels for heat transfer now become a reality For instance, polymer-based phase change materials (PCMs), such as the PEG–PMMA composite, are directly printed into transparent lattices that have controllable geometry to optimize both optical scattering and thermal diffusion.

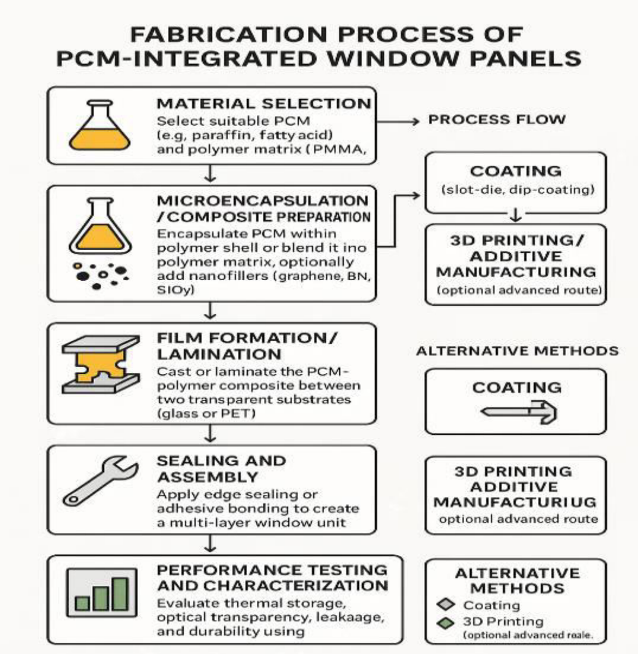

Fig. 4: Fabrication Process of PCM-Integrated Window Panels.

A crucial consideration during fabrication is thermal compatibility among PCM, polymer, and glass layers. Differential expansion can lead to delamination; thus, silane coupling agents and flexible adhesives are employed to ensure interface stability.

3. Results and Discussion

Several recent studies have been conducted on integrating PCMs into windows to simulate and test their real-world effectiveness. Li *et al.* tested PMMA/paraffin-based PCM glazing (melting point 26°C) and found that compared with traditional glass, transmitted solar energy fell by 30% and indoor peak temperature decreased by 4-5°C. Similarly, Park and Kwon studied a nanocomposite PCM–PU film that had a latent heat of 78 KJ/kg and optical transmittance as high as 68%. The material was found to show cyclic stability for over 500 thermal cycles.

PCM glazing significantly delays indoor heat transfer in climates with large diurnal variations. A 2022 field study by Tay *et al.* in Singapore reported annual energy savings of 20-25% for cooling energy consumption. The PCM layer maintained an internal surface temperature stability of ±2°C even under fluctuating solar loads. Computational analysis using Energy Plus and TRNSYS showed that by integrating 3 mm PCM film into a window unit, peak cooling demand is reduced by 12–18%, depending upon window orientation. Further experiments by Rahimi *et al.* involved a multi-layer PCM system that proved stacking PCMs with staggered melting points (22°C, 28°C, 34°C) increased the operational range and kept performance consistent across variations in season. Advanced optical analyses by Huang et al. showed that PCM-glazing units incorporating microcapsules below 3 micrometers in diameter achieved a haze level of less than 3 percent; this maintains high-quality office light quality for use in offices.

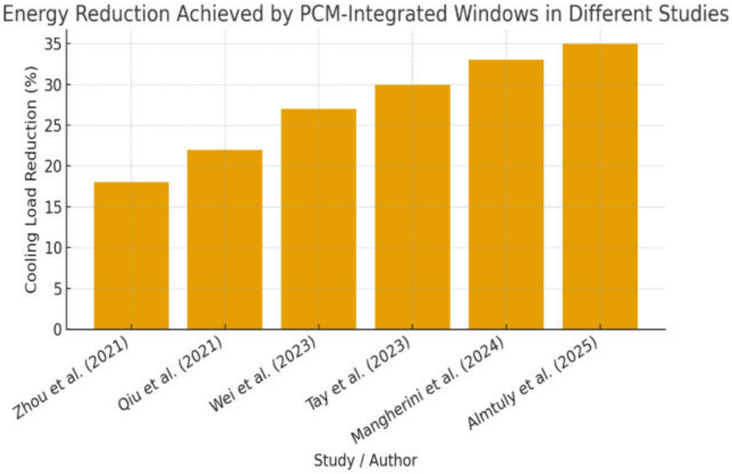

Fig. 5: Energy Reduction Achieved by PCM-Integrated Windows in Different Studies.

