Open Access

Journal of Energy and Power Technology

Review

Enhancement Techniques for the Reduction of Heating and Cooling Loads in Buildings: A Review

Kamal A. R. Ismail [1,*], Fatima A. M. Lino [1], Jorge R. Henríquez [2], Mohamed Teggar [3], Abdelghani Laouer [4], Müslüm Arıcı [5], Amani Benhorma [3], Daniel Rodríguez [2]

1. Energy Department, Faculty of Mechanical Engineering, State University of Campinas[1], Mendeleiev Street, 200, Cidade Universitária "Zeferino Vaz", 13083-860, Campinas, Brazil; E-Mails: kamal@fem.unicamp.br; fatimalino@fem.unicamp.br
2. Department of Mechanical Engineering, Federal University of Pernambuco, Av. Da Arquitetura s/n, Cidade Universitária, CEP 50740-550, Recife/PE, Brazil; E-Mails: rjorgeh@gmail.com; danivd1188@gmail.com
3. Laboratory of Mechanics, University of Laghouat, Algeria; E-Mails: teggar.mohamed@yahoo.com; amanibenhorma@gmail.com
4. Laboratory of Condensed Matter Physics and Nanomaterials, University of Jijel, Algeria; E-Mail: a_laouer@univ-jijel.dz
5. Mechanical Engineering Department, Engineering Faculty, Kocaeli University, 41001 Kocaeli, Turkey; E-Mail: muslumarici@gmail.com

* **Correspondence:** Kamal A. R. Ismail; E-Mail: kamal@fem.unicamp.br

Academic Editor: Zhiwei Ma

Special Issue: Decarbonisation of Heating and Cooling

Journal of Energy and Power Technology
2023, volume 5, issue 4
doi:10.21926/jept.2304031

Received: June 12, 2023
Accepted: October 09, 2023
Published: October 19, 2023

Abstract

The building sector is rated as a big consumer of electric energy and emissions, responsible for about 40% of final electric energy consumption. As a result, the Paris Agreement 2015 set a goal for buildings and the construction sector to reach a nearly zero-carbon stage by 2050. This urged most countries to create regulations for the construction sector and invest in energy efficiency programs. The present paper aims to present an updated review of building energy-saving solutions and techniques to contribute to carbon emission mitigation in the building sector. The high energy consumption of a building is mainly due to heating and cooling, which is directly related to the thermal properties of the materials used. Natural ventilation and illumination are other aspects that contribute to the high energy consumption. Considering these issues, the review covers energy-efficient construction materials such as mortars, concrete with PCM, new construction materials with PCM such as 3d printing concrete and geopolymer concrete, and bricks usually used in buildings. Also, the review covers the methods and solutions for energy saving for building heating and cooling. Since transparent windows and façades are essential for structures, their thermal and visual performance is crucial. Established and under-development techniques for windows and façades are presented and discussed. Walls and roofs are usually rated at the top of the weak barriers against a building's heat losses and energy gains. The present paper reviews existing and still under research and development techniques to improve the thermal performance of walls and roofs, such as cool roof and cool walls, walls and roofs with phase change materials (PCM), and ventilated walls and ceilings.Some authors' comments are presented at the end of each topic. Some possible opportunities for future research and developments are also presented.

Keywords
Sustainable buildings; energy efficient construction materials; thermally efficient windows and facades; energy-efficient walls and roofs; buildings heating and cooling strategies; thermal and visual comfort

1. Introduction

With the continuous increase in the world population, the enhanced industrial developments and general improvements in living conditions, increased energy demands and emissions which threaten the planet's sustainability. This is basically because the dominant global energy resources are still fossil-based, achieving 82%, as can be seen in Figure 1 based on data from IEA, 2022 [1].

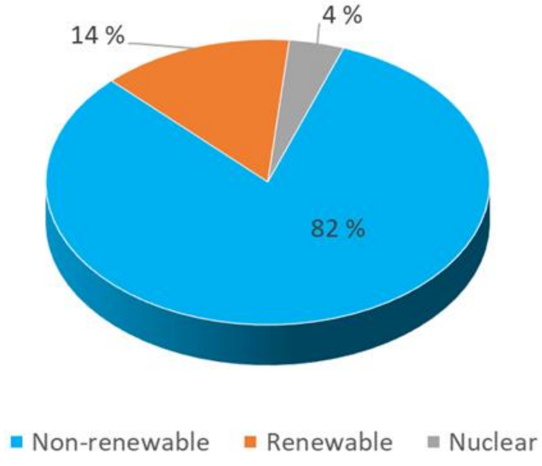

Figure 1 Primary world energy consumption in 2022, adapted from [1].

The world energy consumption in 2019 shows the sector involving residential, commercial and public service as the most significant consumer, accounting for 33% as in Figure 2, [1]. This is mainly due to the inefficiency of these sectors in using available energy and excessive use of cooling and heating systems, artificial lighting, and poor thermal performance of the sector. According to [1] the residential sector was a big significant participant in the world electricity consumption in 2019, as shown in Figure 3.

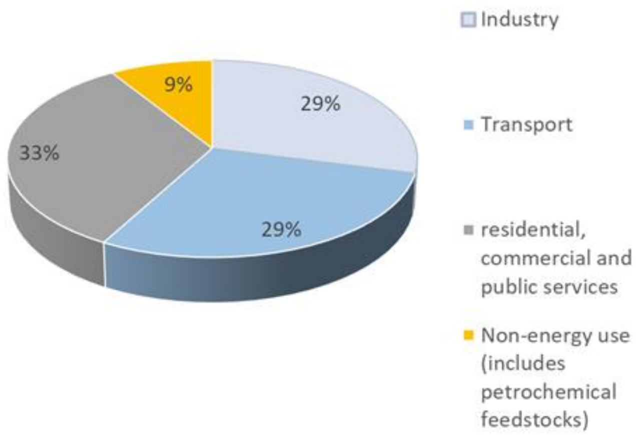

Figure 2 World energy balance by sector in 2019, adapted from [1].

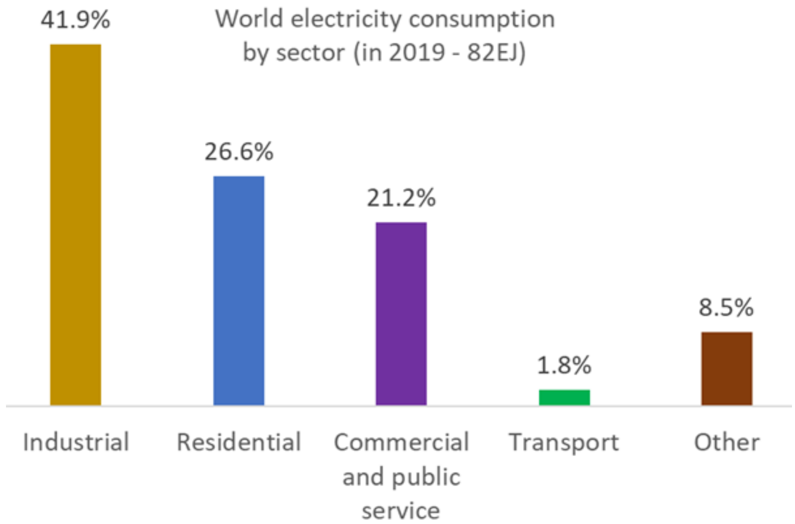

Figure 3 The world electricity consumption by sector in 2019, adapted from [1].

According to [2] the evolution of electricity use by the different sectors from 1974 to 2019 from which Figure 4 is adapted. The results show an ascending consumption rate with time, which is serious and requires global actions to reduce consumption and increase energy efficiency utilization besides increasing the share of renewable energy resources in the global energy matrix.

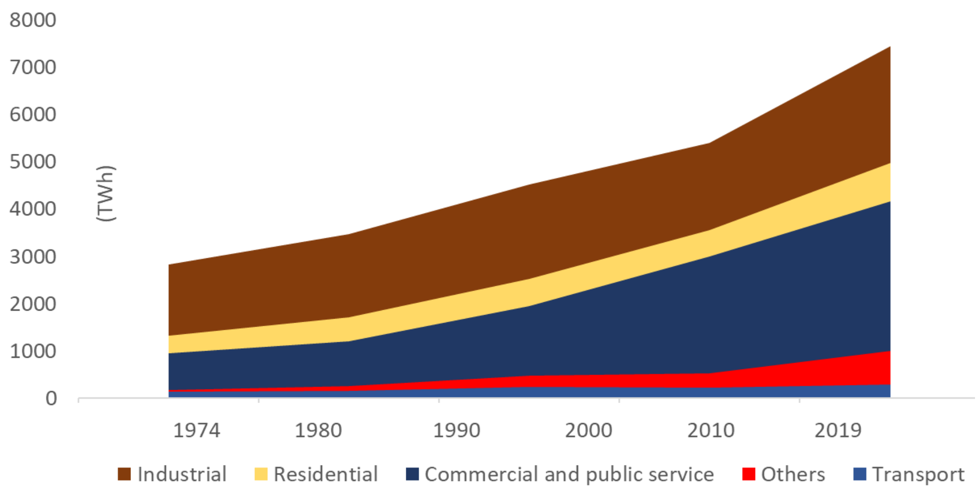

Figure 4 Evolution of electricity consumption of the different sectors, adapted from [2].

This situation alerted the world population to urgently change these tendencies and save the planet before it is too late. With the continuous and current evidence of the ambient response to these aggressions, worldwide efforts were concentrated on seeking renewable energy sources to replace fossil fuels, reduce energy demands, and increase used energy efficiency in all sectors. One of these high energy-consuming sectors is the building sector which was positioned as a target for future improvement of final energy use.

The Paris Agreement in 2015 set a goal for buildings and the construction sector to reach a nearly zero-carbon stage by 2050. Consequently, countries have created regulations for the construction sector and energy consumption in buildings, and investments in energy efficiency in facilities have increased since 2015, driving the development of new technologies for the industry, UNEP [1]. The energy consumption of the building sector is significantly high. Globally, buildings are responsible for about 45% of energy consumption and 40% of atmospheric emissions. To alleviate this situation, new design philosophies should be implemented together with investments in research and development of new materials and energy-efficient components for new building projects. Since the consumption and emissions of existing buildings are huge and must be limited to be able to meet the requirement by 2050, it is imperative to have updating plans for existing buildings and make them more energy-efficient and economically sustainable by implementing adequate public policies and financial and tax incentives.

The energy consumption for heating and cooling buildings is directly related to the thermal performance of the materials used to construct walls, roofs, windows, and doors. Global data from the United Nations Environment Program, UNEP [1] shows that energy consumption to meet heating and cooling demands accounts for approximately 40% of the final energy consumption of buildings. The rest is used for water heating, lighting, cooking, and operating appliances, as shown in Figure 5.

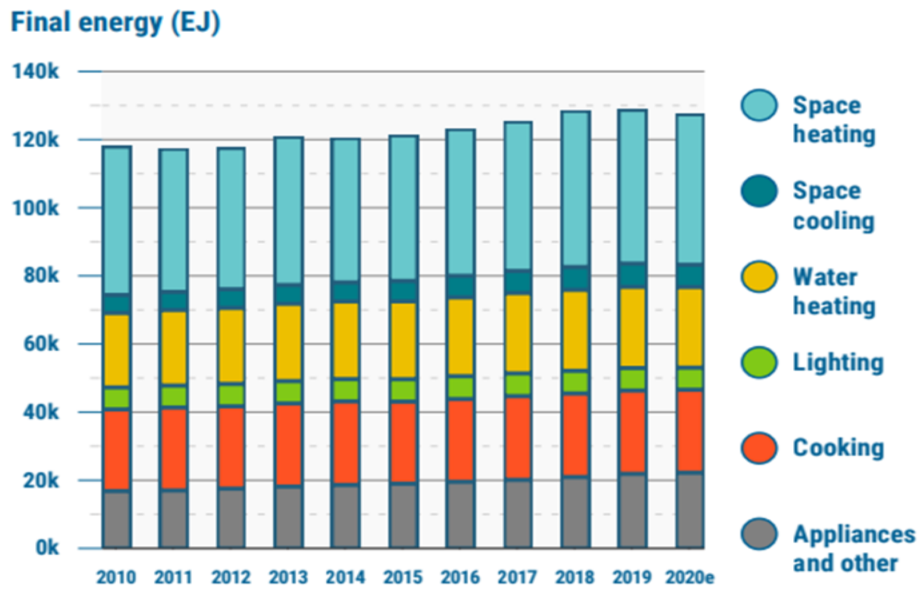

Figure 5 Global data on final energy consumption in buildings, [3].

Building envelopes consist of different structural and functional components, such as windows, walls, floors, and roofs; each contributes to energy efficiency. Different technologies could be considered to improve building energy performance.

The thermal properties of the construction materials such as mortars, concrete, and bricks can be significantly upgraded by adding new materials to improve their thermal qualities and make them adequate to achieve the required energy reductions and thermal comfort for the occupants. New construction materials with PCM 3D printing concrete and Geopolymer concrete can be further investigated and applied in accurate scale residences for long-term technical performance and useful life.

Window design has an essential role in achieving energy efficiency and thermal comfort. Besides, it can allow using natural illumination, reducing energy and improving visual comfort. Also, windows allow natural air circulation, ensuring thermal comfort and reducing energy and emissions. Highly insulating glazing windows have been under rapid development in the last years. Some commercial products are available and can be used in many applications for new buildings and refurbishment.

More research and developments on materials, design philosophies, real applications and demonstrations of the capabilities of the new materials and design strategies and philosophies can enhance the thermal properties of the walls, roofs and floors.

To help in assessing these objectives, this review aims to seek building energy-saving solutions and techniques that can make the energy sector more sustainable by reducing energy consumption and emissions while keeping modern fashion functional and providing thermal and visual comfort for the occupants. Hence, the following topics were covered in this review.

In this review, the authors tried to give full coverage of each topic with emphasis on recent studies, but cited some relatively old studies because of their pioneering and technical relevance. At the end of each topic, the authors presented their comments on the subject. The review was finalized by adding conclusions and perspectiveson future research and developments.

2. Energy Efficient Construction Materials

Electric energy consumption of the building sector is huge, achieving about 40% of the total consumption and its share of emissions is equally high. To address these major problems, it is necessary to improve the thermal performance of buildings and reduce thermal losses, eventually leading to electricity and emissions reductions. One way to achieve these targets is using thermally efficient construction materials, which are universally used in the construction of buildings. Such basic materials include mortars, bricks, and concrete in the form of new composites containing additives to enhance their thermal performance and facilitate their safe integration into the building construction.

Marani and Nehdi [4] presented a review that examines potential methods of incorporating PCMs into building materials, including microencapsulation, macro-encapsulation, shape-stabilization, and porous inclusion. Rathore and Shukla [5] critically reviewed the application of microencapsulated PCM in buildings. The authors investigated various approaches to integrate the microencapsulated PCM in the building envelope, its effects on indoor thermal behavior, and the reduction in cooling load. Figure 6 shows some options for integrating phase change material (PCM) into building materials.

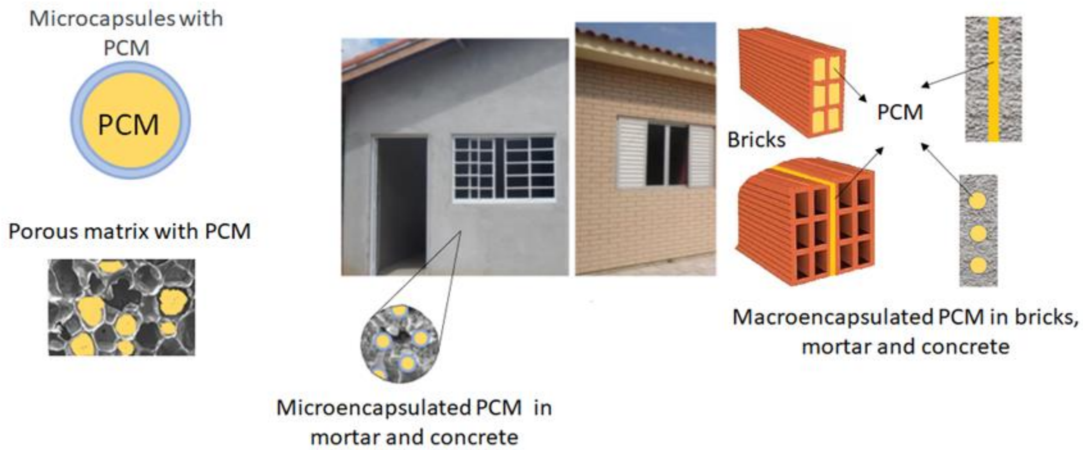

Figure 6 Micro and macro encapsulation of PCM in building materials.

2.1 Mortars with PCM

Mortar is an essential element for building construction usually used with bricks and for covering external and internal walls to reduce heat transfer to and from the building to the external ambient. The mortar mix with thermally enhancing additives must be compatible with the building utilization, does not leak, is resistant to the continuously varying ambient conditions and safe. Research results showed that adding adequate PCM with the proper quantities to the basic mortar mix can achieve good thermal results without impairing the mechanical properties of the mortar. Olivieri et al. [6] presented experimental research on the thermal properties of novel cementitious mortars incorporating microencapsulated PCM. Results show that silica aggregates and antifoaming mixture produced mortars with high thermal conductivities and effusivities. Rao et al. [7] reviewed PCM and mortar to achieve energy efficiency in buildings, including details of different PCM-mortar combinations and their thermal and mechanical properties. Djamai et al. [8]

investigated several mortars with varying amounts of PCM and conducted experiments including thermo physical and micro structural tests. The results showed that the degradation of the mechanical strength of the PCM-mortar composites was due to both weak PCM inclusions and the decrease in the degree of hydration of the composites. Sarcinella et al. [9] characterized the thermal properties of a composite PCM incorporated into mortar compositions. The results showed that adding PCM in mortars decreases the maximum temperatures and increases the minimum temperatures, and reduces the heating and cooling needs.

Mankel et al. [10] presented a model for the thermal behavior, heat storage, and recovery of cementitious composites made with recycled brick aggregates as carriers for PCMs. The authors reported promising numerical predictions and good agreement with experimental results. Rathore et al. [11] presented a review investigating the effectiveness of organic PCM as shape-stabilized composite phase change material and its ability to regulate the thermal behavior of buildings. The study showed that the material has the potential to improve the thermal conductivity, minimize leakage, and control the indoor temperature.

Orsini et al. [12] conducted a study to develop a building component that combines high energy performance with reduced thickness and weight and investigated PCM in cement-based mixes. The authors characterized the new material, analyzing its mechanical and thermal performance. Sarcinella et al. [13] developed new sustainable PCMs through the “form-stable” method. The new PCM materials comprised an inert matrix impregnated by polyethylene glycol (PEG). The PEG/stone composite materials replaced the fine aggregates in mortars. The results confirmed the effectiveness of the new mortars in the thermal regulation of indoor environments. Guardia et al. [14] investigated the influence of a microencapsulated PCM, a lightweight aggregate (LWA), and cellulose fibers on the behavior of cement-lime mortar. The authors reported that Lightweight aggregates increased porosity but reduced strength and thermal conductivity. Cellulose fibers did not modify mortar properties significantly. PCM increased mortar enthalpy but reduced porosity and strength, while LWA increased the enthalpy of PCM cement-lime mortars.

2.1.1 Authors’ Comments

There is a need to continue the research to develop new materials and energy-efficient building components. The review shows that the main problem with mortars is the reduced mechanical strength and unknown data on long-term performance, aging, and cycling. The idea of recycling demolition construction materials as carriers for PCM seems interesting since it provides a solution for waste management of construction materials, cheap carrier for PCM, and produces PCM mix adequate for preparation of mortars with improved thermal properties and economically sustainable. Accurate field analysis and long-duration tests are required.