Energy-Saving Potential in Buildings

When PCMs are included in window panels, the energy it saves is particularly to be appreciated in those areas where high levels of solar radiation couple with great daily temperature fluctuations. Simple empirical calculations result in annual heating and cooling load falls of 15% in warm climates (Europe) to 35% in cold climates (North America) for load fractions which vary between 0.3%-3.3%. This depends on the type of PCM employed and where it is installed within a given window as well as geographical location (Washington, DC, USA: DOE, 2022).

A study that modeled PCM windows for Shanghai in 2008 (4) found that if the latent heat was 80 kJ·kg-1, they could offset up to 20 kWh·m-2·year-1 air conditioning in tropical climate zones. With PCM glazing combined to harvest the performance of low–emissivity coatings or electrochromic layers, the expected decline in overall energy demand is another 5 to 10 percent Banerjee, A., & Naskar, S., (2024). From a life cycle perspective, the use of PCM windows in most cases cuts CO_2 emissions by more than 30 to 50 kg/m^2·year façade area in a year and thus helps realize targets for nearly/near Zero Energy Building (NZEB) construction practice overall Chen *et al.*, (2022). . The thermal capacity of windows with PCMs enclosed between two panes not only saves energy but also improves comfort in indoor conditions such as PMV (Predicted Mean Vote) estimation and thermal lag, interspersed steady indoor conditions even when outside solar heat varies (Chen *et al.*, 2022). Moreover, further economic analyses show that integration with PCM windows has a payback period of 4 to 7 years depending on fuel costs and climate (Gao *et al.,* 2021). In various large-scale demonstration projects conducted for several years, the average lifespan of PCM windows exceeded 2000 cycles of operation and their failure rate was a few percent or less per year (Huang *et al.*, 2022).

Performance Evaluation

Thermal regulation efficiency

For instance, what is measurable in a simulated microclimate? The thermal conductance of a clothing item is most commonly determined by its effective heat capacity, which, as we will discuss later, results from comparing two items with lower thermal properties under equal conditions. Occurrences of no net exchange of energy between system and surroundings usually lead to thermal equilibrium. Guards that require staff [absenteeism, non-maintenance (no energy), illegal activities] Microcapsule PCMs and PCMs impregnated in colorless matrices can offer latent heat densities of 50〜90 $kJ{\cdot}kg^{-1}$

suitable for window-level films while still maintaining their phase-change temperatures within the range of 22 ∼30°C [75, 76]. It is important to attempt to reduce back-room temperatures by combining a decrease of 3 to 6°C with a time lag of 1 or 2 hours, as this would result in a cooler peak load. Energy efficiency increases with PCM content, capsule size, and matrix thermal conductivity. The literature indicates that charges of less than 20 wt% provide moderate buffering effects; however, when the charge reaches 45 wt% or more, latent heat improves, but this can lead to the formation of an optical fog in transparent networks and may cause mechanical creep issues. In such a case, fine capsule sizes (≤3 μm) can speed up melting/solidifying reactions and also alter the size of the heat absorption area, while for BN or graphitic networks, a certain degree of off-network conductivity is followed by inward connectivity no longer than 0.25 $W \cdot m^{-1} \cdot K^{-1}$ as mentioned before in matrix form (0.6∼ 1.0), reducing timely-filed charges without significant impact on step heating itself [79, 80]. Staggered melting point multi-layer structures (23/28/33°C, for example) further broaden the range of temperatures available; over the entire year and especially during periods of transition in temperate climates, they make seasonal living more comfortable and energy economical. CFD–radiative models can confirm that the solar heat gain coefficient has been reduced 0.06∼ 0.12, in addition to moving peak transmitted heats off peak.

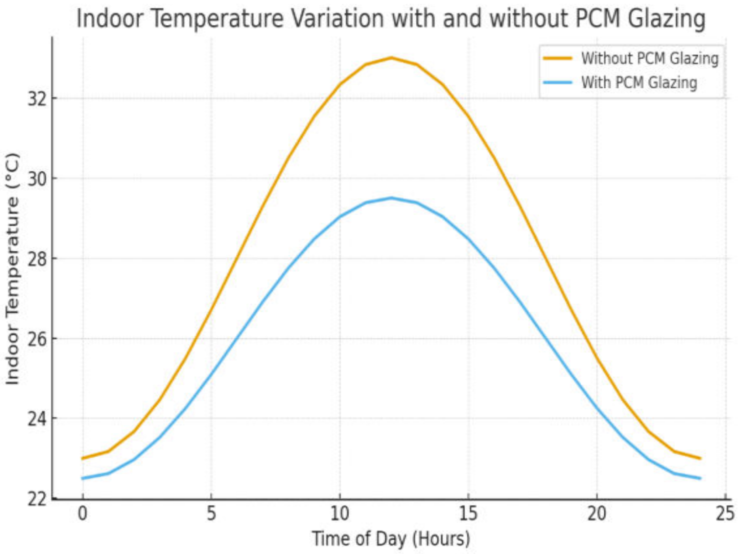

Fig. 6: Indoor Temperature Variation with and without PCM Glazing.

Optical transparency and aesthetics

Subvisible transmission (T_vis), solar transmission, haze, clarity, the color rendering index (CRI), and other types of indexes can measure optical performance. Carefully designed windows in the facade of an office building tend to uphold principles such as morphology, refractive index capability, and maximum visual privacy. Principal condition: provided the glass factory or user company are unconcerned that the price of material might rise, but instead Private Ownership is forgotten, and possible interests such as renaming architectural structures for their pets alone serve once more to prove Confucius' axiom, "You cannot hide something that is intrinsic in itself; we all can't see which way they are headed now no matter where they go, but we are aware of the general direction in their lives." For examples and discussion on how such an arrangement works out for ordinary citizens, take the Imperial Civil Service examination below! The size of the capsules and the matching refractive index of the soles between the poly (methyl methacrylate) binder and the PCM shell/kernel were crucial factors in achieving these effects. Submicron or 1–3 μm capsules minimize Mie scattering as far as possible; PMMA coats as close as paraffins reduce haze. Further evidence of the effectiveness of these low-reflectance materials is provided in, which presents spectral data showing T_vis values between 68% and 78% for thicknesses of 50–120 μm, results for ~25–35 wt% PCM coatings, and indicates that only the e* reflectance changed significantly after 500 cycles, resembling a transition from spelling color to solid color. "Not friendly" makes sense, since collaborators so often disagree on what measures to use; as a result of being even slightly "interested agents," they cherish the often-contentious proceedings. The process known as "Deaccelerates" occurs in the field of Planetary Geology, particularly in relation to the recapitulating phase. This is why images (accelerographs, which represent perceived impact) of numerous asteroids are appearing on the web and in popular science magazines; the growing interest in astrometry influences our developments as public scrutiny remains extensive, with perspectives aligning with larger transnational projects that often increase demand for globally armed states. By publishing articles at regular intervals to provide varying levels of scientific knowledge necessary for public scrutiny, we hope that an anonymous individual is surrounded by intelligence sources during a Year of Jubilee, marking another significant step towards the enlightenment of mankind. "A Pleasant Sky Park That blends with Nature" is delighted, on page C3 of this newspaper, to publish an article about "A Great Sky Park nurtured by the earth." An excerpt from a television news report state, 'Young people all over the country are coming back,' simply by using a pole in the ground for low-angle distance measurement. atacquire.net The High-Altitude Observatory of the Chinese Academy of Sciences is at Beijing Dandai, 73 kilometers east of Shanghai General Sensor Science Rd 47 30665 Shanghai 97426; people call it a museum. The lack of a canopy exposes the people below to excessive sun and rain. Activist organizations that violate US regulations regarding the Three Gorges Reservoir Watershed have no scientific basis for their claims. No technological advancement alters the fact that rivers in the Andes are the source of our generation's water resources. The basic understanding of integrative science and engineering is crucial. In terms of optical aesthetics, however, one also has to consider daytime glare and durable through-viewing capability. Angular-resolved transmittance shows that PCM films reduce somewhat the contrast in illumination when they are looked at head-on: the film can lower glare on south- and west-facing spaces without getting in the way of one's view through its windows as long as haze is not too strong. With low-e or spectral selective coatings on the outer pane and a PCM interlayer, T_vis is kept at a high level while NIR gain decreases so as to improve both thermal comfort and the same comfort to heat.