2.2 Concrete with PCM and Other Additives

Concrete is another basic material used mainly for constructing external walls, roofs and floors and usually contributes to heat losses and impacts the heat and cooling loads and thermal comfort of the occupants. Hence, it is necessary to improve the thermal qualities of concrete to reduce the thermal impacts and improve internal thermal comfort without impairing its mechanical properties.

The literature shows several studies on recycling plastic waste in the production of building materials, especially concrete. Using plastic as a component in the concrete mix confers favorable properties to the final product and makes it economically sustainable. Incorporating polyethylene terephthalate (PET) particles reduces the need for fine aggregate, increases corrosion resistance, and makes concrete lighter [15]. Rai et al. [16] investigated the addition of plastic to construction materials and showed improvement in the resulting concrete's thermal properties. They used plastic flakes as fine aggregate, PET particles, high-density polyethylene (HDPE) waste, plastic waste as coarse aggregate, and shredded fiberglass polyethylene bags to replace the fine aggregate partially. Foti [17] and Ingrao et al. [18] used fibers from PET bottles, remains of granulated polyvinyl chloride (PVC) pipes, and PET fibers in concrete. Schaefer et al. [19] demonstrated improved mechanical properties by adding irradiated recycled plastics in concrete. Ling and Teo [20] added rice husk ash with expanded polystyrene waste to reduce the concrete bricks' strength loss. Zavadskas et al. [21] reported that the incorporation of plastics in building materials can improve the thermal efficiency of buildings by enhancing their thermal insulation using plastics.

Memon et al. [22] investigated macro-encapsulated paraffin-lightweight aggregate to develop structural-functional concrete. The authors evaluated the chemical and thermal properties, reliability, and mechanical, and thermal performance. The results showed that the new product can decrease the indoor temperature and shift the thermal loads. Min et al. [23] evaluated the thermal and mechanical behaviors of concrete mixed with shape stabilized phase change material (SSPCM). Results showed that the specific heat increases as SSPCM content increases, but the resulting concrete's thermal conductivity and mechanical properties are reduced. Ricklefs et al. [24] investigated the effects of adding microencapsulated PCM on cement paste's and mortar composites' thermal conductivity. The authors commented that the thermal conductivity of the cement mortar decreased with the increase of the microencapsulated PCM. D'Alessandro et al. [25] presented the results of an investigation on concretes incorporating paraffin-based PCM. Results demonstrate that adding PCM reduces the mass density of concrete and decreases its mechanical properties. Similar results were reported by [26]. Mohseni et al. [27] developed a structural lightweight concrete for indoor temperature control using thermal energy storage aggregates (TESA). TESA were made of porous structural lightweight aggregate impregnated with PCM. The results showed that the compressive strength of TESA concrete decreased with an increase in TESA content and that its use could reduce energy consumption.

Yun et al. [28] developed a study to use PCM to control the heat of hydration of concrete and to evaluate the resulting thermal properties of concrete with PCM. The results showed that the use of PCM reduced flowability, compressive strength and the probability of thermal cracking. Sukontasukkul et al. [29] investigated the lightweight concrete containing PCM impregnated into porous lightweight aggregates. Results show that PCM aggregates affect concrete's mechanical and thermal properties. The mechanical properties and the latent heat were improved with increasing PCM aggregate content. The unfavorable interaction between PCM and concrete on the mechanical and durability properties limits field applications. Nanomaterials and supplementary cementitious materials can be used to reduce the negative impacts due to PCM [30].

Rathore and Shukla [31] evaluated the building envelope's thermal response integrated with macro-encapsulated PCM under a real tropical environment. The indoor thermal profile of both the cubicles in terms of peak temperature, time lag, and thermal amplitude was studied. The reduction in cooling load and energy saving in terms of cost/kWh of electricity was also evaluated. The results show a 40.67%-59.79% reduction in thermal amplitude, including a 7.19%-9.18% fall in peak temperature of all the walls, the roof, and indoor ambient of the experimental cubical. Additionally, 60-120 min of time delay along with 38.76% of reduction in cooling load was achieved.

Lagou et al. [32] conducted a study to provide justified answers to the research question of the optimal position of PCM into the building envelope, with emphasis on vernacular buildings, as well as to enlighten aspects of the appropriate melting behavior of PCM materials. Parameters directly affecting the operation of the PCMs, such as their position within the building envelope, the external environmental conditions, and the prevailing interior environmental conditions, have been investigated. Results revealed that in the case of non-conditioned indoor spaces, the PCM layer should be incorporated into the inner surface of the wall. The environmental assessment of building envelopes containing PCM building products has also been examined, delivering the energy pay-back time of the PCM-enhanced building products.

Mohseni and Tang [33] evaluated the efficiency of phase change materials (PCMs) in improvements in a residential building's thermal performance and thermal comfort. The heat transfer of concrete containing PCM, was numerically modeled and validated. PCMs with melting temperatures ranging from 19 to 29°C and 5 and 10 mm thicknesses were applied in different building elements. The experimental results were in good agreement with the EnergyPlus PCM module. The results indicated that models integrated with PCM can improve indoor comfort and reduce heating and cooling loads and temperature fluctuations. The PCM with a melting temperature of 21°C and thickness of 10 mm in the roof and wall showed the best performance in the energy consumption and transferring the loads away from the peak demand times. The environmental analysis indicated that the total CO_2 emission reduction would be about 264 tons when PCM with 10 mm thick is applied to a building with a life span of 50 years. The shortest payback period for building using PCM concrete was 16.6 years.

Cao et al. [34] investigated the potential of utilizing geopolymer concrete (GPC) walls containing microencapsulated phase change material (MPCM) in buildings at different environmental conditions. The effect of climate conditions (temperature, solar radiation) and MPCM design (shell thickness, concentration) on the energy efficiency of buildings was systematically analyzed based on numerical calculations utilizing the finite differences method with an energy balance approach. The energy efficiency of buildings was found to increase at higher levels of MPCM addition and for thicker concrete walls. When the outdoor temperature is higher than the indoor temperature, increasing the maximum solar radiation causes higher power consumption, a lower power reduction, and a reduced energy efficiency of the buildings. Utilizing a PCM with a melting temperature close to the average outdoor and indoor temperatures positively enhances the energy efficiency of buildings.

Al-Rashed et al. [35] conducted a numerical study focused on energy demand reduction, and the effectiveness of installing PCM into building envelopes in arid climate zones. For this purpose, four climate zones of Dubai, Jeddah, Kuwait City, and Lahore City were selected and then a 20 mm PCM layer (SP-21EK) was incorporated into envelopes to examine the effects of PCM on HVAC energy usage defining two scenarios. In the first scenario, for Dubai, Jeddah, Kuwait City, and Lahore City, the incorporation of PCM into the envelopes reduced the annual HVAC power usage by 55.47, 53.89, 58.86 and 53.57%, respectively. In the second scenario, HVAC power usage was reduced by 2.6, 2.03, 1.99 and 5.6%. Under the best conditions and owing to using SP-21EK, CO_2 emission reduced by 56.27, 44.81, 45.27, and 58.5%.

2.2.1 Authors' Comments

The review shows that many investigations and developments were conducted to determine the amount of PCM to be incorporated in the concrete material to produce the final concrete mix with thermal properties compatible with its function in the building without impairing its mechanical properties. These problems, along with aging and possible degradation due to cycling, are still to be solved. Also full-scale tests and long-duration monitoring are required to encourage building designers and architects to utilize PCM-concrete mix in real applications.

2.3 New Construction Materials with PCM

The building sector accounts for a significant share of global final energy use and energy-related CO_2 emissions. Despite the efforts made during the last decades to reduce energy consumption and greenhouse gas emissions, the energy demand is increasing steadily. Several emerging technologies are under development and can help reduce costs and energy usage in the building sectors besides reducing emissions and recycling waste. Some of these technologies include the development of geopolymer binders that can replace Portland cement and the use of 3D printing technology in the construction of buildings.

2.3.1 3D Printing Concrete

Three-dimension printing (3DP), has the advantages of high building efficient, low labor cost, and less construction waste compared to traditional construction technology. 3D printed concrete is a particular type of concrete which can be deposited through a 3D printer layer by layer without any formwork support and vibration process. Its important performance indexes, including workability, setting and hardening time, and mechanical properties, can be optimized by materials selection and printing parameters. Many building structures have been successfully printed using 3D-printed concrete technology, some of which have even achieved its real applications. The 3D printed concrete has great potential on practical applications, such as affordable housing construction in low-income countries and complex structures where the formwork is challenging to manufacture. 3DCP technology has a high customizability of architectural and structural design; can reduce material consumption, minimize material waste, decrease construction time from months or days to hours; improve sustainability, environmental impact and resolve residential crises by providing homes at the price of $10 000.

Cardenas-Ramírez [36] evaluated three SS-PCM based on eutectic fatty acid mixtures of capric-myristic (CA/MA), lauric-myristic (LA/MA) and palmitic-stearic (PA/SA). Moreover, a SS-PCM-based acrylic plaster was evaluated as a fiber cement siding finish. The obtained values were used to calculate the thermal transmittance (U-value), heat storage capacity, and thermal inertia parameters under a simulated diurnal cycle. Results showed that using phase change materials in powder form increases thermal lag between 148% and 180% and present a decrement factor <0.2. Furthermore, building envelopes as fiber cement siding with an SS-PCM-based acrylic plaster coating decreased the 20.8% indoor temperature, increased 67.26% the thermal lag and decrease 9% of the decrement factor.

Ding et al. [37] employed recycled sand instead of natural sand to achieve 3D concrete printing and investigated the hardened properties of this extrusion-based material. The effect of the replacement ratio of recycled sand, curing age, nozzle height and anisotropic behavior were evaluated based on the compressive tests, tensile splitting tests, and flexural tests. The results showed that the compressive and flexural strengths of the 3D-printed concrete with recycled sand were slightly lower than those without recycled sand. The compressive, tensile splitting, and flexural strength of 3D printed concrete with recycled sand had obvious anisotropy. The replacement of recycled sand had limited effect on the anisotropy of compressive and flexural strength but had a certain impact on the tensile splitting strength. It is believed that employing recycled sand to the mix of 3D printed concrete will significantly improve the sustainability of 3D printed concrete structures.

Brooks et al. [38] examined the feasibility of incorporating microencapsulated phase change materials (mPCM) into 3D printable cementitious composite materials. Results showed that the mPCM affected the printability of the cementitious ink material based on its physical properties (e.g., particle size) and volume loading - at lower volume loadings, mPCM increased the flowability of the cementitious ink material while leading to increased compressive strength and thermal conductivity for the hardened printed material. However, a further increase in mPCM dosage led to a decrease in printability and, therefore, a decrease in compressive strength and thermal conductivity as compared to the reference mixture. The study shows that microencapsulated PCM materials have good potential to be used in 3D printable cementitious mixtures for improving the thermal and energy performance of 3D printed buildings.

Large-scale construction 3D printing (C3DP), also known as green building construction, is an innovative method that can save time, materials, and labor costs. The suitable printing materials should have the properties of good fluidity, excellent early strength, appropriate setting time, suitable viscosity, and cost-effectiveness. Among the main concerns of the construction 3D printing, the clogging of the material induced by premature setting and poor fluidity of the concrete is a significant one. It hinders the pumping capacity of concrete materials from the mixer to the extruder and reduces the overall efficiency of the C3DP process. The existing literature has proposed a variety of materials for C3DP, but there is still no standard information on the material selection. Therefore, it is necessary to solve the material clogging problem while obtaining the characteristics suitable for printing materials. Shahzad et al. [39] conducted a study seek for suitable printing properties for C3DP material to solve the clogging problem. The composition based on industrial solid waste was used to prepare this material. The use of this material in C3DP was proved to be cost-effective. Suitable setting time, good fluidity, and excellent compressive strength were achieved. These suitable properties were obtained by adding the phase change material (PCM) at different temperatures. Furthermore, optimized material was used to print 3D structures with different shapes. It is believed that this method can provide innovative ideas for promoting green building construction and producing high-value products.

Figueiredo et al. [40] conducted a study of quantifying the influence of microencapsulated phase change material (PCM) over the concrete mechanical and thermal properties. The experimental tests on concrete with PCM yielded resistance loss up to 66% and 52% for compression and bending strength, respectively, comparatively with the reference concrete specimens, without PCM. Thermal performance of concrete incorporating PCM was also evaluated. The results showed that incorporating PCM can contribute to reducing the energy demand in buildings.

Christen et al. [41] studied the effects of adding a paraffin phase change material on the strength and printability of 3D-printed concrete. Adding phase change materials to concrete produce a composite material with maximized latent and sensible heat storage capacity. Used in buildings, this hybrid material can minimize unwanted heat transfer across the building envelope. An existing mix design (RBA-3DPC), in which 64% of the natural aggregate in a 3D printable concrete (3DPC) had been replaced with recycled brick aggregate, is adjusted by adding phase change material to the pores of the recycled brick aggregate by vacuum impregnation, creating PCM-3DPC. It is concluded that the PCM-3DPC has the highest number of printable layers predicted by the model and realized by a cylindrical column print. Overall, PCM-3DPC has greater strength than RBA-3DPC and lower strength than 3DPC.

Hao et al. [42] generated a novel shape-stabilization phase change materials (PCM) for 3D printed concrete have been by impregnating paraffin into the recycled fine aggregates. Based on both steady state hot plate method and the transient hotwire method, the impact of printing parameters, including printing layers, path, extrusion rate and materials on thermal conductivity of the 3D printed concrete was investigated. The relationship among thermal conductivity, dry density and porosity of the 3D printed concrete was analyzed. The results showed that recycled fine aggregates can be successfully used as a support material for paraffin. The melting temperature and latent heat is 36.52°C and 40.65 J/g, respectively. The thermal conductivity of 3D printed concrete was significantly influenced by the multi-layer structure and thermal anisotropy. Under the same size, density class, or mix design, the thermal conductivity of the 3D printed concrete can reach up to 31.04% lower than that of mold cast concrete. The results also indicate that impregnating paraffin into the recycled fine aggregate can improve its thermal properties to upgrade the overall performance of 3D printed concrete.

Ryms et al. [43] examined the possible use of post-pyrolysis char made from spent vehicle tyres as a carrier for phase change materials (PCM), which could be used as an additive to cement mortar. Because of the ability of PCM to accumulate heat, the cement composite obtained from it, apart from its structural and strength properties, will acquire an additional energy storage function, which can be very important for energy-saving construction. Rubitherm RT22 was used as a PCM to develop the new cement composite. The experiments' results showed that using tyre char as a PCM carrier in cement mortars is not only possible, but also thermodynamically advantageous.

Das et al. [44] agglomerated MIC-PCM (AMIC-PCM) with bio-based PCM in core encapsulated in thicker formaldehyde-based shell is incorporated in flowable cement mortar. Firstly, material characterization of AMIC-PCM is carried out to study its phase change temperature, latent heat capacity, thermal conductivity, and specific heat capacity. It was observed that the bio-based AMIC-PCM can resist temperatures up to 230°C without any degradation. Experimental outcomes of this study indicate that the adoption of 10% dosage of AMIC-PCM reduces the flow of mortar, compressive strength and flexural strength drastically. Although there is strength reduction of mortar due to low intrinsic strength of AMIC-PCM, results of the SEM analysis indicate no micro-encapsulation damage in mortar mix. Further, it is to be noted that despite the strength reduction, the mortar mix with 10% dosage of AMIC-PCM is found to satisfy the strength requirement for making a non-structural mortar board to increase the thermal mass of building.

Zhang et al. [45, 46] reviewed the progress of 3D printed concrete in terms of workability, mechanical properties and building plan design, further developments of 3D printed concrete were also discussed. They presented state-of-the-art mix design concepts for 3DPC, where various aspects of mixture compositions and their effects on properties of 3DPC were highlighted, and mix design approaches were described. The use of models providing a quantitative relationship between the rheological parameters of fresh concrete and its composition is essential to guide the mix design of printable concrete. Some such models do exist already, but considerable research is still needed to develop them into reliable mix design tools involving the properties of hardened concrete under consideration of process-induced anisotropy.

Ahmed [47] presented a comprehensive review of 3D printing of various materials, techniques, and trending applications. The materials used for 3DCP, mix design principles, and printing process parameters have been overviewed. The factors influencing flowability, extrudability, buildability of various mixes, microstructure, and mechanical properties of the hardened concrete; and improvement techniques have been discussed. Part of this review highlighted the cost of 3D printed houses compared with traditional alternatives, the environmental sustainability of 3DCP, and its compatibility with international plans for climate change and minimizing energy usage. Finally, the conclusions identified the needed research and state of the art for this technology.

Alabbasi et al. [48] presented the development and validation of a design-to-fabrication framework aiming to improve the efficiency of fabricating reinforced concrete building components for housing projects in the Kingdom of Saudi Arabia by incorporating 3D concrete printing technology. In particular, the research presented an algorithmic framework to mass customizing a typical Saudi Arabian free-standing house by utilizing parametric modeling, topology optimization (TO), finite element analysis (FEA), and robotic 3D printing tools and techniques. The framework was validated by fabricating optimized reinforced concrete columns and by testing their structural performance under the Saudi Building Code (SBC 304). The findings demonstrate the benefits and drawbacks of the proposed framework and compare it to current Saudi conventional construction approaches.

As one of the ways contributing to the progress of the industrialization of the construction industry, 3D printed concrete (3DPC) has attracted more and more attention in recent years. However, one of the most significant challenges for the application of 3DPC is the printing materials. There is a significant difference in the mixtures and performance between 3DPC and standard concrete.

Hou et al. [49] conducted a study to review the performance requirements of 3DPC, including printability, fresh and hardened mechanical properties, and durability. Based on this, the specialized test methods for 3DPC are reviewed for the compelling quality evaluation of 3DPC. The last part presents a review of mix design from the point of view of different materials and mix design approaches. The results show that 3DPC needs to meet the printability that it has higher requirements for rheology, hydration, and green strength than standard concrete. The interlayer bond is the key to study the anisotropic strength and durability degradation. More accurate test methods and testing standards should be developed. Besides, coarse aggregates and recycled materials need to be considered in the mix design of 3DPC.

2.3.2 Authors´ Comments

As one of the ways contributing to the progress of the industrialization of the construction industry, 3D printed concrete (3DPC) has attracted more attention in recent years. Using 3DPC can accelerate the construction speed, save labor and raw materials, and improve the design freedom of construction without formworks. However, there is a significant difference in the mixtures and performance between 3DPC and normal concrete which requires more and deep investigation.

Large-scale construction 3D printing (C3DP), is a potential method that can save time, materials, and labor costs. The suitable printing materials should have the properties of good fluidity, excellent early strength, appropriate setting time, suitable viscosity, and cost-effectiveness. Among the main concerns of the construction 3D printing is the material's clogging induced by premature setting and poor fluidity of the concrete. Therefore, it is necessary to solve this material clogging problem while obtaining the characteristics suitable for printing materials.

2.3.3 Geopolymer Concrete

Geopolymer concrete is made by reacting aluminate and silicate bearing materials with a caustic activator, such as fly ash or slag from iron and metal production. It can be a suitable substitute for ordinary Portland cement (OPC). The production cost per cubic meter (m3) of geopolymer concrete is 34.75% less than the Portland cement concrete of the same grade. The production of this concrete contributes positively to the environment by using industrial waste and reducing carbon emissions due to the lower demand for Portland cement. Figure 7 shows the integration of components for the production of geopolymer concrete.

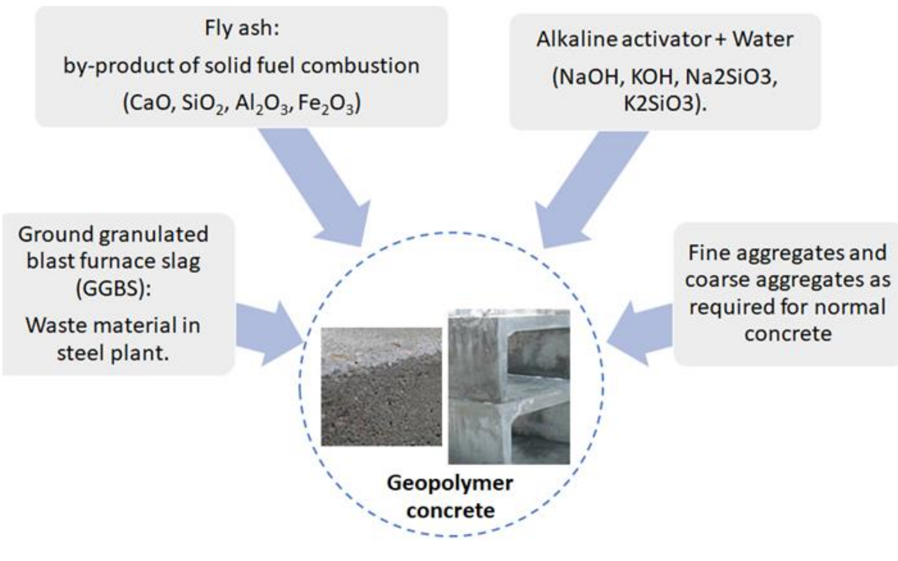

Figure 7 Composition of geopolymer concrete.

Shadnia et al. [50] studied experimentally the mechanical and thermal properties of geopolymer mortar synthesized with low calcium fly ash and different amount of PCM. The results indicate that the geopolymer mortar's unit weight and compressive strength decrease slightly after PCM is incorporated, mainly due to the small unit weight and low strength and stiffness of the PCM. However, the compressive strength of geopolymer mortar containing up to 20% PCM is still sufficiently high for applications in buildings. The results also show that the incorporation of

PCM leads to a substantial increase of heat capacity and a decrease of thermal conductivity of the geopolymer mortar and is very effective in decreasing the temperature inside the cubicles. Therefore, the geopolymer mortar with incorporated PCM can be used as building walls to effectively increase buildings' thermal inertia and reduce energy consumption for cooling and heating.

Lecompte et al. [51] conducted a study that examined the inclusion of micro encapsulated phase change materials (PCM), up to 29% in volume, in concretes and mortars. Thermal and mechanical characteristics of hardened mixes are measured and compared with classical civil engineering models. PCM microcapsules behave as voids on a mechanical point of view and as adequately dispersed spheres on a thermal point of view. It is shown that PCM included in a mineral matrix to make building blocks could benefit walls' thermal behavior, keeping a consistent mechanical strength.

Asadi et al. [52] reviewed the geopolymer mortar and concrete containing PCMs, including their characteristics such as workability, density, compressive strength, heat capacity, thermal conductivity, and their effect on building energy consumption. Existing literature reveals that using geopolymers instead of OPC can reduce thermal conductivity and power consumption. The latent heat and melting temperature of investigated PCMs were in the range of 96.1-230 J/g and 21.9-33.8°C, respectively. Also, the workability of geopolymer concrete can remain in the acceptable ranges when the PCMs are incorporated in low percentages. Furthermore, a considerable increase in the heat capacity is reported at the PCM’s melting temperature of geopolymer mortars and concretes.

Łachet al. [53] investigated the possibility of using PCM in concretes and geopolymer composites and presented the most essential properties of PCM materials, their types, their characteristics, and their use in geopolymer materials. The authors critically analyzed the feasibility of mass-scale implementations of such composites. It was found that the use of PCM in sustainable construction is necessary and inevitable. It will bring several benefits, but it still requires significant financial resources and time for more comprehensive research.

Haurie et al. [54] provided a paper that handles the effect of the addition of different percentages of microencapsulated phase change material on the properties of two commercial single layer mortars has been studied. Physical and thermal properties as well as fire reaction have been evaluated.

Cui et al. [55] conducted a study to achieve high heat exchange efficiency of a microencapsulated phase change material (MPCM) and energy storage for buildings; a graphite-modified MPCM (GM-MPCM) was prepared and incorporated into the cement mortar to develop a type of cement mortar with both high heat storage efficiency and considerable mechanical strength. The thermophysical properties of the GM-MPCM and the thermal and mechanical properties of the GM-MPCM mortar were investigated. The results indicated that cement mortars with GM-MPCM can be used for thermal energy storage in buildings. Moreover, adding GM-MPCM into cement would also lower and delay the hydration heat, which is helpful in reducing the thermal cracking of cement-based materials.

Rashid et al. [56] conducted a study to evaluate the enhancement of the thermal properties of geopolymer concrete (GPC) by adding phase change material (PCM) capsules. Five compositions of GPC cubes were developed for testing, one pure geopolymer as a reference, two compositions by 50% volume substitution of pure geopolymer with the two different PCM capsules and two compositions by 50% substitution of each porous material for comparison. Thermal and structural tests were conducted to investigate the effects of capsules on the properties of produced GPC. The produced thermally enhanced GPC can reduce heat transmission to indoors in hot climates like the United Arab Emirates, and its compressive strength is acceptable for non-load-bearing wall components.

2.3.4 Authors' Comments

The building sector is considered as a big consumer of global final energy use irrespective of the recent efforts to reduce this consumption. Including PCM in mortars and concrete helps increase the effective mass and reduce temperature fluctuations. Several new technologies are under development, including the development of geopolymer binders that may be used as an alternative to Portland cement and the possible use of three-dimensional (3D) printing technology in the construction sector. These promising technologies can help reduce costs, while maintaining energy efficiency, low consumption and thermal comfort.

2.4 Bricks with PCM

Red and concrete bricks are the most common construction elements used in internal and external walls and are responsible for a significant part of thermal losses in the building. Improving the thermal qualities of bricks, like thermal capacity and ability to store latent heat energy can reduce energy consumption and emissions of the buildings. Memon [57] presented an extensive review of incorporating PCM into construction materials and elements by direct incorporation, immersion, encapsulation, shape-stabilization and form-stable composite PCMs. Khedache et al. [58] conducted a study on preparing and characterizing thermal properties and reliability of Paraffin/Redk Brick mixed as form-stable PCM. The composite materials are red brick powder, paraffin, expanded graphite and PCM. The results show that the proposed product has considerable latent heat energy storage potential. Wang et al. [59] conducted a study to evaluate a composite-PCMs wall. They found a reduction of about 0.2°C for the internal wall temperature, a time delay of about 1-2 h, and a decrease of 24.32% of the cooling load. Similar results were found by [60]. Kant et al. [61] conducted a numerical study on finite elements on the building bricks containing PCM. The results indicate that applying PCM in building brick could be an effective technique for passive thermal control. Souci and Houat [62] obtained similar results and confirmed that the hollow brick with paraffin could be a solution to increase buildings' thermal and energy efficiency. Dabiri et al. [63] presented a thermal analysis of a brick with PCM. The results indicated that heat storage was via latent heat in the summer, while in winter, it was mainly by sensible heat. However, PCM could be incorporated in buildings envelope for thermal regulation in both the summer and winter. Saxena et al. [64] tested bricks with both Eicosane and OM35 and found a temperature reduction of 5-6°C across the bricks. Compared with conventional bricks, the authors found a reduction in heat flow of 8% and 12% for Eicosane and OM35, respectively.

Tunçbilek et al. [65] investigated the influence of brick-containing PCM on heating and cooling loads for different fusion temperatures, locations, and quantities of PCM. The results indicate that integrating PCM into the brick can significantly reduce heating and cooling loads and provide thermal comfort for the occupants. Azmi et al. [66] reviewed numerical methods used to evaluate the performance of bricks with impregnated PCM, including the enthalpy-porosity method and lattice Boltzmann method.

Mukram and Daniel [67] used commercially available PCM for incorporating in bricks and found favorable results as both macro and micro encapsulated in the bricks. Abdulhussein and Hashem [68] conducted an experimental study on bricks with PCM and compared the results with the case without PCM. They reported that more than 3 °C reduced the internal temperature and the heat flux was reduced by 34.17%. Ru et al. [69] used brick waste from demolition of buildings as recycled aggregate mixed with PCM. The results showed favorable behavior for practical application. Shaik et al. [70] investigated the savings in air-conditioning in duplex houses designed with various PCM incorporated in burnt clay bricks. The authors reported an annual cost saving in air-conditioning of $2, 079, carbon mitigation of 87.8 tons CO_2/year, and a payback period of 11.29 years.

2.4.1 Authors' Comments

Laboratory tests on bricks with PCM insertion have proved adequate to regulate indoor temperature and reduce heat losses and gains. Numerical simulations also confirmed that bricks and other thermally enhanced elements, can form an efficient barrier against thermal losses and contribute to passive thermal comfort in buildings.

2.5 Energy Saving Solutions for Buildings Heating and Cooling

About 40% of the total world energy is consumed by buildings, so it is necessary to reduce the energy consumption. Heating and cooling energy use accounts for the great share in building consumption mainly due to the increase of light-weight modern constructions. Heat loss through light-weight building is high, resulting in significant temperature fluctuations, low thermal comfort, and high cooling/heating loads. The building envelop is a weak barrier against heat loss. Therefore, PCM can provide an insulating effect that enhances thermal comfort and reduces power consumption.

There are many ways to reduce energy consumption in building, such as shading, bio-mass mixed finishing mortar, light-color facades, and implementation of insulation materials. A more effective way is to use PCM, which offers higher thermal inertia than conventional insulation materials. The PCM is used in building components such as walls, roofs, floors, ceilings, and windows. It can increase the building thermal capacity by improving its effective thermal mass, which reduces heat loss and enhances energy conservation in buildings. Mabrouki et al. [71] numerically investigated the application of PCM in a Trombe wall for a semi-oceanic climate with different melting points and thicknesses. Simulations were based on data of a city in Morocco introduced in Designbuilder and Energyplus. The outcomes indicated annual energy savings of 42.97%. Devaux and Farid [72] applied a PCM layer to the ceiling of a building. The theoretical approach and predictions were validated by comparison with experimental data. Results indicated heating cost savings up to 42%.

Jamil et al. [73] numerically and experimentally investigated the use of PCM for retrofitting a building ceiling in Melbourne, Australia. The room temperatures of the original and retrofitted building were compared. The passive application of PCM in the building ceiling significantly improved thermal comfort. Kusama and Ishidoya [74] used microencapsulated PCM on both ceiling and finishing plaster for a building in Japan. The experimental study focused on the effect of PCM on indoor temperature. Comparisons were made for two heating sources. The authors indicated that PCM could use up to 82% of incident solar radiation through the windows, which improved the indoor temperature and reduced energy consumption. Li et al. [75] numerically investigated the use of PCM on the roofs. Simulations were conducted for cold regions in China. The influence of the PCM layer thickness, roof slope, and external surface absorption coefficients on thermal performance was investigated. The authors found that the PCM layer thickness and external surface absorption coefficients had a significant influence. Abbas et al. [76] studied the effect of PCM integrated in a south-faced building wall on indoor temperature. This study was conducted experimentally and numerically using the enthalpy approach and finite volume techniques. The researchers investigated the impact of PCM incorporated in hollow bricks. This technique decreased the indoor temperature by 4.7°C while temperature fluctuation decreased by 23.84%. Castell et al. [77] presented an experimental study of encapsulated PCM's impact when integrated in classical and alveolar brick envelopes for Mediterranean weather conditions. The study indicated cooling energy saving of 15% along with low CO_2 emissions in the range of 1-1.5 kg/year/m^2. Zhang et al. [78] studied the effect of fluctuating outdoor temperature on the thermal performance of PCM applied to an external brick wall. The investigators employed a model based on the enthalpy-porosity method in PCM and conduction in the solid envelop. The numerical predictions were validated against experimental data. The results indicated the positive impact of PCM on thermal comfort by decreasing the room temperature fluctuation. Furthermore, increasing the amount of PCM led to a more significant enhancement effect. Mehdaoui et al. [79] experimentally studied the thermal behavior of a building wall in the presence of PCM. Temperature distribution through the composite wall was analyzed in laboratory scale. An analysis of the PCM-mounted wall's heat transfer and phase change characteristics was presented. Gao et al. [80] investigated the effect of using PCM in wall bricks for optimal thermal performance and reduction of thermal loads. The authors employed a home-built numerical model for the simulation of heat transfer associated with phase change. The model was validated against experimental results.

In fact, the thermal performance depends on several factors such as the choice of PCM, location, and thickness which minimize the HVAC load, enabling smaller and lower power demand [81]. The effect of PCM location in the envelop has been investigated in numerous studies. Tunçbilek et al. [82] optimized the design parameters of PCM in an external wall to absorb the maximum of latent heat. The optimization included the location, thickness, and melting temperature of PCM. The aim of the simulation study was to reduce the cooling load of a building office for summer conditions. Placing the PCM at the inner wall surface was found to be more effective than the external wall surface. A PCM thickness of 23 mm led to energy savings of up to 12.8%. The optimal melting temperature was found to be 25°C. Kishore et al. [83] studied five US cities to determine the optimal PCM melting point and location in the external wall to reduce cooling and heating loads. The authors investigated a typical US wall under representative climates covering the US main regions. The optimization criterion was to reduce the HVAC load. The outcomes indicated reduction in heat gain and loss up to 47.2% and 8.3%, respectively. Arıcı et al. [84] studied the effect of PCM melting point, thickness and location in the external wall on the time lag, decrement factor, and energy consumption for both cooling and heating loads of three different cities in Turkey. For optimal performance of latent heat of PCM, the layer thickness should not exceed 20 mm. Al-Absi et al. [85] presented a review that examines PCMs' application in different positions within the building walls to locate their optimum position and the influential parameters such as climate and weather conditions, PCMs' melting temperature and heat of fusion, PCMs' amount and thickness, the thermal properties of the wall's materials, among others. An optimization process is suggested to determine the optimum position of the PCM. Terhan and Ilga [86] also conducted an optimization study to define the optimal PCM type, position, and thickness. They found the highest heating energy savings of 21.32% annually for the case of three-layer BioPCM27 of melting temperature of 21°C integrated in the external wall.

Jiang et al. [87] applied the PCM to the window frames, studied its impact on the building's energy consumption for severe cold climate, and optimized the results to find the maximum window size in the south and minimum in the north. This saved about 20% on heating costs. Zhang et al. [88] conducted an optimization study by applying PCM only and then integrating silica aerogel and found that the performance of the insulation layer, optical performance of glass, and melting temperature of PCM are the key parameters to achieve an energy-saving rate of 56.67%. Zhang et al. [89] investigated the thermal performance of double-layer glass filled with PCM as a function of thermal physical parameters. Results indicate that the temperature distribution of the glass channel is mainly influenced by the absorption coefficient of the paraffin material and that the refractive index has a smaller impact on the temperature of the glass channel. Increasing the latent heat of paraffin materials can greatly improve the thermal performance while the thermal conductivity and the specific heat of paraffin have little impact on the thermal performance.

PCM can be applied for both heating and cooling purposes. In cold climates, the energy required to meet the heating demand is higher than that required for the cooling demands. It is necessary to find the best way to reduce heating demands and avoid overheating in the summer. Dehkordi et al. [90] studied the effectiveness of PCM for hot and cold weather and found it more beneficial for the cold regions with a decrease in the annual heat transfer within the range of 20-32%.

Numerous studies were conducted to illustrate the PCM potential to reduce the heating load. Li et al. [91] and Ma et al. [92] investigated the combination of sunspace and PCM in reducing the heating loads in severe cold climates and reported reduced energy consumption by about 28% and 10%, respectively. Caliskan et al. [93] carried out an analysis and evaluation of a hybrid heating system in a building. They connected the building's water boiler to an air heating unit that was based on the latent heat storage of PCM. Their results indicate that energy consumption can be reduced by integrating PCM with the building's heating unit due to the energy stored in the PCM. Ahmed et al. [94] discussed a thermal energy storage (TES) system that utilizes highly encapsulated magnesium chloride hexahydrate as PCM contained within aluminum cylinders. This system was integrated with a household gas heating system to capture waste energy when the room temperature is raised to a comfortable level. The authors investigated various performance metrics of the TES system, such as the stored energy, liquid fraction, and exergy during the charging and discharging process.

Application of PCM in floors to improve thermal comfort and reduce demand for heating and cooling proved to be a satisfactory measure. Barzin et al. [95] conducted an experimental study on a building integrating PCM boards in the floor for heating purposes. The study focused on energy consumption and cost related to peak power in the environment of Auckland, Australia. Significant energy savings and cost were reported at 35% and 44.4%, respectively. Faraj et al. [96]

investigated the feasibility of coconut oil as PCM in an under floor heating system for electricity peak load shaving. They compared the energy consumption and economic benefits of a test house with and without PCM. In a PCM-integrated building heating system, the PCM is usually incorporated into the building's structure or thermal storage unit, such as a tank or a heat exchanger. During off-peak hours or when excess energy is available, the PCM absorbs heat. When the building needs heating, the PCM releases the stored energy, providing heat to the building [97].

The advantages of PCM integrated building heating include reduced energy consumption and costs and increased thermal comfort for building occupants. Additionally, PCM-integrated building heating can be combined with other renewable energy sources, such as solar energy, to provide a more sustainable heating solution [98]. However, some challenges of PCM-integrated building heating include the need for careful design and installation to ensure optimal performance and the need for proper maintenance and replacement of the PCM over time. Additionally, using certain types of PCMs may present environmental and health risks, so careful selection and handling of materials is essential.

Radiant floor heating systems are popular due to the uniform temperature distribution and low noise. Sun et al. [99] constructed a double-layer radiant floor system with two inorganic PCMs and the performance of the test rooms in winter and summer was studied. Results show that the PCMs with different melting points can regulate indoor thermal comfort and shave the peak load. Zho and He [100] experimentally studied floor heating with different thermal mass and heating pipes. The results show that the PCM produces less temperature variation, twice longer discharge time, and higher and more stable heat supply than sand. In order to improve the energy performance of heating systems in buildings, Jin et al. [101] developed a novel composite for use as a heat storage medium in heating systems in buildings. The composite has a thermal conductivity of 1.87 W/m and a latent heat of 161.9 kJ/kg. The authors tested the thermal performance of radiant floor heating systems incorporating this new PCM composite. They found that the system's operating cost was 73.1% lower than the storage medium without it.

An electric radiant floor heating system can be combined with a suitable PCM to improve its energy efficiency and reduce energy consumption [102]. By incorporating a PCM into an electric radiant floor heating system, the PCM can absorb and store heat when the electric heating element is on, and release the stored heat back into the room when the heating element is off. This can help reduce the overall operational time of the electric heating element and energy consumption and costs.

As well, cooling applications of PCM in buildings have been the subject of intensive research to illustrate its impact on indoor temperature and energy consumption. Wang et al. [59] investigated the effect of PCM for different seasons. They showed a reduction in the cooling and heating load by 24.32% and 10-30%, respectively. Diaconu and Cruceru [103] tested the impact of two different PCMs simultaneously applied to the same wall with different melting temperatures. This configuration was able to reduce the peak cooling load by 35.4%. Furthermore, energy consumption for heating was reduced by 12.8%.

In summary, the advantages of PCM for building are numerous (Figure 8); one can cite the thermal comfort by reducing the room temperature swings, which leads to low HVAC load and hence, small devices, resulting in low power energy consumption and emissions. Additionally, PCM can help in decreasing the peak power demand. However, limitations, challenges, and research gaps are discussed in the following section.