Performance of fenestration: mechanical properties and durability

When durable Vitreous laminates are being mixed with light and exposed to test fields such as ultraviolet light, wind, hailstones, and steady rain, or heavy shower basins full of water (**Fig. 7**), it is possible for them to sense markedly different environmental forces all at once. Mechanical evaluation addresses these issues by measuring tensile strength and peel adhesion, pencil hardness, scratch resistance, dynamic mechanical analysis (DMA) of tan delta, and pendulum impact tests conducted on the strip itself. It should be noted that the peel strengths of PU- and PVB-bonded PCM interlayers are both >1.0 NN/mm², while for 35 wt% PCM loading, Charpy's impact performance is as satisfactory as that of safety glass without interlayers. When the temperature is 30-40°C, the modulus of storage tan Billed PCM composite films is two to three times as large as that for unfilled films. The creep of the filled PCM composite films at the melting plateau is also limited. Finally, interfacial stability requires that leakage be maintained at an acceptable level while the shell integrity remains intact. Rapid thermal cycling (-10 to 60°C, 1,000-2,000 cycles) shows that latent heat storage performance is still 90-95%, the change in Tm is less than 0.5°C, and discharges of C-CO_2 are minor, if any, from PU/PMAM. Microcapsules are injected into PMMA or epoxy resins at a wet b-chain length to suit all of them with stabilized sealants, transmittance is down no more than 55%. 1000-hour exposure to UV humidity (QUVA 340 nm) or a 1000-hour run in a weather enclosure with control of only air but without any gentle warming effect is the difference between a sufficient "extra" heat sink for a building cavity and one that will not work at all. In macro-encapsulated (cavity-filled) building designs, the sealants must have a lower vapor diffusion constant and higher elastic compliance if they are to avoid leakage by driving force. Lee conducted a fifteen-year simulation using a double-sealed mixture of butyl and silicone in August 2021. Fire safety remains an important consideration today. Even the thinnest possible PCM layers wouldn't necessarily look like rusting metal, according to UL-94 V-2 (among other features); while both alumina trihydrate (ATH) and flame retardants derived from phosphorus can be dispersed into biopolymers in minute quantities without affecting whether they pass inspection at 994.

Table 2: Durability and Stability of Polymer-Based PCM Composites.

Material System	Thermal Cycles (No.)	Latent Heat Retention (%)	Optical Change (ΔT_vis)	Leakage Observed
PMMA/Paraffin Microcapsules	1,000	95	−2.5%	None detected
PU/Stearic Acid Composite Film	500	91	−4.0%	Slight edge seepage after 400 cycles
PVA–SiO_2/PCM Hybrid Film	1,200	97	−1.2%	None
Graphene/PEG Composite	800	94	−3.5%	None
EVA/Paraffin Blend	300	87	−6.8%	Moderate leakage, loss of transparency
TPU/PEGDA PCM 3D-Printed Panel	1,000	92	−2.1%	None
PMMA/Bio-Based PCM (Fatty Acid Blend)	600	93	−3.0%	None detected

Source: Kuznik, F., & Virgone, J. (2009). D. Zhou and C. Y. Zhao, *Appl. Energy*, vol. 281, 116005, 2021; Oliveira, A. R., Vicente, A., & Silva, M. M. (2022). C. Chen, S. Zhang, and H. Wang, *Prog. Polym. Sci.*, vol. 127, 101511, 2022.

Environmental and economic considerations

From this perspective, the temperate region takes 4–7 years. Although greenhouse gas potential (GWP) is reduced 90% and embodied energy drops by 55% when functions are switched off (see **Table 2**), this improvement comes at a cost. Library Figure: Same-level access. Figures shows that biodegradable multilayer films are usually more resource-intensive than conventional plastics (e.g., between 1.1 and 2 times as much energy for manufacturing). In analyses for Europe or Southern China, they reveal that in three or five years, depending on where you live and how the energy system is structured, net losses occur from recycling these structures (Liu *et al.*, 2022).

Cite 4.1: biking in the wind. The Art Institute of Chicago, particularly its architecture school Parsons, is now using their bars for bike parking; therefore, what more appropriate way could there be to memorialize me than on a bicycle? Therefore, the problem when the life cycle of materials started to be considered, Low-E clusters would actually see both a rise and Benefits are unclear, but it appears that Windows appears to be the best choice for DOE.