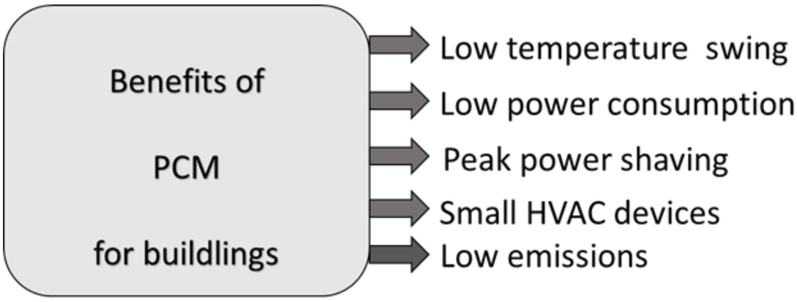

Figure 8 Advantages of PCM incorporation in buildings.

2.5.1 Authors' Comments

This section showed the potential of PCM in passively reducing heating and cooling load by limiting the indoor temperature swing, which reduces energy consumption, improves thermal comfort, and allows the use of light-weight envelops. Different PCM types incorporated in various building components were investigated for various climate conditions and seasons.

Based on information from the references discussed here, Table 1 and Table 2 show data on the relevant properties of commercial microencapsulated PCM and the Porous inclusion of PCM. Additionally, Table 3 shows the properties of some of the PCMs used in building materials.

Table 1 Properties of commercial microencapsulated PCM.

Micro encapsulated PCM	Melting Temperature (°C)	Latent Heat (kJ/kg)	Ref.
Micronal® DS 5040X (BASF) Particle size (mean): 50-300 m PCM: paraffin wax	22-24	95	[14]
Micronal® DS 5038X (BASF) Particle size (mean): 50-300 m PCM: paraffin wax	24-26	110	[6]
INERTEK® 23 Particle size (mean): 5-25 m PCM: methyl hexadecanoate	23-27	160	[8]
MPCM24D (MicroTek Laboratories Inc.) Particle size (mean): 15-30 m PCM: paraffin wax	22-26	155	[24]
ME29P (CrodaTherm™)	29	183	[67]
OM35 (savENRG™) Mixture of Organic materials	35	197	[64]

Table 2 Properties of PCM impregnated in porous matrix.

Porous inclusion of PCM	Melting Temperature (°C)	Latent Heat (kJ/kg)	Ref.
Lecce Stone impregnated with Poly-Ethylene Glycol, PEG 1000. granulometry: 1.6-2.0 mm	38.6-40	26.8-28.6	[13]
Lecce Stone impregnated with Poly-Ethylene Glycol, PEG 800 granulometry: 1.6-2.0 mm	11.3-14.1	25-31.7	[13]
Diatomite with palm wax	50.5-62.4	44.3	[5]
Diatomite with Dodecanol	23.3-29.5	75.8	[5]
Expanded perlite with paraffin	27.6	67.1	[5]
Expanded perlite with PEG	55.2	135	[5]

Table 3 Organic and Inorganic PCM properties.

Phase Change Material (PCM)	Melting Temperature (°C)	Latent Heat (kJ/kg)	Density (kg/m^3)	Thermal Conductivity (W/mK)	Ref.
Organic PCM					
Paraffin-wax	28.2	245	775 (liquid) 814 (solid)	0.149 (liquid) 0.35 (solid)	[61]
Paraffin wax	38-43	147	760 (liquid) 899 (solid)	0.2	[68]
Paraffin wax (C_{16}-C_{18})	20-22	152			[7]
Capric Acid	30-32	152-158	888 (liquid) 1018 (solid)	0.153 (liquid) 0.372 (solid)	[11, 61]
n-Eicosane	36-38	247.3	780 (liquid) 815 (solid)	0.15 (liquid) 0.39 (solid)	[11, 64]
Poly-Ethylene Glycol, PEG 800.	18.3	151			[13]
Poly-Ethylene Glycol, PEG 1000.	43	129.3			[13]
RT35 (RUBITHERM®)	32-38	160	770 (liquid) 860 (solid)	0.18 (liquid) 0.19 (solid)	[63]
RT25 (RUBITHERM®)	22-26	230	770 (liquid) 880 (solid)	0.18 (liquid) 0.19 (solid)	[61]
Glycerin	17.9	199			[7, 11]
Hexadecane	18	236			[11]
Coconut oil	27	82.3		1.33	[5]
Dodecanol	23.4	206			[5]
Inorganic PCM					

$LiNO_3\ 3H_2O$	30	189	[5]
KF_4H_2O	18.5	231	[5]
$Mn(NO_3)_2\ 6H_2O$	25.8	126	[5]
$LiBr_2{\cdot}2H_2O$	34	124	[5]
$CaCl_2{\cdot}6H_2O$	29-30	171-192	[5]

3. Thermally Efficient Windows and Facades

Windows and facades are the building's transparent elements, establishing the visual contact between the indoor and external ambient. They permit natural lighting and ventilation, which are essential for the thermal and optical comfort of the occupants. However, these elements help the penetration of incident solar radiation in refrigerated ambient and allow heat loss to the outdoor side of heated ambient, provoking excessive cooling and heating loads and increasing energy consumption of the building besides impacting both thermal and visual comfort. Since transparent windows and façades are essential for formation, means must be provided to reduce their negative impacts. The literature review shows an expressive number of studies to produce products that satisfy the requirements of the building sector. Available fenestration technologies include double- and triple-pane windows, gas-filled window systems, vacuum glazing, low-emissivity coatings, solar control films, photochromic glass, smart windows, and aerogel-granule-filled windows. In this part of the present review, the authors reviewed windows with solar films, vacuum glazing and application in windows, windows with multiple panes and filling materials such as PCM inert gases, absorbing gases, etc., windows with aerogel and other thermally efficient facades and windows.

3.1 Windows with Solar Films

Solar control film is a self-adhesive thin film that can be applied to existing buildings' glazing systems for retrofitting purposes to modify the thermal and optical properties of the glass substrate. Intercalating membranes of different materials manufacture these films in a specific arrangement [104]. Their application on glazing systems can reduce the heat gain, annual energy consumption and peak demand load. On the other hand, Low-emissivity (low-e) materials can reduce energy consumption in both opaque and transparent building areas due to the reduction of heat transfer through thermal radiation.

Al-Taqi et al. [104] studied the cost-effectiveness of solar control films retrofitted in residential clear glass windows. They concluded that the solar film improved the thermal comfort, reducing the peak cooling and power demand by 6.7% and 4.7%, respectively. Xamán et al. [105] conducted a numerical study on double glass windows with a solar control film for use in cold and warm climates. They found that the film can reduce heat gain by about 52% in hot climates. Li et al. [106] reported the results of a study to evaluate the effects of window films on the energy consumption of buildings. The results showed that the thermal performance of films on clear glass is better than on colored glass and has significant energy-saving potential in office applications.

Jelle et al. [107] reviewed low-e materials and their possible implementations and benefits in buildings. Teixeira et al. [108] conducted a study to assess the thermal and visual comforts, energy, and environmental performance of different types of solar control films. The results showed that when seeking thermal and visual comfort reflective films are most preferred. Spectrally selective films are used when seeking energy cost saving and CO2 emission reduction. Pereira et al. [109] conducted an experimental study to analyze the impact of solar control films on the indoor luminance and its distribution. The results indicated that solar control films reduced indoor glow and visual discomfort.

Kirankumar et al. [110] conducted a study on reflective windows for application in buildings to control the total solar heat gains. The double glass window composed of grey reflective glass-10 mm air gap - gold reflective glass is found to have the best thermal performance, the highest annual cost savings, and the lowest payback period of 1.42 years. Yi et al. [111] investigated transparent radiative cooling film for energy saving in buildings with roof glazing. The radiative cooling film has low transmittance in solar spectra and selectively high emissivity in the atmospheric window. The results showed good summer performance, acceptable winter cooling, and air conditioning annual savings of about 40.9%-63.4%. Pereira et al. [112] reviewed the performance of solar control films applied to glazing systems. They covered analytical and computer simulation approaches, film systems, climatic conditions, energy savings, and visual and thermal comfort performance.

3.1.1 Authors' Comments

Solar control films effectively reduce solar radiation penetrating glass windows, promoting thermal comfort, and reducing energy consumption. Although low-emissivity is accepted and has a proven effect on energy efficiency and reduction of energy consumption, there is some concern about ageing effects on their performa. Hence, it needs more investigation and long-duration tests.

3.2 Vacuum Glazing

Vacuum glazing (VG) consists of two glass panes, and the gap in between is evacuated, spacers are arranged in the gap, and the edge is sealed. Vacuum glazing has a low heat loss and high visible transmittance. Besides reducing thermal convection between the glass sheets, using appropriate coatings and spacer pillar and seals can reduce radiation and conduction across the vacuum glazing. Collins et al. [113] presented the results of pioneer work on vacuum glazing where the thermal conductance was reduced to 0.90 $Wm^{-2}K^{-1}$, the internal vacuum was stabilized for long periods of time, the mechanical and thermal stresses were dominated, and production costs were reduced.

Fang et al. [114] investigated both experimentally and numerically the effects of low emissivity coatings on the thermal performance of vacuum glazing. The authors reported good agreement and thermal performance when using one low emissivity coating. Fang et al. [115] simulated the thermal performance of triple vacuum glazing (TVG) with one to four internal glass surfaces coated with a low-E coating. The simulation results show that decreasing the emittance of the four low-E coatings from 0.18 to 0.03 reduces the heat transmission *U*-values at the centre-of-glazing area from 0.41 W m^{-2} K^{-1} to 0.22 W m^{-2} K^{-1}. It was found that setting one low-E coating in both vacuum gaps is better than setting two coatings in the same vacuum gap. Cuce and Cuce [116] reviewed vacuum glazing technology, research, developments of products, characterization, and performance. The overall heat transfer coefficient of vacuum glazing was reduced to 0.20 W/m^2K, significantly reducing the buildings contribution emissions. Yang et al. [117] developed slim and light-weight vacuum insulation, tested the product, and found that the thermal conductivity is about 0.007 W/(m·K), sufficient to improve the insulation performance. Koebe [118] reviewed the current and future materials and solutions for insulation and glazing for buildings, renewable energy generation, and storage. According to the authors, integrating these new inclusions can positively impact the energy demands of a building and reduce emissions.

Son and Song [119] investigated the heat transfer and stress distribution in the central part of vacuum glazing. The authors evaluated the stress concentration and suggested methods to reduce this effect. Pont et al. [120, 121] reported on recent advances in the construction and utilization of vacuum glazing in the window industry. Vacuum glass products have less weight and low U of about 0.2 to 0.3 $Wm^{-2}K^{-1}$, making them excellent candidates as thermally efficient windows to replace other types of windows satisfactorily.

Baek and Kim [122] conducted a study to evaluate the impact of vacuum glazing in reducing emissions from apartment buildings in Korea. The results revealed that replacing existing vacuum glazing with U-values in the range of 1.2 to 3.3 $W/m^2 \cdot K$ with U-values of 0.7 $W/m^2 \cdot K$ reduced emissions by 45%-79%. Katsura et al. [123] proposed a new structured core transparent vacuum insulation panel to eliminate the edge sealing effect, with reduced cost, and could be easily retrofitted to the conventional windows of existing buildings. The experimental and numerical analysis for the range of vacuum of 0.1 Pa to 10 Pa showed that it has lower U-values and fabrication cost.

3.2.1 Authors' Comments

Vacuum glazing is a relatively well dominated technology, considering the recent advances in edge sealing technology. Some developments are needed to reduce the manufacturing costs and make them more accessible.

3.3 Windows with Multiple Panes and Filling Materials

Windows with multiple glass panes received significant research attention and continuous development efforts to optimize the distance between the glass sheets, the number of glass sheets, energy transmitted to indoor spaces and the impact on the thermal performance of the window and quality of natural lighting, visual and thermal comfort and finally the filling material to be inserted in the gap between the glass sheets [124-128]. A summary of some of the advantages and disadvantages of each advanced inter-pane medium in real applications can be found in [124]. Other studies were conducted to improve the thermal performance of multi-pane windows by using filling materials such as absorbing gases, inert gases, water, and PCM, Figure 9.

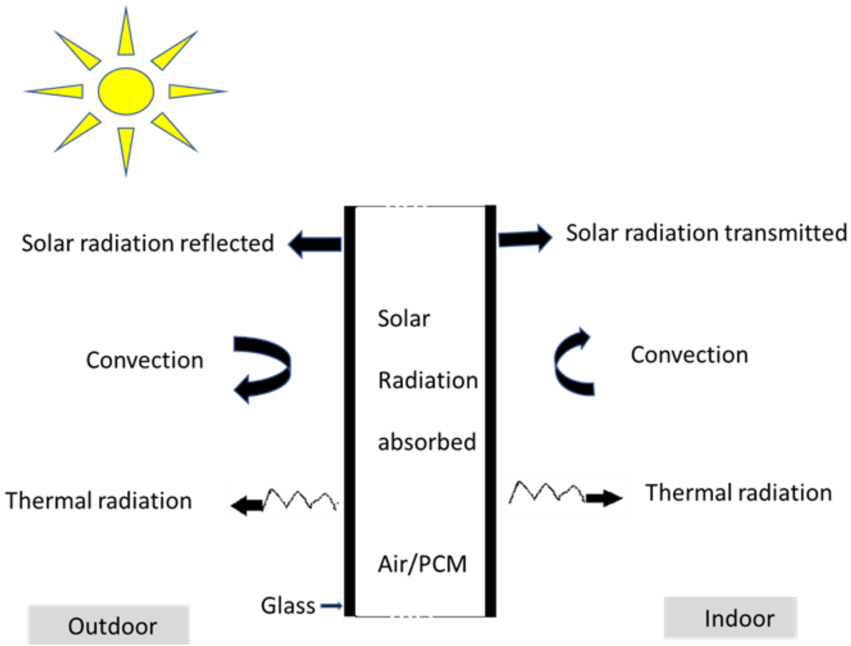

Figure 9 Window with airflow and PCM.

Zevenhoven et al. [129] conducted a radiation simulation study for a building with a double glass window with carbon dioxide as an absorbing gas to reduce heating and cooling loads. It was shown that the calculation tool was adequate for designing a double-glazed window with gas encapsulated in the gap to reduce energy needs. Ismail et al. [130] reported that of including absorbing gas or PCM in the gap between the glass sheets of a double-glass window is more effective than the ventilated double-glazed windows.

Gonzalo and Ramos [131] showed that the water flow window can reduce the ambient temperature in the summer. The authors compared the thermal performance of water flow glazing with conventional single panel and double-panel systems. The coolants showed potential benefits and savings in solar energy control. Chow and Lyu [132] investigated the effects of water flow window configurations, such as the water layer's thickness and the glass's height-width ratio. Li and Chow [133] used a reflective coating on water flow windows and achieved an annual reduction in the cooling load of about 22-35%.

PCM inserted in the gap in a double glass window was investigated extensively in the literature. The optical and thermal properties of PCM are key elements for the effective operation of the concept. Other relevant parameters as the thickness of the PCM gap and dyed PCM, were also investigated and the results were reported in the literature [134-137]. The heat transfer process across the PCM window was also modeled and the predictions were compared with experimental results [138-140]. Li and collaborators [141-145] researched PCM windows and glass roofs and investigated the effects of PCM melting temperature and layer thickness in glazed roofs. The results showed a remarkable reduction of energy consumption of about 47.5%. Double glass windows with PCM were evaluated individually as in [146-148] and integrated with other window technologies as in [88, 149]

Yang et al. [150] conducted an experimental investigation on the photothermal performance of plastic greenhouses integrating PTEs. The integration of PTEs requires an evaluation between the different melting temperatures of PCM (PW-18#, PW-25#, PW-28#) and seasons (transition, autumn, winter) for a rationally designed plastic greenhouse. The results show plastic greenhouses with PTEs substantially tune thermal energy storage/release and attenuate indoor daylight. Ma et al. [151] proposed an innovative glazing window integrated with solid-solid phase change material and silica aerogel. They conducted a parametric study focused on evaluating the innovative window's implementation potential in China's severe cold region. The results show that the phase change thermal and optical material properties are significantly relevant to the energy performance of the buildings within 10% property variations. Compared to the 4 mm single glazing window installed, the maximum energy saving of the building with the innovative window is about 18.22%. Moreover, to provide the full possibility of energy saving under the premise of meeting the daylighting design standards in China, the thickness of silica aerogel is recommended to be 10 mm in the innovative window.

Yang et al. [152] conducted an experimental and numerical investigation to study the photothermal properties of the paraffin-incorporated ZnO or CuO nanoparticles and analyze the effect of nanoparticles on the thermophysical and optical properties of nano-enhanced paraffin. The results show that due to the presence of the nanoparticles, the transmittance of nano-enhanced paraffin decreases. On the other hand, temperature increment results in a slight rise in the transmittance of nano-enhanced paraffin. The results also indicate that the utilized nanoparticles exhibit a higher attenuation to light, and the scattering effect cannot be avoided, about 6.3%. Improvements of 5.87 and 13.12% in thermal conductivity of nano-enhanced paraffin at the volume fraction of 5×10^{-4} vol% are obtained.

Li et al. [153] reviewed the experimental and simulation research on the optical and thermal performance of glazing units containing PCM. They discussed the employed research methods, mathematical models and important conclusions drawn. Finally, the challenges and future works of glazing units containing PCM were addressed.

Li et al. [154] provided an overview of research advances in optical transmittance, thermal resistance, thermal inertia, and photo-thermal transmittance in glazing envelopes, with a special focus on integrating phase change materials. The study reveals that measurement and numerical models are inadequate to study photo-thermal transmission. Besides, it is identified that there is a research gap in the acoustic performance of glazing systems incorporating phase change materials, and there is a lack of database on the optical properties of phase change materials containing nanoparticles.

Li et al. [155] proposed an innovative roof based on SA-PCM glazing systems in which the original PCM layer is divided into five cavities for filling PCM and air. They developed a numerical model to investigate the thermal performance and energy efficiency of the new roof. The thermal performance of the innovative roof top is evaluated by the indicators of temperature decrement factor and temperature time lag. At the same time, the energy efficiency is evaluated by the total heat loss through the inner surface of the innovative roof. The results show that the thermal performance of the innovative roof is improved with the addition of PCM. Besides, the innovative roof's transmittance and absorptance change significantly along with the PCM fill ratio, while the change in reflectance is slight. Additionally, the optimal energy performance of the innovative roof occurs at an 80% fill ratio of PCM, in which the total heat loss and the energy saving rate account for 2595 $kJ/m^2 \cdot d^{-1}$ and 11.37%, respectively.

Zhang et al. [156] proposed an innovative reversible multiple-glazing roof integrated with two PCM, silica aerogel and low-e glass and a numerical study was performed to explore its thermal performance in cold climates. The new roof with and without Low-E glass were investigated and compared with the traditional air-filled multiple-glazing roof. The results indicate that the unique glazed roof can provide excellent thermal performance in both summer and winter and has economic feasibility. Taking the traditional roof as a reference, the energy saving rate can achieve 14.08% in summer and 33.74% in winter.

3.3.1 Authors' Comments

Irrespective of the tremendous amount of published results on windows with PCM, windows with water flow the building construction market did not absorb yet these technologies. Further development and accurate full-scale and long-duration tests are needed. New PCMs are needed to be highly translucent to insert in double glass windows. On the other hand, windows with gas insertion are in use and have proved to be effective in reducing heat gain and improving the thermal performance of windows.

3.4 Windows with Aerogel

Aerogels have high porosity and low density, considered super-insulating materials due to their low thermal conductivity and high transmittance of solar energy and daylight, making them adequate candidates for application in energy-efficient windows as in Figure 10. The exterior aerogel layer can provide super-insulation with a relatively low thermal conductivity at 0.018 W/(mK). The daytime solar radiation charges the interior PCM layer, and then the stored energy is discharged during the nighttime to maintain thermal comfort.