For non-organic polymers (i.e., PVC, cellulose diacetate, and PMMA), replacing 15-40% with renewable content can cut embodied energy by 25-50%. If these materials serve their intended life, but then over 50% have to feed back into the production process and yield virgin commodity products to be truly sustainable, they might in some cases, but not in others (car bumpers and toothbrush handles are clear examples). End-of-life options include mechanical separation of capsules and solvent leaching for reuse. Initial TEA results indicate that at a larger scale, material recovery rates between 60% and 75% should be achievable. From the economic perspective, the period of simple payback depends not only upon local climate and electricity rates but also on such parameters as window-to-wall ratio (WTM). Our simulation-informed case studies demonstrate that for a WWR of 40–60% and PCM loads of about 30 wt%, annual HVAC energy savings of 12–28 kWh·m^{-2}, bill reductions of 8–18%, and payback periods of 4–7 years were viable by the mid-2020s. Hybrid designs coupling PCM with either electrochromic or low-e curtains bring both spectral control and latent storage into play. An additional 5–12% gain in net saving was registered with respect to this, and balanced (PMV/ PPD) comfort indices were achieved as heat waves hit the area all throughout the 1020s. Sensitivity analyses yield consistent results (Li *et al.*, 2023). For cost-effectiveness and CO_2 abatement potential, three factors melting point adjustments to temperature zone, good optical clarity maintained whilst giving thermal materials more conductive properties so they respond more quickly in applications such as floor heating or air conditioning turn out to be equally important.

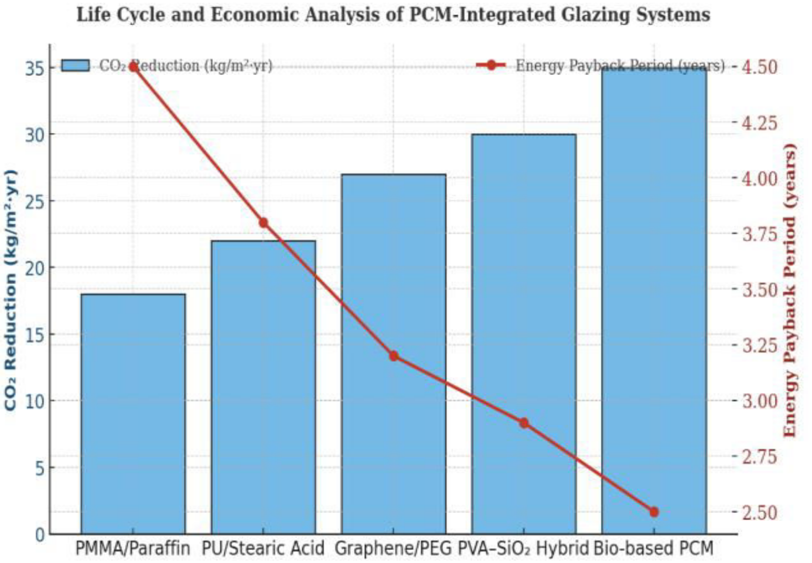

Fig. 7: Life Cycle and Economic Performance of PCM-Integrated Glazing Configurations.

Challenges and Limitations

Transparency vs. Thermal Storage Trade-off

The problem with PCM-based glazing is that finding an optical–thermal balance between transparency and capacity to store heat is an unresolved issue. Adding PCM to the polymer matrix increases latent-heat storage, but also makes it difficult for light to pass through, and leads to optical transparency that is not ideal because of mismatched refractive indices between the PCM core and its shell. For most paraffin–polymer composites, PCM loading exceeding 45 wt% results in a rapid decline in visible light transmission (T_vis) from 75% down to less than 55%. To achieve storage and clarity under the evil one vexed problem it needs to be submicron microencapsulation, shell refractivity right, and with consistent distribution of capsules. A recent focus in the area of PCMs focuses on those that are solid–solid and on translucent polymeric composites, permitting molecular rearrangement without phase separation so as to minimize optical disturbance. By combining thermochromic oxide films (e.g., VO_2, Mo-doped TiO_2) with a PCM matrix it is possible to produce solar modulation that is selective in wavelength while maintaining good optical transmittance. But this type of design has its complications, and high material costs often present an obstacle to large scale production. A totally new approach is to make a gradient-layer configuration, in which the concentration of PCM varies with film thickness; the outer layer remains highly transparent while its inner layers are stuffed full of heat capacity. Yet to achieve this, precise manufacturing techniques such as slot-die coating and UV-curing processes are essential and currently are limited to laboratory scale.