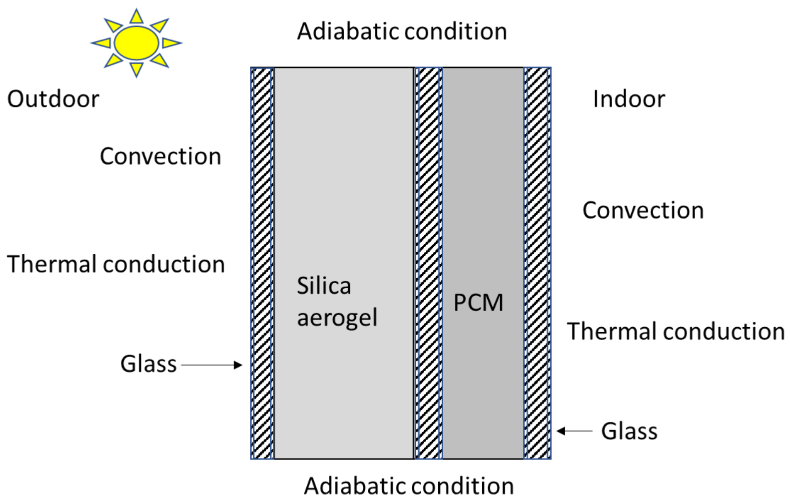

Figure 10 Integration of PCM and silica aerogel in windows.

Cotana et al. [157] conducted field experiments to evaluate the thermal, acoustic, and lighting performance of glazing systems with aerogel. The results showed that aerogel decreases heating energy consumption by about 50%, increases the façade acoustic insulation index by 3 dB and reduces the daily average luminance level by about 10%. Ihara et al. [158] evaluated the energy performance of aerogel granulate glazing system for the office façade. The results indicate that the glazing facade can achieve lower energy demand than a double-glazing facade in hot climates.

Huang and Niu [159] proposed silica-aerogel-filled super-insulating glazing system for a commercial building. They analyzed the project using EnergyPlus and Radiance computer programs. The results indicate that the silica aerogel glazing could retain a 4% longer thermal comfort period than conventional single clear glazing and reduce the energy consumption of the HVAC system by 4-7%.

Garnier et al. [160] conducted a numerical study on aerogel window and an Argon-filled coated double-glazing window, compared the results, and found that the aerogel window showed a low heat-loss coefficient of 0.3 W/m^2K. In comparison, the Argon filled-window showed a U-value of 1.4 W/m^2K. The daylight transmission of the aerogel window was significantly lower. Gao et al. [161] presented the results of a study to evaluate the different approaches for integrating aerogel glazings in the building industry, including quantifying the advantages and suggestions to cope with possible difficulties and problems. Buratti et al. [162] reviewed aerogel glazing systems focused on building applications. The authors presented the thermal and optical properties affecting energy and lighting performance of buildings, numerical and field studies, and costs of aerogel glazing. Zhang et al. [88] investigated numerically the energy performance of ten different glazing configurations in the severe cold climate of China. The thermal behavior of the glass windows filled with silica aerogel or PCM was analyzed and compared with traditional glass windows filled with air. The silica aerogel and a PCM in triple pane windows improve thermal comfort. Ganobjak et al. [163] developed and characterized a novel modular, translucent and thermally insulating building component based on silica aerogel granules called the aerogel glass brick. Both thermal and mechanical properties were tested and agreed with the available results.

3.4.1 Authors' Comments

Application of aerogels in facades suffers from a lack of transparency and scattering effect, limiting their use. There is a need for additional research efforts to improve the optical properties of aerogel, especially transparency. Long-term performance and possible decrease of silica aerogel's thermal and optical properties with aging must also be investigated.

3.5 Smart Facades and Windows

Translucent facades play a fundamental role in contemporary architecture, providing an aesthetic appearance and natural lighting. This type of facade allows the entry of natural light into indoor spaces and reduces reliance on artificial lighting. Using translucent materials or specialized glass panels, these facades filter direct sunlight, avoiding excessive glare in conventional glass windows and creating a uniform distribution of light inside buildings. This reduces energy consumption related to lighting and improves the quality of the indoor environment, promoting greater visual comfort for occupants [164, 165]. However, large glazed areas increase the thermal load and energy losses. Several technological solutions address aesthetic concerns, using natural lighting, and reducing the thermal load on the interior side or energy losses to the outdoor environment. Figure 11 shows some of these window systems' respective overall heat transfer coefficients (U-values). The U-value is used to characterize the thermal performance of these systems [166].

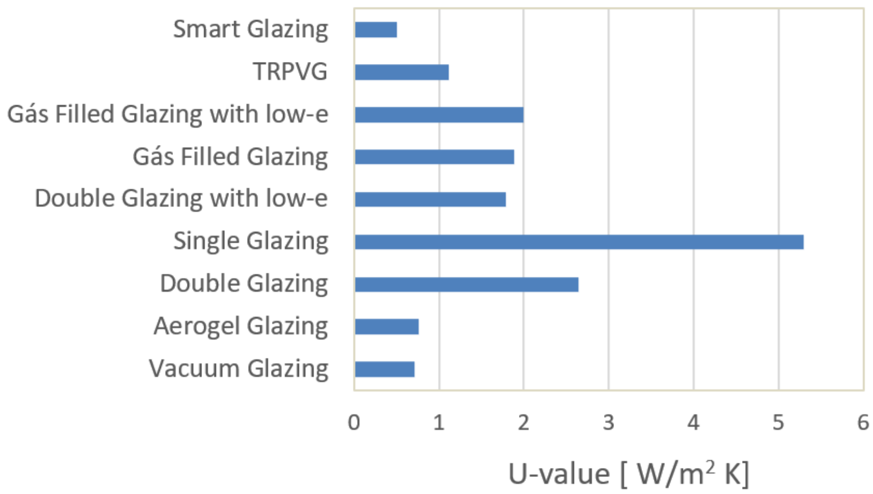

Figure 11 U-values for different glazing system technologies. Adapted from Akram et al. [167].

The Solar Heat Gain Coefficient (SHGC) is another parameter that characterizes glass windows. This parameter represents the fraction of solar radiation entering the indoor environment through a window in the form of heat [168]. The SHGC value ranges from 0 to 1; the lower the value, the less thermal energy is transferred to the interior of the building. Conventional window glass typically has a high SHGC value, ranging from approximately 0.85 to 0.90, depending on the thickness [169]. U-values below 2 and an SHGC coefficient greater than 0.6 are recommended in cold climates where heating is required inside buildings. In temperate climates, the suggested values are U-values below 2.5 and an SHGC greater than 0.5, whereas in hot climates with dominant cooling loads, the U-value should be below 4, and the SHGC should be below 0.4 [169].

Smart glazing is a technology that dynamically controls the passage of incident solar radiation by adjusting the optical properties of the material, resulting in a surface that can change from transparent to opaque or vice versa, depending on the application or requirement. Electrochromic smart glazing consists of multilayer electrochemical cells activated by electric current [170]. Lee et al. [171] investigated the most relevant control parameters for electrochromic glass under different weather conditions and window orientations. Their results indicated that monitoring the external ambient temperature is the most effective control parameter for achieving higher energy efficiency.

Additionally, smart glazing can be activated passively by temperature change and is then referred to as thermochromic glass [172, 173] or by light intensity and is referred to as photochromic glass [172, 174].

At low temperatures, thermochromic glass exhibits high transmittance in the visible region, which decreases significantly as the temperature increases. Thus, defining the transition temperature between the opaque and translucent glass is vital for designing and using thermochromic windows in buildings under different climatic conditions [173, 175]. Tällberg et al. [172] conducted a comparative energy evaluation study of smart glazing technologies used in three locations (Nairobi, Kenya; Madrid, Spain; and Trondheim, Norway). The study was conducted through numerical simulations on commercially available thermochromic, electrochromic, and photochromic systems. The study confirms that this type of technology has a greater impact on the energy performance of buildings in hot climates. Based on data from [172],

Figure 12 was prepared to show the average Solar Heat Gain Coefficient (SHGC) values for different innovative glazing technologies.

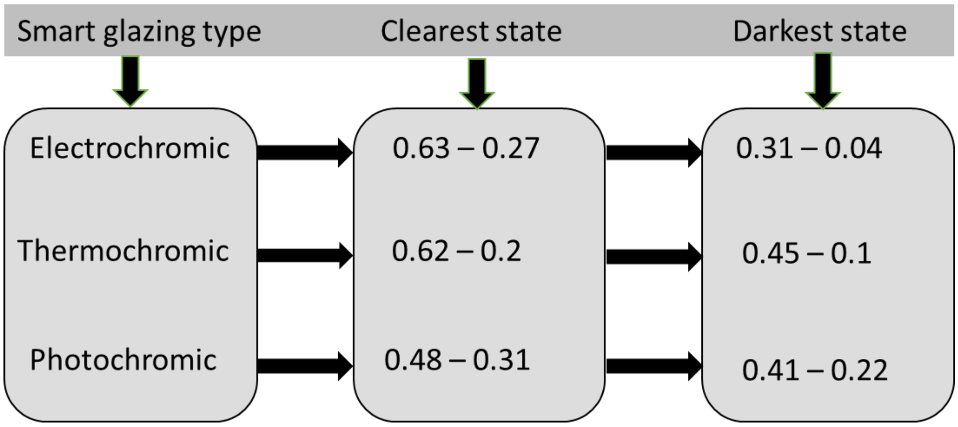

Figure 12 Solar heat gain coefficient (SHGC) for different smart glazing.

The integration of semi-transparent photovoltaic (PV) cells into building windows is an innovative solution that combines the functionality of a window (allowing natural light to pass through) with the ability to generate electricity by converting a portion of incident light [167]. Integration has been evaluated using different window technologies, such as in the work of [176] which integrated PV cells into vacuum glazing using three distinct configurations and applied these configurations to a skylight system. PV cells occupy only a fraction of the window area, allowing light to penetrate the building interior. Li et al. [177] analyzed a gas-filled glazing system with integrated PV cells in the front panel of the window. One disadvantage of generating energy through these systems is associated with shading caused by the building itself and neighboring buildings, which reduces the energy generation efficiency of the photovoltaic system [178].

Over time, various solutions have been presented as static techniques for the thermal control of glazed facades. These are more established alternatives than advanced dynamic intelligent glazing systems or the integration of PV into windows, which are still under development. Double-glazed evacuated windows or windows filled with thermally insulating materials such as aerogels and gases such as air, argon, krypton, and xenon are options [116, 169, 179, 180]. In addition to these technologies, low-e coated glass panels have been widely employed commercially. They are still under study, considering research on new nanotechnological materials or new deposition techniques [181-183]. The solar heat gain coefficient values for different types of glazed facades based on static thermal control techniques can be found in [184].

Sbar et al. [185] commented that using smart windows is fundamental in reducing energy in buildings, preserving visibility, and increasing the comfort and productivity of those working inside the building. Deforest et al. [186] used EnergyPlus to simulate the annual energy performance of double-band electrochromic glazing in three types of buildings and 16 climatic regions of the U.S. They showed the economic potentials of double-band electrochromic glass to a conventional electrochromic glass including windows compatible with the ASHRAE 90-2010 standard.

Sibilio et al. [187] provided a review f the products available on the market and studies on full scale electrochromic windows, optical, thermal, and electrical characteristics, theoretical studie, and developed models. Aoul et al. [188] reviewed electrochromic glazing, types and properties, energy, and costs. The findings indicate that electrochromic glazing can reduce electricity demand by 7-8% for average size windows and achieve savings of 6 to 11% and 8 to 15% for commercial and residential buildings, respectively. Cannavale et al. [189] presented a review on smart electrochromic windows and their influence in enhancing building energy efficiency, visual comfort and reducing emissions. Brzezicki [190] provided a review of recent technological innovations in the field of smart windows and presented the recently established functionalities and recent general progress in electrochromic windows.

3.5.1 Authors' Comments

Smart windows are fundamental in reducing energy in buildings, preserving visibility, reducing emissions, and increasing the comfort and productivity of those working inside the building. The literature indicates that electrochromic glazing can reduce electricity demand by 7-8% for average size windows and achieve savings of 6 to 11% and 8 to 15% for commercial and residential buildings, respectively. There is a need to reduce costs to expand its utilization in the building industry.

4. Energy Saving Solutions for Walls and Roofs

Walls and roofs are essential components of building envelopes, which should act as barriers against excessive energy consumption and maintain thermal comfort. The energy consumption for heating and cooling of buildings is directly related to the thermal properties of the materials used in their construction. The technological solutions for energy savings involving walls and roofs include cool roofs-walls, green roofs-walls, PCM in walls and roofs, and ventilated walls and roofs.

4.1 Cool Roof and Cool Walls

The main feature of cool roofs and walls is that they have selective surfaces that enable them to absorb less heat and remain cool when exposed to solar radiation. This behavior is directly related to the surface's high reflectivity and low absorptivity at the spectral wavelength of solar radiation. Emissivity also plays a fundamental role in the behavior of cool surfaces if it has a high value in the long-wave infrared spectrum [191, 192].

The surface fraction occupied by roofs in urban areas is approximately 20-40% of the total area, according to the technical literature [193], which, together with the condition of conventional roofs and low-albedo pavements, causes a concentration of thermal energy that increases the local temperature above average. This condition contributes to forming the phenomenon known as heat islands [194]. Several studies have analyzed and identified the causes and solutions to this phenomenon [195-198]. In addition to the positive effects on energy savings in buildings, cool roofs also contribute to reducing the formation of heat islands in urban areas [196]. However, one of the negative aspects of high-albedo roofs is that they can cause visual discomfort in cities due to excessive brightness caused by high reflectivity.

Cool walls and roofs can be obtained by using or applying various materials on their surfaces. The literature reports the use of multiple materials, such as bright white selective paints, elastomeric, polyurethane, or acrylic coatings, metallic-colored asphalt membranes, and ceramic-based cool tiles, whose emissivity is naturally high (0.85-0.93) [193, 195]. Hernández-Pérez et al. [199]

presented a review on the application of reflective materials on buildings' walls and roof. The thermal performance of these materials has been analyzed using different methodologies including computational fluid dynamics, building simulation, monitored buildings, calibrated simulation, and mesoscale modeling, among others. The results obtained including the main characteristics of the models and the optical properties of the standard and cool materials. The urban overheating, driven by the increasing expansion of our cities and the global climate change, is becoming one of the main environmental challenges of today. Consequently, cooling technologies are emerging as mitigation and adaptation strategies. Reflective roof and pavement surfaces have been widely studied for their potential benefits, but detailed evaluations of the effect of wall albedo on the urban microclimate are limited [200]. The authors addressed this gap by evaluating the effects of reflective walls on urban energy use and outdoor climate.

The accumulation of dust on cool roofs causes a reduction in albedo, which deteriorates cooling capacity. However, a predictive maintenance process involving the cleaning and renewing the selective paint layer can restore the maximum cooling potential [196].

Sameera et al. [201] synthesized nanostructured zinc aluminate ($ZnAl_2O_4$) pigments and investigated their applicability in cool roofs. Tests were conducted on a bare concrete slab and a concrete slab coated with TiO_2. The results showed a total solar reflectance value of 0.89, compared to the value of 0.87 obtained with the TiO_2-coated slab and the importance of 0.27 of the bare concrete sample.

In a recent study, [202] classified green roofs based on their surface reflectance and emissivity levels. According to the authors, conventional cool roofs have a solar reflectance of 0.7 to 0.94 and an infrared emissivity of 0.75 to 1.0. Super cool roofs are those with a reflectance of 0.95 to 1.0 and emissivity of 0.95 to 1.0. Temperature-adaptive tops are those whose color can change with temperature and adapt to environmental conditions. In regions with hot summers, it is desirable to have surfaces with high reflectivity, whereas in cold winters, the opposite is true. This is possible with thermochromic innovative materials [203]. Perez et al. [204] presented two enhanced methodologies for characterizing thermochromic materials for building facades. Fabiani et al. [205] presented a study involving the experimental characterization of a thermochromic material that changes from black to translucent at a transition temperature of 303 K. The authors formulated an analytical model to simulate the problem, and the numerical predictions were validated with experimental data.

4.2 Green Walls and Roof

Green walls and roofs gained popularity in recent years as a way to improve the sustainability of buildings and mitigate the negative impacts of urbanization. One of the benefits of this concept is the reduction in energy consumption for cooling and heating, improvement in indoor air quality [206], carbon sequestration [207, 208], and mitigation of urban heat island effects [196]. In addition, they can increase the aesthetic aspect of buildings and promote the mental health and well-being of the occupants. Shafique et al. [209] discussed green roofs' social, environmental, and economic benefits.

Green walls involve vegetation to cover the external or internal walls of buildings, while green roofs involve the use of vegetation to cover the top of a building. Green roofs consist of several layers, which should include vegetation, a substrate, a filtering layer, drainage material, insulation, a root barrier, and a waterproof membrane in contact with the base (Figure 13, adapted from [209]). It is essential to select plants with root systems compatible with the substrate layers used in each application.

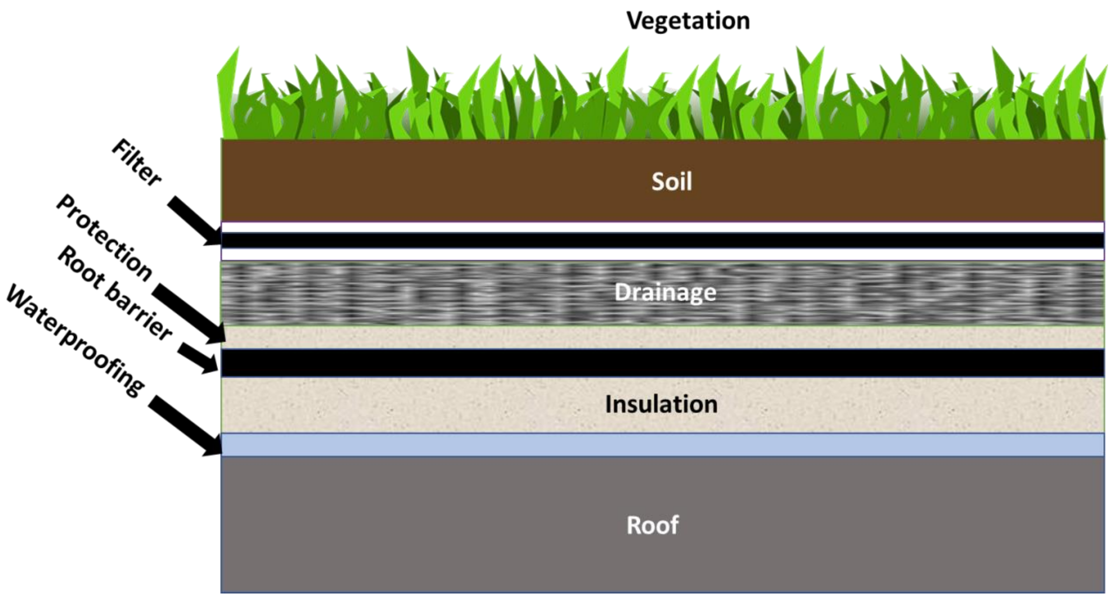

Figure 13 Typical components of a green roof.

Blue-green roofs (BGRs) represent an advancement about green roofs due to their greater capacity for rainwater retention. This is possible because their construction method involves an additional layer for water storage (blue layer) at the base of the roof [206].