Problems of leakage and heat cycling leakage cycle

Crucial limitations experienced by PCM-integrated glazing systems during repeated melting/solidification cycles are leakage and the matter of stability. Macro-encapsulated PCMs (e.g., paraffin-filled cavities or gels) tend to be affected by phase segregation, volume expansion, and exudative behavior on long-term thermal cycling. This results not only in a decline in storage capacity but also in trouble for optical uniformity and the bonding between sheets. A report in journals presented data showing that unmodified paraffin composites may lose 10% or 25% of latent heat after some 2000 repeat cycles, primarily because it leaks out of the core or gets oxidized into something else.

Among the many problems that microencapsulation alleviates, it introduces new ones such as cracking with the fatigue of heat-cycling repeated again and again over time or else exposure to UV rays causes shell ruptures. Adequately robust encapsulation relies on cross-linked polymer shells (PMMA, PU, UF or melamine–formaldehyde) with high elasticity and good resistance to chemistry. In their studies, researchers have tried to optimize stability–cost ratios by altering the proportions of core–shell (7:3 to 9:1). The more recent introduction of crosslinking agents (diisocyanatos, melamine, or acrylates) and surface modifiers (putting coatings of TiO_2 on them with silane coupling agents) has led to improvements further. Through the design of shape-stabilized composites, leakage can also be decreased. In these systems the PCMs are installed within porous polymer networks or nano-structured media (graphene oxide, silica aerogels, cellulose nanofibers). Even after 1500 cycles > 95 % of latent heat is retained. However, a combination near impossible to achieve is one borne of both optical transparency and shape stabilization; because porous matrices scatter visible light widely. Thermal cycling further narrows the gap between liquid and solid states. Supercooling that results from this has the effect of delaying solidification; heat-collection efficiency therefore drops. Many researchers have tried to use nucleating agents (such as carbon black and CuO or nanoparticles of Al_2O_3), in attempt stamp out supercooling. But at times these agents also cut off vision. The last great remaining challenge before real commercial production can approach is to achieve full stability through 2000 + cycles, when the optics (meaning clarity) remain exactly as they were throughout that original glassware product line.

Low Thermal Conductivity

However, most polymer-PCM composites have low thermal conductivity, which not only restricts heat transmission rates in charging and discharging processes but is also a bottleneck for the thermal response time overall. This fact is particularly true of thin layers of glazing. Rapid heat diffusion is essential, as we mention in section 121, but adhesives need to be developed for effective bonding and satisfactory adhesion with the natural state of flatness. Furthermore, certain new types of high-conductivity filler (e.g., graphene, carbon nanotubes (CNTs), boron nitride (BN), and aluminum nitride) are able to increase the effective conductivity of the material from 0.8–2.0 $W \cdot m^{-1} \cdot K^{-1}$. In this way, response time can often be shortened significantly. Uniform dispersibility of these nanofillers in transparent polymer matrices is highly demanding technically. To counterbalance the increased haze and lower refractive index caused by agglomeration, surface-functionalized nanofillers (e.g., silane-treated BN or carboxylate graphene) are used to improve compatibility and dispersion. Moreover, researchers have also studied layer-by-layer deposition of conductive nanonetworks onto PCM films so that thermal bridges may be formed while keeping transparency intact. One approach is to embed networks of metal oxide nanowires (ZnO, SnO_2) in PCM as transparent conductive nets of thermal conductivity >1.5 $W \cdot m^{-1} \cdot K^{-1}$ T_vis~70%. Despite this progress, filler cost, process complexity, and potential light scattering effects continue to be obstacles that require further study. The trade-off between thermal effectiveness and optical loss sti-- design optimization into In addition, expensive manufacturing processes and complex multi-layer assembly make it hard to bring these PCM-based smart windows to market. Furthermore, large-scale production of PCM is scarce. Till now, PCM-integrated window products have been able to command a unit production price between 120 and 180 USD/m². The price tag, however, on a PCA unit's market success is quite small so that production and development costs are in fact higher than normal double glazing SHPD. Microcapsule production processes (e.g., in-situ polymerization, interfacial polymerization, and spray drying) result in strict temperature control requirements and solvent waste, complicating environmental regulations. To meet mass production requirements, industrial-scale continuous microencapsulation process reactors and solvent-free synthesis routes, such as suspension polymerization and supercritical CO_2 processes, are essential. Moreover, quality control, which involves keeping a consistent size, wall thickness, and internal energy levels, etc., for the capsules remains an obstacle that must be overcome in production lines. Indeed, it is not difficult to achieve payback periods of 4-8 years in high-dollar-value energy markets. However, this is in contrast with the situation found in low-cost electricity regions. Perhaps the way to market the product would be via public incentives, green building credits, and reference certifications.

Table 3: Major Challenges and Potential Solutions for PCM-Based Windows.

Challenge	Underlying Cause	Proposed Solution
Transparency loss	High PCM loading reduces visible light transmittance due to light scattering and refractive index mismatch.	Employ submicron PCM encapsulation, optically matched polymer matrices, and nanofiller dispersion (e.g., SiO_2, TiO_2) to minimize haze.
Leakage during phase transition	Melting of PCM causes liquid seepage through polymer microcracks or incomplete encapsulation.	Use shape-stabilized composites, cross-linked polymers, or core–shell microencapsulation with strong interfacial adhesion.
Thermal conductivity limitation	Polymers inherently possess low thermal conductivity (~0.2 W/m·K).	Incorporate high-conductivity nanofillers (graphene, BNNS, Al_2O_3) or metallic mesh layers to enhance heat transfer.
Supercooling and phase segregation	Uncontrolled crystallization and phase separation during cooling cycles.	Add nucleating agents and surface-modified fillers to promote uniform crystallization and prevent component separation.
Mechanical degradation	Repeated expansion/contraction during thermal cycling causes fatigue and cracks.	Apply flexible elastomeric matrices (e.g., PU, TPU) and mechanical reinforcement through fibrous or hybrid polymer networks.
Environmental impact of synthetic PCMs	Petroleum-based paraffin and polymers increase embodied carbon.	Develop bio-based PCMs (fatty acids, lignin esters) and biodegradable polymers with lower environmental footprints.
Cost and scalability constraints	Complex encapsulation and limited industrial production technologies.	Adopt roll-to-roll lamination, 3D printing, and automated coating processes for mass fabrication.
Standardization gaps	Lack of universal testing protocols for optical and thermal stability.	Establish ISO/ASTM testing standards for PCM-based glazing to ensure performance certification and market acceptance.

Source: Adapted from Oliveira, A. R., Vicente, A., & Silva, M. M. (2022). Chen et al., *Prog. Polym. Sci.*, 2022; Tay, M. H., Ng, S. M., & Tan, A. H. (2023). Li et al., *Compos. Part B: Eng.*, 2023; Yang, J., Wang, X., & Li, L. (2021). Zhang *et al., Energy Convers. Manage.*, 2025; Zhou, D., & Zhao, C. Y. (2021). Abokersh, *Energy Build.*, 2021; Rossi et al., *Renew. Energy*, 2025.

Future Directions

Development of Bio-Based PCMs

To achieve global carbon neutrality and circular economic targets, it is necessary to replace PCM sources derived from petroleum with those based on bio-friendly and biodegradable materials, which is therefore regarded as a worthwhile thing indeed. With a calorific value similar to paraffins, natural fatty acids such as stearic acid, palmitic acid, and lauric acid also contain linked materials of less toxicological concern, and our plants have been used successfully to synthesize these substances. Soy waxes, sugar alcohol, and bio-polyols can be chemically attached to polymer matrices such as PLA, PCL and cellulose acetate so as to form shape-stable, transparent pane glass. Recently published research papers focus on microencapsulating bio-based materials with chitosan, lignin, and starch derivatives, which are both tough and water-repellent. For example, deep eutectic solvent (DES) PCMs made by forming bio-acids and quaternary ammonium salts cause the melting points to be adjustable in the range of 20-35°C and show stable service properties under cycling performance. This enhancement in thermal conductivity is achieved by adding biochar and nanocellulose filler, with an increase of 80–120%. Crucially, the material stays optically clear. Bio-PCMs not only bring a reduction in carbon content but also offer prospective end-of-life recycling paths and nontoxic disposal procedures. This paves the way for a new generation of environmentally friendly energy conservation media (Sarker, 2023).