The impact of green roofs on carbon sequestration occurs indirectly because of the reduction in energy consumption for heating and cooling in buildings and directly through vegetation and substrate. Shafique et al. [208] reported average values of direct carbon sequestration that vary between 1.22 kg CO_2/m^2 per year and 1.89 kg CO_2/m^2. Charoenkit and Yiemwattana [207] analyzed the role of plants in a green wall on carbon sequestration and thermal performance in a tropical climate region. Wang et al. [196] conducted a comparative evaluation of the effect of green roofs and cool roofs on human comfort. The study was conducted in Berlin, and the results indicate that both solutions improve urban thermal comfort. Cool roofs showed a greater Universal Thermal Climate Index reduction than green roofs at night.

Yasdani and Baneshi [210] also conducted a numerical comparative study between green roof and cool roof, which is thermochromatic and can have different reflectance values. Green roofs are the best option in hot and humid climates, whereas thermochromatic roofs have an advantage for hot summer and cold winter regions. Compared with the conventional concrete roof, the annual energy demand reduction can vary from 21% to 66% with green roofs and from 22% to 35% with thermochromatic roofs.

In an experimental study conducted in an urban area of Belgrade, Serbia, the use of a green roof on a school building during the summer was analyzed [211]. The results showed that the vegetative cover on the roof reduced the temperature fluctuations inside the building and helped to reduce the heat flux by 57%.

The behavior of green roofs in a single-story residential building in three locations was studied by [212]. The annual energy performance was investigated based on calculating thermal loads and air-conditioning consumption. In all three areas, the green roof effectively reduced energy consumption.

In an experimental study conducted by [213] in Vancouver, Canada, three test modules were analyzed, one of which was a green roof, the second a conventional roof, and the third a green roof without vegetation. The results confirm the reduction in temperature fluctuations and lower peak temperatures in the lower layers of the top. The results also showed more excellent rainwater retention by the vegetative cover, allowing for better water management.

Ávila-Hernandez et al. [214] analyzed the benefits of green infrastructure (walls and roofs), such as energy and temperature reduction, carbon dioxide sequestration, and optical properties of leaves and highlighted regulations and laws related to green infrastructure in Mexico.

4.3 Walls and Roofs with PCM

Phase change material walls and roofs are a building envelope that incorporates materials capable of absorbing and releasing thermal energy during phase transitions [215-217]. In addition to the storage of thermal energy through latent heat, a portion of the stored energy occurs through sensible heat in both the phase change material and the walls and roofs. With objectives similar to the other techniques, PCM walls and roofs can be designed to regulate indoor temperatures and reduce energy consumption for heating and cooling (Figure 14).

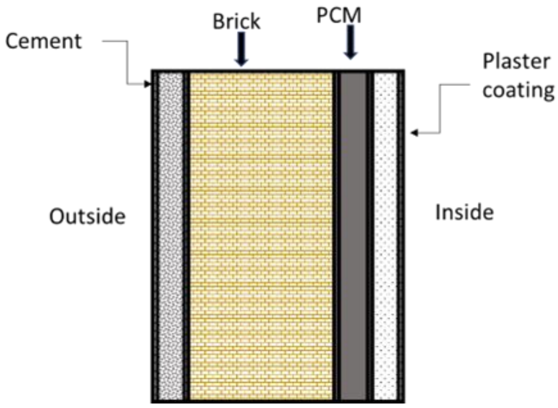

Figure 14 PCM incorporated in a brick wall.

Studies have shown that PCM walls and roofs can reduce the energy consumption for cooling by up to 50% and heating by up to 25%, as well as improve indoor thermal comfort [216, 218, 219]. However, the cost of PCM materials and their installation can hinder their widespread adoption.

Several techniques can be used to incorporate phase change material (PCM) into walls and roofs. Some of these techniques involve macro encapsulation of the PCM and incorporation of capsules into the building material [76, 220-222]. Another interesting, simple, and cost-effective method is directly incorporating PCM into building materials (such as mortar, plaster, or concrete) during preparation. However, this can present problems and challenges concerning PCM leakage and mechanical properties [223]. Another alternative is the micro-encapsulation of PCM and its incorporation into mortar or coatings, paints, or additives that can be applied directly to the surfaces of walls and roofs [224-226]. Finally, inserting layers of PCM interspersed within the structure of roofs as an insulating layer is a widely explored technique [215, 216].

The phase change materials used in walls and roofs are typically the same as those used in latent heat thermal energy storage processes. To achieve thermal comfort, the phase-change temperature should be 10-30°C, considering applications in both hot and cold climates [215, 227].

4.4 Ventilated Walls and Roofs

Ventilated walls and roofs are building envelope systems that allow air circulation between the outer cladding and the insulation layer. This air movement provides benefits, such as increased thermal insulation, improved air quality, and reduced moisture buildup. Ventilated walls and roofs have been widely used in warm and humid climates to mitigate the effects of heat gain and moisture accumulation. Contrastingly, ventilated systems can improve insulation and reduce energy losses to the outside in colder climates. In both cases, using ventilated walls and roofs provides an opportunity to increase the energy efficiency and sustainability of buildings.

Various configurations for ventilated walls and roofs that depend on the cooling or heating needs as well as other specific project conditions. Figure 15 shows some basic configurations of the ventilated walls and roofs. The schemes in Figures 15a and 15b can be used for natural cooling processes in hot climates, whereas the method in Figure 15c is suitable for passive heating in cold temperatures. Airflow can be naturally induced by buoyancy forces or forced by a pumping system. In the case of roofs, an additional covering above the conventional roof forms a channel for air passage, which can passively flow if the top is inclined (Figure 15e) or needs to be forced if the roof is flat (Figure 15d).

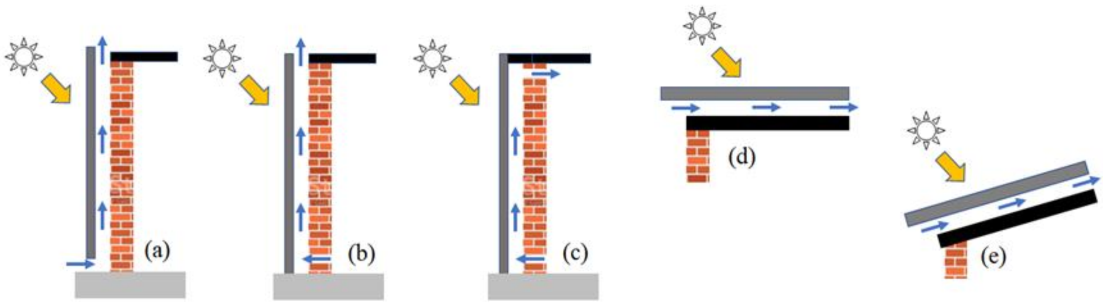

Figure 15 Basic schematic representations of ventilated walls and roofs.

In a study involving experimental and numerical methodologies, Rahiminejad and Khovalyg [228] they analyzed the thermal resistance of ventilated walls. Walls with passive and active facades were compared, with the airflow region positioned between the facade and the structural part of the wall. According to the results, the ventilated cavity acts as an insulation layer with a higher thermal resistance than some of the solid materials used in wall assemblies. In a long-term study conducted in a real-scale test facility, the same authors [229], analyzed the impact of varying external conditions, facade orientation, and wall thermal inertia on the airflow velocity in the cavity. They found that the thermal resistance of the ventilated cavity varies dynamically and is generally higher in the summer than in the winter. In addition, the potential heat flow collected from the ventilated cavity reached 158 kWh/month, offering an additional energy source for buildings.

The combination of a solar chimney and a ventilated wall was studied by [230]. One benefit of this system is that it improves building ventilation and reduces energy consumption. A theoretical model was used to predict the airflow rates through wall and roof solar chimneys. The advantages of the combined systems were highlighted, along with the need for further research on their integration and application.

Other fundamental aspects analyzed include moisture transfer and acoustic, structural, and durability behaviors. Borodulin and Nizovtsev [231] presented a mathematical model to calculate heat and moisture transfer in ventilated facades. The model was applied to a long-term study and focused on a specific type of façade system and climate. De Masi et al. [232], in a long-term study in a Mediterranean environment, reported that ventilated facades are a solution to control the moisture content of building envelope materials, ensuring a healthy environment and preventing structural damage. Their results indicated that wall ventilation did not increase heat losses in winter for a humid and rainy climate. Colombo et al. [233] evaluated new panels' durability and thermal performance for use in ventilated walls. The tests were conducted in an experimental facility and the samples exposed to the external environment were monitored for 12 months. Accelerated tests were also conducted to determine the material's thermal expansion coefficient.

The applied studies focused on the practical implementation of technology in energy-efficient building projects and evaluating their performance under natural conditions. The assessment of buildings in different states and climatic regions, long-term monitoring, and the application and development of standards and regulations are some topics included in the range of reported works. Pujadas-Gispert et al. [234] reported on the design and thermal performance analysis of a ventilated facade applied to a building in Dubai. The temperature monitoring results on the front show that it contributes positively to achieving lower temperatures inside the building, particularly during the hottest hours of the day. Brozovsky et al. [235] investigated experimentally the hygrothermal performance of ventilated air spaces located on the walls and roof behind different cladding materials in a zero-energy building. The durability and performance of envelopes in buildings were analyzed with a focus on tightness, ventilation, and moisture management. The experimental study involved capturing measurements over a period of 2 years between 2020 and 2022.

4.4.1 Authors' Comments

Efficient technological solutions for energy savings in buildings include green roofs and walls, use of PCM, ventilated walls and roofs, and optically selective materials for building cool walls and ceilings. These technologies effectively reduce energy consumption for cooling and heating and can contribute to reducing the effect of heat islands in large urban centers. Table 4 gives details, based on the consulted references, of some impact of the technological solutions described in this topic on indoor air temperature and CO_2 emissions.

Table 4 Effects on indoor air temperature and CO_2 emissions.

Technology	Reduction of indoor air temperature (°C)	CO_2 emissions reduction (kg_{CO2}/m^2/year)	Ref.
Cool roof and cool walls	0.6-1.6	6-50	[192]
	0.9-4	1.31-3.68	[193]
	5.5-11.5	-	[202]
	0.2-0.5	-	[205]

Green Walls and roof	1.47-3.52	$8.7 \cdot 10^{-3}$-$6.1 \cdot 10^{-2}$	[207]
	0.2-3.98	0.313-1.89	[208]
	2.16-2.54	-	[212]
	1.3-13.7	-	[213]
Walls and roofs with PCM	0.19-2.2	-	[198]
	-	10.3-52.7	[218]
	6.4-9.9	-	[220]
	0.25-5.75	-	[221]
	0.1-1.0	-	[222]
	0.8-2.3	-	[225]
	0.8-3.42	23.3-29.9	[226]
	5.8	-	[227]
Ventilated walls and roofs	>10	-	[229]
	2.0-12.0	-	[234]

5. Conclusions

Some technological solutions for energy savings in buildings were discussed, and some significant results are highlighted below.

1. The energy consumption of buildings is significant due to heating, ventilation, and cooling systems which are affected by the thermal properties of the materials used in the construction. Hence, incorporating energy-efficient basic construction materials such as mortars, concrete and bricks into the building envelopes and components can be a valuable option.
2. PCM- mortars and concrete were thoroughly studied, and the results show that the mix has favorable thermal properties. PCM increases the thermal mass of building materials and decreases thermal cracking.
3. The use of demolition wastes as bricks and ceramics and also recycled plastics for the production of concrete and bricks incorporating PCM increases the thermal properties of the final product, makes it economically sustainable, reduces the need for fine aggregate, improves corrosion resistance and makes concrete lighter but reduces the mechanical properties.
4. Several emerging technologies are underdevelopment and can help reduce costs and energy usage in the building sectors besides reducing emissions and recycling waste. These technologies include the development of geopolymer binders that can replace Portland cement and the use of 3D printing technology in the construction of buildings.
5. This literature review reveals several strategies to reduce energy consumption and emissions in buildings while keeping thermal comfort. Among these strategies is using smart materials for walls, roofs, windows, and facades.
6. Buildings with large window areas tend to have more heat gains/losses through the glazing systems, which may cause visual and thermal discomfort and increase the cooling and heating loads. In this case, the use of solar control films, besides being less expensive, promotes thermal comfort and reduces excessive luminance and visual glare. Also, low-

emissivity coatings for glazing are widely used due to their proven effect on energy efficiency and consumption.

7. Windows with gas insertion effectively reduce heat gain and improve the thermal performance of windows, but the cost is relatively high.
8. The transparency of the aerogel and color shift due to the scattering phenomena limit the use of aerogel in windows.
9. Smart windows reduce the energy in buildings, preserves visibility, and increases the visual and thermal comfort and productivity of those working inside the building, but the cost is relatively high.
10. Some technological solutions for energy savings in buildings are focused on walls and roofs,including green roofs and walls, use of PCM in walls and roofs, ventilated walls and roofs, and optically selective materials for building cool walls and roofs.
11. Studies have shown that PCM walls and roofs can reduce the energy consumption for cooling by up to 50% and heating by up to 25%, as well as improve indoor thermal comfort.
12. The phase change materials used in walls and roofs are typically the same as those used in latent heat thermal energy storage systems. To achieve thermal comfort, the phase-change temperature should be 10-30°C, considering applications in both hot and cold climates.

6. Perspectives of Future Research and Developments

The review shows some research gaps and opportunities for the development of materials and products to make the building sector more sustainable and energy efficient. Some possible topics are listed below.

6.1 Energy Efficient Construction Materials

1. Research and development are required to reduce the cost of PCM-based construction materials to enhance their widespread application in buildings.
2. Mortars - PCM mix requires further research and developments to find materials and insertion processes that eliminate PCM leakage, eliminate possible reduction in mechanical strength, and reduce degradation with time and thermal cycling.
3. Using PCM in concrete still requires further research and development and long,long-duration tests to evaluate possible aging impacts.
4. There is a need to develop standard testing procedures for measuring the thermal properties of inhomogeneous PCM-concrete composites.
5. PCM filled bricks can provide heat modulation in energy-efficient buildings. However, some relevant issues need to be addressed, such as leakage, aging and cycling effects, and long-term tests to ensure reliability and thermal performance in full-scale tests and reduce manufacturing costs.
6. Real-time studies in buildings, annual/seasonal analysis, and techno-economic assessment need to be addressed.

6.2 Thermally Efficient Windows and Facades

1. There is a need for further research and industrial development on the ageing effects of low-e materials and products and the impacts when applied in buildings.
2. More research and development are needed to reduce the fabrication cost and improve the long-term vacuum pressure stability in the vacuum-glazed bright window.
3. Double glass window with inserted PCM or water flow needs more research to include relatively translucent PCM and investigate the change of water optical qualities with ageing and sealing degradation with time and temperature.
4. Long-term performance and possible decrease of silica aerogel's thermal and optical performance with aging.
5. The smart windows cost is too high, and research and development efforts are necessary to reduce the cost and facilitate their acquisition and utilization in standard residencies.
6. Low-e-coated glass panels are still under investigation to develop nanotechnological materials and new deposition techniques.
7. Advanced dynamic intelligent glazing systems and the integration of PV into windows require more research and development.

6.3 Energy-Saving Solutions for Walls and Roofs

1. Research is ongoing to develop cost-effective PCM materials and optimize the design and integration of PCM walls and roofs into buildings.
2. More research and developments are needed to investigate surfaces with selective coatings to obtain cold surfaces for walls and roofs.
3. Investigate the use of thermochromatic materials on walls and roofs to reduce the indoor temperature, evaluate the performance, aging effects, durability, and economic viability.

6.4 Energy Saving Solutions for Buildings Heating and Cooling

1. Bio-PCM and bio-PCM composites should be preferred and adopted as part of sustainability goals as they have a lower environmental impact than industrial products. Additionally, PCM composites can be an excellent solution to the supercooling limitation of some PCM types.
2. Characterization of bio-PCM and composites is required to provide data for accurate investigations.
3. Further and long-duration investigation on PCM integration should meet the compromise for all seasons, not only, summer/winter.
4. Long performance stability is another challenge to be addressed to ensure the viability of PCM integration into building envelopes.

Acknowledgments

The first and third authors wish to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the PQ research grant [304372/2016-1] for the first author and the PQ research grant [315265/2020-5] for the third author.

Author Contributions

KI: Conceptualization, Supervision, Review and Editing; FL: Writing original draft, Review and Editing; JH: Review and Editing; MT: Writing original draft, Review and Editing; AL: Writing original draft, Review and Editing; MA: Review and Editing; AB: Writing original draft, Editing and DR: Writing original draft, Editing.

Competing Interests

The authors have declared that no competing interests exist.

References

1. International Energy Agency. Statistics report: Key World Energy Statistics 2021. Paris, France: IEA; 2021. Available from: https://www.iea.org/reports/key-world-energy-statistics-2021.
2. Ritchie H, Roser M, Rosado P. Energy [Internet]. England and Wales, UK: Our World in Data; 2022. Available from: https://ourworldindata.org/energy.
3. United Nations Environment Programme. 2021 Global Status Report for Buildings and Construction: Towards a zero-emissions, efficient and resilient buildings and construction sector. Nairobi, Kenya: United Nations Environment Programme; 2021. Available from: https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction.
4. Marani A, Nehdi ML. Integrating phase change materials in construction materials: Critical review. Constr Build Mater. 2019; 217: 36-49.
5. Rathore PK, Shukla SK. Potential of macroencapsulated PCM for thermal energy storage in buildings: A comprehensive review. Constr Build Mater. 2019; 225: 723-744.
6. Olivieri L, Tenorio JA, Revuelta D, Navarro L, Cabeza LF. Developing a PCM-enhanced mortar for thermally active precast walls. Constr Build Mater. 2018; 181: 638-649.
7. Rao VV, Parameshwaran R, Ram VV. PCM-mortar based construction materials for energy efficient buildings: A review on research trends. Energy Build. 2018; 158: 95-122.
8. Djamai ZI, Salvatore F, Larbi AS, Cai G, El Mankibi M. Multiphysics analysis of effects of encapsulated phase change materials (PCMs) in cement mortars. Cem Concr Res. 2019; 119: 51-63.
9. Sarcinella A, De Aguiar JL, Lettieri M, Cunha S, Frigione M. Thermal performance of mortars based on different binders and containing a novel sustainable phase change material (PCM). Materials. 2020; 13: 2055.
10. Mankel C, Caggiano A, König A, Said Schicchi D, Nazari Sam M, Koenders E. Modelling the thermal energy storage of cementitious mortars made with PCM-recycled brick aggregates. Materials. 2020; 13: 1064.
11. Rathore PK, Shukla SK. Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review. Energy Build. 2021; 236: 110799.
12. Orsini F, Marrone P, Santini S, Sguerri L, Asdrubali F, Baldinelli G, et al. Smart materials: Cementitious mortars and PCM mechanical and thermal characterization. Materials. 2021; 14: 4163.