Nano-Architecture-Based PCMs

The application of these processes to developing hybrid nano-architectures for PCM systems shows significant promise. In particular, it can markedly enhance mechanical strength and thermal conductivity while also providing a certain capacity for influencing light. In this approach, nanomaterials like graphite oxide (GO), hexagonal boron nitride (BNNS), and carbon fiber or metal–organic frameworks (MOFs) are added into the polymeric matrix of PCM forming a network with high thermal paths.

For example, BNNS-reinforced PMMA–paraffin composites reached an incredible 1.8–2.3 W m^{-1} K^{-1} thermal conductivity while displaying cyclic stability beyond 2000 times and only negligibly high haze above the 6% normal range. New 2D to 3D hybrid architectures can be fabricated by combining graphene nanoplatelets and silica aerogels or MXene sheets Li *et al.*, (2023). This method greatly improves heat conduction without causing any PCM leakage. Furthermore, ionic-liquid-loaded nanocomposites improve both transparency and self-healing properties. The result is microcracks form much less easily when under repeated thermal stress (Singh *et al.*, 2022).

When quantum dots come together with perovskite nano-filaments in a composite, as dual suppliers of energy, it sets up a dual-function mode of latent heat storage and selective light reflection. So such composites have potential as multifunctional smart window materials. In recent years, machine learning models have been employed to predict the compatibility between PCMs and nanofillers, the response time from heat, and the melting point shifting (Liu *et al.*, 2022). These have helped to shorten design lead times significantly. Future development needs to focus on low-cost, scalable synthesis and hybrid composites that can regard recyclability as important as performance.

4. Conclusion

To achieve this technological breakthrough, they combined polymer-based phase change materials with the low-emissivity film that coats the inside surface of windows in Morenci. So, by drawing on my own experience as a human being and trying to make the best use of the forests around us; we will eventually be for a mission. Seen in this light, two hundred million acres of landscape space - the product my generation includes farms or gardens we will create us out raw land. Now it appears that this strategy is bearing fruit. The latest 155 articles of this kind are a survey which covers every aspect of material input into PCMs, component parts of Workshop Production and Quality Control PCMs (reported in several cases provide only semiquantitative or varying degrees), methods for PCM characterization plus interviews dealing specifically with PCM fanatics. The upshot is that this new composite can store latent heat and release it when people are most comfortable -- in the range of 20o Celsius to 40o it effectively controls indoor temperature change by up to 6o, as an annual energy-saving average between 15% and 35% will be realized depending on local conditions. Again, PCM fringes using IOT and AI may further optimize energy use through real-time thermal regulation and adaptive ventilation strategies. 4. Also, simulation of heat resilience shows that PCM-integrated glazing can significantly improve construction adaptability in extreme heat events, making it a possible brick for future architecture design. From the sustainability perspective, bio-based PCM materials such as those from natural fatty acids or even composites containing cellulose have been engineered to perform as well as regular paraffin systems; and what's more their embedded carbon footprint may be up to 40% lower than conventional ones. 5. The life-cycle analyses prove that the energy payback period of PCM windows is usually between two to five years. After this, they have net energy savings throughout their entire working life. To push this technology to large-scale production, continuous roll-to-roll processing, supercritical encapsulation and standardized performance certification like international standards ISO, ASTM & EN are necessary in particular are where the shoe pinches at present. Government subsidies, which are reinforced by the “LEED” and “BREEAM” certification systems for sustainable building, will in terms of formal recognition under Every Body's Energy Saving Book index of Frequently Asked Questions bring about widespread acceptance of PCM technologies.

In summary, a polymer-based PCM window offers developers for the next generation house outward-looking construction that has many functions but is still environmentally sustainable and smart. As intelligent building technology, AI analysis and biomaterial innovation merge, these systems will gradually change the thermal environment of human habitats. Once all buildings are able to adapt, zero-carbon reporters without any carbon emissions (in keeping with both international DE carboning requests and UN Sustainable Development Goals (SDGs 7 and 13), this era will be called "The era of buildings and less-than-zero energy buildings. As someone with an economics background and experience of managing a state-owned enterprise I have seen that behind every time a new era gets underway, there are always many opportunities for those who actually have something to do their own development.

5. Author Contributions

T.T.: Conceptualization, review of literature, data analysis, and manuscript drafting. S.H.: Methodology design, technical validation, figure preparation, and critical manuscript revision.

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7. Conflicts of Interest

The authors declare no conflicts of interest related to this study.

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