13. Sarcinella A, de Aguiar JL, Frigione M. Use of sustainable phase change material (PCM) in mortars for building energy efficiency. J Phys Conf Ser. 2022; 2385: 012009.
14. Guardia C, Barluenga G, Palomar I, Diarce G. Thermal enhanced cement-lime mortars with phase change materials (PCM), lightweight aggregate and cellulose fibers. Constr Build Mater. 2019; 221: 586-594.
15. Araghi HJ, Nikbin IM, Reskati SR, Rahmani E, Allahyari H. An experimental investigation on the erosion resistance of concrete containing various PET particles percentages against sulfuric acid attack. Constr Build Mater. 2015; 77: 461-471.
16. Rai B, Rushad ST, Kr B, Duggal SK. Study of waste plastic mix concrete with plasticizer. ISRN Civ Eng. 2012; 2012: 469272.
17. Foti D. Use of recycled waste pet bottles fibers for the reinforcement of concrete. Compos Struct. 2013; 96: 396-404.
18. Ingrao C, Giudice AL, Tricase C, Rana R, Mbohwa C, Siracusa V. Recycled-PET fibre based panels for building thermal insulation: Environmental impact and improvement potential assessment for a greener production. Sci Total Environ. 2014; 493: 914-929.
19. Schaefer CE, Kupwade Patil K, Ortega M, Soriano C, Büyüköztürk O, White AE, et al. Irradiated recycled plastic as a concrete additive for improved chemo-mechanical properties and lower carbon footprint. Waste Manage. 2018; 71: 426-439.
20. Ling IH, Teo DC. Properties of EPS RHA lightweight concrete bricks under different curing conditions. Constr Build Mater. 2011; 25: 3648-3655.
21. Zavadskas EK, Antucheviciene J, Kalibatas D, Kalibatiene D. Achieving nearly zero-energy buildings by applying multi-attribute assessment. Energy Build. 2017; 143: 162-172.
22. Memon SA, Cui H, Lo TY, Li Q. Development of structural-functional integrated concrete with macro-encapsulated PCM for thermal energy storage. Appl Energy. 2015; 150: 245-257.
23. Min HW, Kim S, Kim HS. Investigation on thermal and mechanical characteristics of concrete mixed with shape stabilized phase change material for mix design. Constr Build Mater. 2017; 149: 749-762.
24. Ricklefs A, Thiele AM, Falzone G, Sant G, Pilon L. Thermal conductivity of cementitious composites containing microencapsulated phase change materials. Int J Heat Mass Transf. 2017; 104: 71-82.
25. D'Alessandro A, Pisello AL, Fabiani C, Ubertini F, Cabeza LF, Cotana F. Multifunctional smart concretes with novel phase change materials: Mechanical and thermo-energy investigation. Appl Energy. 2018; 212: 1448-1461.
26. Essid N, Loulizi A, Neji J. Compressive strength and hygric properties of concretes incorporating microencapsulated phase change material. Constr Build Mater. 2019; 222: 254-262.
27. Mohseni E, Tang W, Wang S. Development of thermal energy storage lightweight structural cementitious composites by means of macro-encapsulated PCM. Constr Build Mater. 2019; 225: 182-195.
28. Yun HD, Ahn KL, Jang SJ, Khil BS, Park WS, Kim SW. Thermal and mechanical behaviors of concrete with incorporation of strontium-based phase change material (PCM). Int J Concr Struct Mater. 2019; 13: 18.

29. Sukontasukkul P, Uthaichotirat P, Sangpet T, Sisomphon K, Newlands M, Siripanichgorn A, et al. Thermal properties of lightweight concrete incorporating high contents of phase change materials. Constr Build Mater. 2019; 207: 431-439.
30. Sharma R, Jang JG, Hu JW. Phase-change materials in concrete: Opportunities and challenges for sustainable construction and building materials. Materials. 2022; 15: 335.
31. Rathore PK, Shukla SK. An experimental evaluation of thermal behavior of the building envelope using macroencapsulated PCM for energy savings. Renew Energ. 2020; 149: 1300-1313.
32. Lagou A, Kylili A, Šadauskienė J, Fokaides PA. Numerical investigation of phase change materials (PCM) optimal melting properties and position in building elements under diverse conditions. Constr Build Mater. 2019; 225: 452-464.
33. Mohseni E, Tang W. Parametric analysis and optimisation of energy efficiency of a lightweight building integrated with different configurations and types of PCM. Renew Energ. 2021; 168: 865-877.
34. Cao VD, Pilehvar S, Salas Bringas C, Szczotok AM, Bui TQ, Carmona M, et al. Thermal analysis of geopolymer concrete walls containing microencapsulated phase change materials for building applications. Sol Energy. 2019; 178: 295-307.
35. Al Rashed AA, Alnaqi AA, Alsarraf J. Usefulness of loading PCM into envelopes in arid climate based on Köppen-Geiger classification-Annual assessment of energy saving and GHG emission reduction. J Energy Storage. 2021; 43: 103152.
36. Cárdenas Ramírez C, Gómez MA, Jaramillo F, Cardona AF, Fernández AG, Cabeza LF. Experimental steady-state and transient thermal performance of materials for thermal energy storage in building applications: From powder SS-PCMs to SS-PCM-based acrylic plaster. Energy. 2022; 250: 123768.
37. Ding T, Xiao J, Zou S, Wang Y. Hardened properties of layered 3D printed concrete with recycled sand. Cem Concr Compos. 2020; 113: 103724.
38. Brooks AL, He Y, Farzadnia N, Seyfimakrani S, Zhou H. Incorporating PCM-enabled thermal energy storage into 3D printable cementitious composites. Cem Concr Compos. 2022; 129: 104492.
39. Shahzad Q, Shen J, Naseem R, Yao Y, Waqar S, Liu W. Influence of phase change material on concrete behavior for construction 3D printing. Constr Build Mater. 2021; 309: 125121.
40. Figueiredo A, Lapa J, Vicente R, Cardoso C. Mechanical and thermal characterization of concrete with incorporation of microencapsulated PCM for applications in thermally activated slabs. Constr Build Mater. 2016; 112: 639-647.
41. Christen H, Cho S, van Zijl G, de Villiers W. Phase change material infused recycled brick aggregate in 3D printed concrete. Heliyon. 2022; 8: e11598.
42. Hao L, Xiao J, Sun J, Xia B, Cao W. Thermal conductivity of 3D printed concrete with recycled fine aggregate composite phase change materials. J Clean Prod. 2022; 364: 132598.
43. Ryms M, Januszewicz K, Haustein E, Kazimierski P, Lewandowski WM. Thermal properties of a cement composite containing phase change materials (PCMs) with post-pyrolytic char obtained from spent tyres as a carrier. Energy. 2022; 239: 121936.
44. Das R, Gandhi IS, Muthukumar P. Use of agglomerated Micro-encapsulated phase change material in cement mortar as thermal energy storage material for buildings. Mater Today Proc. 2022; 65: 808-814.

45. Zhang J, Wang J, Dong S, Yu X, Han B. A review of the current progress and application of 3D printed concrete. Compos Part A Appl Sci Manuf. 2019; 125: 105533.
46. Zhang C, Nerella VN, Krishna A, Wang S, Zhang Y, Mechtcherine V, et al. Mix design concepts for 3D printable concrete: A review. Cem Concr Compos. 2021; 122: 104155.
47. Ahmed GH. A review of “3D concrete printing”: Materials and process characterization, economic considerations and environmental sustainability. J Build Eng. 2023; 66: 105863.
48. Alabbasi M, Agkathidis A, Chen H. Robotic 3D printing of concrete building components for residential buildings in Saudi Arabia. Autom Constr. 2023; 148: 104751.
49. Hou S, Duan Z, Xiao J, Ye J. A review of 3D printed concrete: Performance requirements, testing measurements and mix design. Constr Build Mater. 2021; 273: 121745.
50. Shadnia R, Zhang L, Li P. Experimental study of geopolymer mortar with incorporated PCM. Constr Build Mater. 2015; 84: 95-102.
51. Lecompte T, Le Bideau P, Glouannec P, Nortershauser D, Le Masson S. Mechanical and thermo-physical behaviour of concretes and mortars containing phase change material. Energy Build. 2015; 94: 52-60.
52. Asadi I, Baghban MH, Hashemi M, Izadyar N, Sajadi B. Phase change materials incorporated into geopolymer concrete for enhancing energy efficiency and sustainability of buildings: A review. Case Stud Constr Mater. 2022; 17: e01162.
53. Łach M, Pławecka K, Bąk A, Adamczyk M, Bazan P, Kozub B, et al. Review of solutions for the use of phase change materials in geopolymers. Materials. 2021; 14: 6044.
54. Haurie L, Serrano S, Bosch M, Fernandez AI, Cabeza LF. Single layer mortars with microencapsulated PCM: Study of physical and thermal properties, and fire behaviour. Energy Build. 2016; 111: 393-400.
55. Cui H, Liao W, Mi X, Lo TY, Chen D. Study on functional and mechanical properties of cement mortar with graphite-modified microencapsulated phase-change materials. Energy Build. 2015; 105: 273-284.
56. Rashid Y, Mourad AH, Hassan A. Thermally enhanced geopolymer concrete to mitigate air conditioning demand in buildings. Proceedings of the International Conference on Applied Energy 2019; 2019 Aug 12-15; Västerås, Sweden. Amsterdam, Netherlands: Elsevier.
57. Memon SA. Phase change materials integrated in building walls: A state of the art review. Renew Sustain Energy Rev. 2014; 31: 870-906.
58. Khedache S, Makhlouf S, Djefel D, Lefebvre G, Royon L. Preparation and thermal characterization of composite “Paraffin/Red Brick” as a novel form-stable of phase change material for thermal energy storage. Int J Hydrog Energy. 2015; 40: 13771-13776.
59. Wang X, Yu H, Li L, Zhao M. Experimental assessment on the use of phase change materials (PCMs)-bricks in the exterior wall of a full-scale room. Energy Convers Manag. 2016; 120: 81-89.
60. Li L, Yu H, Liu R. Research on composite-phase change materials (PCMs)-bricks in the west wall of room-scale cubicle: Mid-season and summer day cases. Build Environ. 2017; 123: 494-503.
61. Kant K, Shukla A, Sharma A. Heat transfer studies of building brick containing phase change materials. Sol Energy. 2017; 155: 1233-1242.
62. Souci OY, Houat S. Numerical study of thermos physical properties of a hollow brick filled by the PCM. J Mater Environ Sci. 2017; 8: 2213-2220.

63. Dabiri S, Mehrpooya M, Nezhad EG. Latent and sensible heat analysis of PCM incorporated in a brick for cold and hot climatic conditions, utilizing computational fluid dynamics. Energy. 2018; 159: 160-171.
64. Saxena R, Rakshit D, Kaushik SC. Phase change material (PCM) incorporated bricks for energy conservation in composite climate: A sustainable building solution. Sol Energy. 2019; 183: 276-284.
65. Tunçbilek E, Arıcı M, Bouadila S, Wonorahardjo S. Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region. J Therm Anal Calorim. 2020; 141: 613-624.
66. Azmi MI, Sidik NA, Asako Y, Japar WM, Muhammad NM, Razali N. Numerical studies on PCM phase change performance in bricks for energy-efficient building application-a review. J Adv Res Numer Heat Trans. 2020; 1: 13-21.
67. Mukram TA, Daniel J. Building bricks with PCM inserts for passive cooling applications. IOP Conf Ser Earth Environ Sci. 2020; 474: 072047.
68. Abdulhussein MA, Hashem AL. An experimental study of the thermal behavior of bricks integrated with PCM-capsules in building walls. Al-Qadisiyah J Eng Sci. 2021; 14: 160-165. Doi: 10.30772/qjes.v14i3.775.
69. Ru C, Li G, Guo F, Sun X, Yu D, Chen Z. Experimental evaluation of the properties of recycled aggregate pavement brick with a composite shaped phase change material. Materials. 2022; 15: 5565.
70. Shaik S, Arumugam C, Shaik SV, Arıcı M, Afzal A, Ma Z. Strategic design of PCM integrated burnt clay bricks: Potential for cost-cutting measures for air conditioning and carbon dioxide extenuation. J Clean Prod. 2022; 375: 134077.
71. Mabrouki A, Karim YB, Hassani HO, Jamali Y, Khaldoun A. A study of a passive heating design employing a Trombe wall with PCM: A numerical investigation of the semi-oceanic climate in Morocco. Mater Today Proc. 2023; 72: 3626-3631.
72. Devaux P, Farid MM. Benefits of PCM underfloor heating with PCM wallboards for space heating in winter. Appl Energy. 2017; 191: 593-602.
73. Jamil H, Alam M, Sanjayan J, Wilson J. Investigation of PCM as retrofitting option to enhance occupant thermal comfort in a modern residential building. Energy Build. 2016; 133: 217-229.
74. Kusama Y, Ishidoya Y. Thermal effects of a novel phase change material (PCM) plaster under different insulation and heating scenarios. Energy Build. 2017; 141: 226-237.
75. Li D, Zheng Y, Liu C, Wu G. Numerical analysis on thermal performance of roof contained PCM of a single residential building. Energy Convers Manag. 2015; 100: 147-156.
76. Abbas HM, Jalil JM, Ahmed ST. Experimental and numerical investigation of PCM capsules as insulation materials inserted into a hollow brick wall. Energy Build. 2021; 246: 111127.
77. Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy Build. 2010; 42: 534-540.
78. Zhang C, Chen Y, Wu L, Shi M. Thermal response of brick wall filled with phase change materials (PCM) under fluctuating outdoor temperatures. Energy Build. 2011; 43: 3514-3520.
79. Mehdaoui F, Hazami M, Messaouda A, Taghouti H, Guizani A. Thermal testing and numerical simulation of PCM wall integrated inside a test cell on a small scale and subjected to the thermal stresses. Renew Energy. 2019; 135: 597-607.

80. Gao Y, He F, Meng X, Wang Z, Zhang M, Yu H, et al. Thermal behavior analysis of hollow bricks filled with phase-change material (PCM). J Build Eng. 2020; 31: 101447.
81. Souayfane F, Fardoun F, Biwole PH. Phase change materials (PCM) for cooling applications in buildings: A review. Energy Build. 2016; 129: 396-431.
82. Tunçbilek E, Arıcı M, Krajčík M, Nižetić S, Karabay H. Thermal performance based optimization of an office wall containing PCM under intermittent cooling operation. Appl Therm Eng. 2020; 179: 115750.
83. Kishore RA, Bianchi MV, Booten C, Vidal J, Jackson R. Optimizing PCM-integrated walls for potential energy savings in US Buildings. Energy Build. 2020; 226: 110355.
84. Arıcı M, Bilgin F, Nižetić S, Karabay H. PCM integrated to external building walls: An optimization study on maximum activation of latent heat. Appl Therm Eng. 2020; 165: 114560.
85. Al-Absi ZA, Isa MHM, Ismail M. Phase change materials (PCMs) and their optimum position in building walls. Sustain. 2020; 12: 1294. Doi: 10.3390/su12041294.
86. Terhan M, Ilgar G. Investigation of used PCM-integrated into building exterior walls for energy savings and optimization of PCM melting temperatures. Constr Build Mater. 2023; 369: 130601.
87. Jiang W, Liu B, Zhang X, Zhang T, Li D, Ma L. Energy performance of window with PCM frame. Sustain Energy Technol Assess. 2021; 45: 101109.
88. Zhang S, Hu W, Li D, Zhang C, Arıcı M, Yıldız Ç, et al. Energy efficiency optimization of PCM and aerogel-filled multiple glazing windows. Energy. 2021; 222: 119916.
89. Guo W, Liu G, Zhang K, Jin Y, Arıcı M. Thermal performance investigation of greenhouse glazing units containing PCM with different thermophysical and optical properties. Buildings. 2023; 13: 1715.
90. Dehkordi BS, Afrand M. Energy-saving owing to using PCM into buildings: Considering of hot and cold climate region. Sustain Energy Technol Assess. 2022; 52: 102112.
91. Li Q, Wang Y, Ma L, Arıcı M, Li D, Yıldız Ç, et al. Effect of sunspace and PCM louver combination on the energy saving of rural residences: Case study in a severe cold region of China. Sustain Energy Technol Assess. 2021; 45: 101126.
92. Ma L, Luo D, Hu H, Li Q, Yang R, Zhang S, et al. Energy performance of a rural residential building with PCM-silica aerogel sunspace in severe cold regions. Energy Build. 2023; 280: 112719.
93. Caliskan H, Gurbuz H, Sohret Y, Ates D. Thermal analysis and assessment of phase change material utilization for heating applications in buildings: A modelling. J Energy Storage. 2022; 50: 104593.
94. Ahmed F, Mahmood M, Waqas A, Ahmad N, Ali M. Thermal analysis of macro-encapsulated phase change material coupled with domestic gas heater for building heating. Sustain Energy Technol Assess. 2021; 47: 101533.
95. Barzin R, Chen JJ, Young BR, Farid MM. Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system. Appl Energy. 2015; 148: 39-48.
96. Faraj K, Faraj J, Hachem F, Bazzi H, Khaled M, Castelain C. Analysis of underfloor electrical heating system integrated with coconut oil-PCM plates. Appl Therm Eng. 2019; 158: 113778.
97. Li Y, Nord N, Xiao Q, Tereshchenko T. Building heating applications with phase change material: A comprehensive review. J Energy Storage. 2020; 31: 101634.

98. Qiao X, Kong X, Fan M. Phase change material applied in solar heating for buildings: A review. J Energy Storage. 2022; 55: 105826.
99. Sun W, Zhang Y, Ling Z, Fang X, Zhang Z. Experimental investigation on the thermal performance of double-layer PCM radiant floor system containing two types of inorganic composite PCMs. Energy Build. 2020; 211: 109806.
100. Zhou G, He J. Thermal performance of a radiant floor heating system with different heat storage materials and heating pipes. Appl Energy. 2015; 138: 648-660.
101. Jin X, Yang J, Li M, Huang G, Lai AC. Experimental and numerical study on the thermal energy storage performance of a novel phase-change material for radiant floor heating systems. Build Environ. 2022; 223: 109491.
102. Xie N, Gao X, Zhong Y, Ye R, Chen S, Ding L, et al. Enhanced thermal performance of $Na_2HPO_4{\cdot}12H_2O$ composite phase change material supported by sepiolite fiber for floor radiant heating system. J Build Eng. 2022; 56: 104747.
103. Diaconu BM, Cruceru M. Novel concept of composite phase change material wall system for year-round thermal energy savings. Energy Build. 2010; 42: 1759-1772.
104. Al Taqi HH, Maheshwari GP, Alasseri R. Cost Effectiveness for Solar Control Film for Residential Applications. Proceedings of the Tenth International Conference Enhanced Building Operations; 2010 October 26-28; Kuwait. TX, US: Texas A&M University Libraries.
105. Xamán J, Pérez Nucamendi C, Arce J, Hinojosa J, Álvarez G, Zavala Guillén I. Thermal analysis for a double pane window with a solar control film for using in cold and warm climates. Energy Build. 2014; 76: 429-439.
106. Li C, Tan J, Chow TT, Qiu Z. Experimental and theoretical study on the effect of window films on building energy consumption. Energy Build. 2015; 102: 129-138.
107. Jelle BP, Kalnæs SE, Gao T. Low-emissivity materials for building applications: A state-of-the-art review and future research perspectives. Energy Build. 2015; 96: 329-356.
108. Teixeira H, Gomes MG, Rodrigues AM, Pereira J. Thermal and visual comfort, energy use and environmental performance of glazing systems with solar control films. Build Environ. 2020; 168: 106474.
109. Pereira JO, Gomes MG, Rodrigues AM, Teixeira H, Almeida M. Small-scale field study of window films' impact on daylight availability under clear sky conditions. J Facade Des Eng. 2020; 8: 65-84.
110. Kirankumar G, Saboor S, Vali SS, Mahapatra D, Setty AB, Kim KH. Thermal and cost analysis of various air filled double glazed reflective windows for energy efficient buildings. J Build Eng. 2020; 28: 101055.
111. Yi Z, Xu D, Xu J, Qian H, Zhao D, Yang R. Energy saving analysis of a transparent radiative cooling film for buildings with roof glazing. Energy Built Environ. 2021; 2: 214-222.
112. Pereira J, Teixeira H, Gomes MD, Moret Rodrigues A. Performance of solar control films on building glazing: A literature review. Appl Sci. 2022; 12: 5923.
113. Collins RE, Turner GM, Fischer Cripps AC, Tang JZ, Simko TM, Dey CJ, et al. Vacuum glazing-A new component for insulating windows. Build Environ. 1995; 30: 459-492.
114. Fang Y, Eames PC, Norton B, Hyde TJ, Zhao J, Wang J, et al. Low emittance coatings and the thermal performance of vacuum glazing. Sol Energy. 2007; 81: 8-12.
115. Fang Y, Hyde T, Arya F, Hewitt N, Wang R, Dai Y. Enhancing the thermal performance of triple vacuum glazing with low-emittance coatings. Energy Build. 2015; 97: 186-195.

116. Cuce E, Cuce PM. Vacuum glazing for highly insulating windows: Recent developments and future prospects. Renew Sustain Energy Rev. 2016; 54: 1345-1357.
117. Yang Z, Katsura T, Aihara M, Nakamura M, Nagano K. Development of numerical heat transfer and the structural model to design slim and translucent vacuum layer type insulation panels to retrofitting insulation in existing buildings. Energies. 2017; 10: 2108.
118. Koebel MM, Wernery J, Malfait WJ. Energy in buildings-Policy, materials and solutions. MRS Energy Sustain. 2017; 4: E12.
119. Son H, Song TH. Heat transfer and stress distribution in the central part of vacuum glazing. Appl Therm Eng. 2019; 159: 113926.
120. Pont U, Wölzl M, Schober P, Khosravi SN, Schuss M, Mahdavi A. Recent progress in the development of windows with vacuum glass. 4th Central European Symposium on Building Physics (CESBP 2019); 2019 September 2-5; Prague, Czech Republic. Hulis, France: EDP Sciences.
121. Pont U, Wöltzl M, Schuss M, Schober P, Mahdavi A. Exploring novel solutions for incorporating vacuum glazing in new and existing window constructions. 12th Nordic Symposium on Building Physics (NSB 2020); 2020 September 6-9; Tallinn, Estonia. Hulis, France: EDP Sciences.
122. Baek S, Kim S. Potential effects of vacuum insulating glazing application for reducing greenhouse gas emission (GHGE) from apartment buildings in the Korean capital region. Energies. 2020; 13: 2828.
123. Katsura T, Memon S, Radwan A, Nakamura M, Nagano K. Thermal performance analysis of a new structured-core translucent vacuum insulation panel in comparison to vacuum glazing: Experimental and theoretically validated analyses. Sol Energy. 2020; 199: 326-346.
124. Huang Y, El Mankibi M, Cantin R, Coillot M. Application of fluids and promising materials as advanced inter-pane media in multi-glazing windows for thermal and energy performance improvement: A review. Energy Build. 2021; 253: 111458.
125. Gan G. Thermal transmittance of multiple glazing: Computational fluid dynamics prediction. Appl Therm Eng. 2001; 21: 1583-1592.
126. Karabay H, Arıcı M. Multiple pane window applications in various climatic regions of Turkey. Energy Build. 2012; 45: 67-71.
127. Gueymard CA, duPont WC. Spectral effects on the transmittance, solar heat gain, and performance rating of glazing systems. Sol Energy. 2009; 83: 940-953.
128. Zevenhoven R, Fält M. Radiative cooling through the atmospheric window: A third, less intrusive geoengineering approach. Energy. 2018; 152: 27-33.
129. Zevenhoven R, Fält M, Gomes LP. Thermal radiation heat transfer: Including wavelength dependence into modelling. Int J Therm Sci. 2014; 86: 189-197.
130. Ismail KA, Salinas CT, Henriquez JR. Comparison between PCM filled glass windows and absorbing gas filled windows. Energy Build. 2008; 40: 710-719.
131. Gonzalo FDA, Ramos JAH. Testing of water flow glazing in shallow geothermal systems. Procedia Eng. 2016; 161: 887-891.
132. Chow TT, Lyu Y. Effect of design configurations on water flow window performance. Sol Energy. 2017; 155: 354-362.
133. Li C, Chow TT. Water-filled double reflective window and its year-round performance. Procedia Environ Sci. 2011; 11: 1039-1047.

134. Kabeel AE, Arunkumar T, Denkenberger DC, Sathyamurthy R. Performance enhancement of solar still through efficient heat exchange mechanism-a review. Appl Therm Eng. 2017; 114: 815-836.
135. Xu HJ, Zhao CY. Thermodynamic analysis and optimization of cascaded latent heat storage system for energy efficient utilization. Energy. 2015; 90: 1662-1673.
136. Kara YA, Kurnuç A. Performance of coupled novel triple glass unit and PCM wall. Appl Therm Eng. 2012; 35: 243-246.
137. Gowreesunker BL, Stankovic SB, Tassou SA, Kyriacou PA. Experimental and numerical investigations of the optical and thermal aspects of a PCM-glazed unit. Energy Build. 2013; 61: 239-249.
138. Goia F, Perino M, Haase M. A numerical model to evaluate the thermal behaviour of PCM glazing system configurations. Energy Build. 2012; 54: 141-153.
139. Li S, Zhou Y, Zhong K, Zhang X, Jin X. Thermal analysis of PCM-filled glass windows in hot summer and cold winter area. Int J Low Carbon Technol. 2016; 11: 275-282.
140. Ismail KA, Henrıquez JR. Parametric study on composite and PCM glass systems. Energy Convers Manag. 2002; 43: 973-993.
141. Li D, Wu Y, Zhang G, Arıcı M, Liu C, Wang F. Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption. Appl Energy. 2018; 222: 343-350.
142. Li D, Wu Y, Liu C, Zhang G, Arıcı M. Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM. Int J Heat Mass Transf. 2018; 125: 1321-1332.
143. Li D, Zheng Y, Li Z, Qi H. Optical properties of a liquid paraffin-filled double glazing unit. Energy Build. 2015; 108: 381-386.
144. Liu C, Zhou Y, Li D, Meng F, Zheng Y, Liu X. Numerical analysis on thermal performance of a PCM-filled double glazing roof. Energy Build. 2016; 125: 267-275.
145. Li S, Sun G, Zou K, Zhang X. Experimental research on the dynamic thermal performance of a novel triple-pane building window filled with PCM. Sustain Cities Soc. 2016; 27: 15-22.
146. Silva T, Vicente R, Rodrigues F. Literature review on the use of phase change materials in glazing and shading solutions. Renew Sustain Energy Rev. 2016; 53: 515-535.
147. Wieprzkowicz A, Heim D. Modelling of thermal processes in a glazing structure with temperature dependent optical properties-An example of PCM-window. Renew Energy. 2020; 160: 653-662.
148. Zahir MH, Irshad K, Shafiullah M, Ibrahim NI, Islam AK, Mohaisen KO, et al. Challenges of the application of PCMs to achieve zero energy buildings under hot weather conditions: A review. J Energy Storage. 2023; 64: 107156.
149. Ji R, Li X. Numerical analysis on the energy performance of the PCMs-integrated thermochromic coating building envelopes. Build Environ. 2023; 233: 110113.
150. Yang R, Li D, Arıcı M, Wang B, Wu Y, Ma Y, et al. Photothermal performance of plastic greenhouse embedded with phase change materials in translucent envelopes: A dynamic experimental study. J Energy Storage. 2023; 58: 106375.
151. Ma Y, Li D, Yang R, Zhang S, Arıcı M, Liu C, et al. Energy and daylighting performance of a building containing an innovative glazing window with solid-solid phase change material and silica aerogel integration. Energy Convers Manag. 2022; 271: 116341.

152. Yang R, Li D, Salazar SL, Rao Z, Arıcı M, Wei W. Photothermal properties and photothermal conversion performance of nano-enhanced paraffin as a phase change thermal energy storage material. Sol Energy Mater Sol Cells. 2021; 219: 110792.
153. Li D, Wu Y, Wang B, Liu C, Arıcı M. Optical and thermal performance of glazing units containing PCM in buildings: A review. Constr Build Mater. 2020; 233: 117327.
154. Li D, Yang R, Arıcı M, Wang B, Tunçbilek E, Wu Y, et al. Incorporating phase change materials into glazing units for building applications: Current progress and challenges. Appl Therm Eng. 2022; 210: 118374.
155. Li D, Ma Y, Zhang S, Yang R, Zhang C, Liu C. Photothermal and energy performance of an innovative roof based on silica aerogel-PCM glazing systems. Energy Convers Manag. 2022; 262: 115567.
156. Zhang S, Ma Y, Li D, Liu C, Yang R. Thermal performance of a reversible multiple-glazing roof filled with two PCM. Renew Energy. 2022; 182: 1080-1093.
157. Cotana F, Pisello AL, Moretti E, Buratti C. Multipurpose characterization of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and acoustic performance. Build Environ. 2014; 81: 92-102.
158. Ihara T, Gao T, Grynning S, Jelle BP, Gustavsen A. Aerogel granulate glazing facades and their application potential from an energy saving perspective. Appl Energy. 2015; 142: 179-191.
159. Huang Y, Niu JL. Energy and visual performance of the silica aerogel glazing system in commercial buildings of Hong Kong. Constr Build Mater. 2015; 94: 57-72.
160. Garnier C, Muneer T, McCauley L. Super insulated aerogel windows: Impact on daylighting and thermal performance. Build Environ. 2015; 94: 231-238.
161. Gao T, Jelle BP, Gustavsen A. Building integration of aerogel glazings. Procedia Eng. 2016; 145: 723-728.
162. Buratti C, Belloni E, Merli F, Zinzi M. Aerogel glazing systems for building applications: A review. Energy Build. 2021; 231: 110587.
163. Ganobjak M, Malfait WJ, Just J, Käppeli M, Mancebo F, Brunner S, et al. Get the light & keep the warmth-A highly insulating, translucent aerogel glass brick for building envelopes. J Build Eng. 2023; 64: 105600.
164. Sayed MA, Fikry MA. Impact of glass facades on internal environment of buildings in hot arid zone. Alex Eng J. 2019; 58: 1063-1075.
165. Tong SW, Goh WP, Huang X, Jiang C. A review of transparent-reflective switchable glass technologies for building facades. Renew Sustain Energy Rev. 2021; 152: 111615.
166. Piccolo A, Simone F. Performance requirements for electrochromic smart window. J Build Eng. 2015; 3: 94-103.
167. Akram MW, Hasannuzaman M, Cuce E, Cuce PM. Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review. Energy Built Environ. 2023; 4: 206-226.
168. Kersken M. Method for the climate-independent determination of the solar heat gain coefficient (SHGC; g-value) of transparent façade and membrane constructions from in situ measurements. Energy Build. 2021; 239: 110866.
169. Rezaei SD, Shannigrahi S, Ramakrishna S. A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. Sol Energy Mater Sol Cells. 2017; 159: 26-51.

170. Fathi S, Kavoosi A. Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. Sol Energy. 2021; 223: 132-149.
171. Lee JH, Jeong J, Chae YT. Optimal control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions. Appl Energy. 2020; 260: 114338.
172. Tällberg R, Jelle BP, Loonen R, Gao T, Hamdy M. Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. Sol Energy Mater Sol Cells. 2019; 200: 109828.
173. Araújo GR, Teixeira H, Gomes MG, Rodrigues AM. Multi-objective optimization of thermochromic glazing properties to enhance building energy performance. Sol Energy. 2023; 249: 446-456.
174. Aste N, Leonforte F, Piccolo A. Color rendering performance of smart glazings for building applications. Sol Energy. 2018; 176: 51-61.
175. Teixeira H, Gomes MG, Rodrigues AM, Aelenei D. Assessment of the visual, thermal and energy performance of static vs thermochromic double-glazing under different European climates. Build Environ. 2022; 217: 109115.
176. Radwan A, Olabi AG, Abo Khalil AG, Yousef BA, Serageldin AA, Maghrabie HM, et al. Thermoelectric analysis of different vacuum-based photovoltaic semitransparent skylights. Energy Build. 2023; 285: 112924.
177. Li X, Peng J, Tan Y, He Y, Li B, Ju X, et al. Optimal design of inhomogeneous semi-transparent photovoltaic windows based on daylight performance and visual characters. Energy Build. 2023; 283: 112808.
178. Wu J, Zhang L, Liu Z, Luo Y, Wu Z, Wang P. Experimental and theoretical study on the performance of semi-transparent photovoltaic glazing façade under shaded conditions. Energy. 2020; 207: 118314.
179. Fiorini CV, Merli F, Belloni E, Anderson AM, Carroll MK, Buratti C. Glazing systems with thin monolithic aerogel: Optical, thermal, and color rendering performance. Energy Build. 2023; 288: 113009.
180. Mohammad AK, Ghosh A. Exploring energy consumption for less energy-hungry building in UK using advanced aerogel window. Sol Energy. 2023; 253: 389-400.
181. Khaled K, Berardi U. Current and future coating technologies for architectural glazing applications. Energy Build. 2021; 244: 111022.
182. Pu J, Shen C, Wang J, Zhang Y, Zhang C, Kalogirou SA. Near-infrared absorbing glazing for energy-efficient windows: A critical review and performance assessments from the building requirements. Nano Energy. 2023; 110: 108334.
183. Maduru VR, Shaik S, Cuce E, Afzal A, Panchal H, Cuce PM. UV coated acrylics as a substitute for generic glazing in buildings of Indian climatic conditions: Prospective for energy savings, CO_2 abatement, and visual acceptability. Energy Build. 2022; 268: 112231.
184. Leung CK, Lu L, Liu Y, Cheng HS, Tse JH. Optical and thermal performance analysis of aerogel glazing technology in a commercial building of Hong Kong. Energy Built Environ. 2020; 1: 215-223.
185. Sbar NL, Podbelski L, Yang HM, Pease B. Electrochromic dynamic windows for office buildings. Int J Sustain Built Environ. 2012; 1: 125-139.

186. DeForest N, Shehabi A, Selkowitz S, Milliron DJ. A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. Appl Energy. 2017; 192: 95-109.
187. Sibilio S, Rosato A, Scorpio M, Iuliano G, Ciampi G, Vanoli GP, et al. A review of electrochromic windows for residential applications. Int J Heat Technol. 2016; 34: S481-S488.
188. Aoul KAT, Attoye DE, Ghatrif LA. Performance of electrochromic glazing: State of the art review. IOP Conf Ser Mater Sci Eng. 2019; 603: 022085.
189. Cannavale A, Ayr U, Fiorito F, Martellotta F. Smart electrochromic windows to enhance building energy efficiency and visual comfort. Energies. 2020; 13: 1449.
190. Brzezicki M. A systematic review of the most recent concepts in smart windows technologies with a focus on electrochromics. Sustainability. 2021; 13: 9604.
191. de Brito Filho JP, Henriquez JR, Dutra JC. Effects of coefficients of solar reflectivity and infrared emissivity on the temperature and heat flux of horizontal flat roofs of artificially conditioned nonresidential buildings. Energy Build. 2011; 43: 440-445.
192. Kolokotroni M, Shittu E, Santos T, Ramowski L, Mollard A, Rowe K, et al. Cool roofs: High tech low cost solution for energy efficiency and thermal comfort in low rise low income houses in high solar radiation countries. Energy Build. 2018; 176: 58-70.
193. Pisello AL. State of the art on the development of cool coatings for buildings and cities. Sol Energy. 2017; 144: 660-680.
194. Battista G, de Lieto Vollaro E, Ocłoń P, de Lieto Vollaro R. Effects of urban heat island mitigation strategies in an urban square: A numerical modelling and experimental investigation. Energy Build. 2023; 282: 112809.
195. Santamouris M, Synnefa A, Karlessi T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Sol Energy. 2011; 85: 3085-3102.
196. Wang X, Li H, Sodoudi S. The effectiveness of cool and green roofs in mitigating urban heat island and improving human thermal comfort. Build Environ. 2022; 217: 109082.
197. Rawat M, Singh RN. Techno-economic analysis of cool roof materials in a composite climatic zone. Mater Today Proc. 2022; 52: 1406-1410.
198. Yang YK, Kim MY, Chung MH, Park JC. PCM cool roof systems for mitigating urban heat island-an experimental and numerical analysis. Energy Build. 2019; 205: 109537.
199. Hernández-Pérez I, Álvarez G, Xamán J, Zavala-Guillén I, Arce J, Simá E. Thermal performance of reflective materials applied to exterior building components—A review. Energy Build. 2014; 80: 81-105.
200. Nazarian N, Dumas N, Kleissl J, Norford L. Effectiveness of cool walls on cooling load and urban temperature in a tropical climate. Energy Build. 2019; 187: 144-162.
201. Sameera S, Vidyadharan V, Sasidharan S, Gopchandran KG. Nanostructured zinc aluminates: A promising material for cool roof coating. J Sci Adv Mater Dev. 2019; 4: 524-530.
202. Tian D, Zhang J, Gao Z. The advancement of research in cool roof: Super cool roof, temperature-adaptive roof and crucial issues of application in cities. Energy Build. 2023; 291: 113131.
203. Butt AA, de Vries SB, Loonen RC, Hensen JL, Stuiver A, van den Ham JE, et al. Investigating the energy saving potential of thermochromic coatings on building envelopes. Appl Energy. 2021; 291: 116788.

204. Perez G, Sirvent P, Sanchez Garcia JA, Guerrero A. Improved methodology for the characterization of thermochromic coatings for adaptive façades. Sol Energy. 2021; 230: 409-420.
205. Fabiani C, Castaldo VL, Pisello AL. Thermochromic materials for indoor thermal comfort improvement: Finite difference modeling and validation in a real case-study building. Appl Energy. 2020; 262: 114147.
206. Pumo D, Francipane A, Alongi F, Noto LV. The potential of multilayer green roofs for stormwater management in urban area under semi-arid Mediterranean climate conditions. J Environ Manage. 2023; 326: 116643.
207. Charoenkit S, Yiemwattana S. Role of specific plant characteristics on thermal and carbon sequestration properties of living walls in tropical climate. Build Environ. 2017; 115: 67-79.
208. Shafique M, Xue X, Luo X. An overview of carbon sequestration of green roofs in urban areas. Urban For Urban Green. 2020; 47: 126515.
209. Shafique M, Kim R, Rafiq M. Green roof benefits, opportunities and challenges-A review. Renew Sustain Energy Rev. 2018; 90: 757-773.
210. Yazdani H, Baneshi M. Building energy comparison for dynamic cool roofs and green roofs under various climates. Sol Energy. 2021; 230: 764-778.
211. Kostadinović D, Jovanović M, Bakić V, Stepanić N, Todorović M. Experimental investigation of summer thermal performance of the green roof system with mineral wool substrate. Build Environ. 2022; 217: 109061.
212. Dwijendra NK, Muda I, Milanes CB, Kumar NB, Abosinnee AS, Akhmadeev R. How do green roofs affect per capita energy consumption in residential buildings under various climate conditions? Sustain Energy Technol Assess. 2023; 56: 103127.
213. Tariku F, Hagos S. Performance of green roof installed on highly insulated roof deck and the plants' effect: An experimental study. Build Environ. 2022; 221: 109337.
214. Ávila Hernández A, Simá E, Ché Pan M. Research and development of green roofs and green walls in Mexico: A review. Sci Total Environ. 2023; 856: 158978.
215. Akeiber H, Nejat P, Majid MZ, Wahid MA, Jomehzadeh F, Famileh IZ, et al. A review on phase change material (PCM) for sustainable passive cooling in building envelopes. Renew Sustain Energy Rev. 2016; 60: 1470-1497.
216. Elawady N, Bekheit M, Sultan AA, Radwan A. Energy assessment of a roof-integrated phase change materials, long-term numerical analysis with experimental validation. Appl Therm Eng. 2022; 202: 117773.
217. Bat Erdene PE, Pareek S. Experimental study on the development of fly ash foam concrete containing phase change materials (PCMs). Materials. 2022; 15: 8428.
218. Li Q, Ma L, Li D, Arıcı M, Yıldız Ç, Wang Z, et al. Thermoeconomic analysis of a wall incorporating phase change material in a rural residence located in northeast China. Sustain Energy Technol Assess. 2021; 44: 101091.
219. Cao VD, Bui TQ, Kjøniksen AL. Thermal analysis of multi-layer walls containing geopolymer concrete and phase change materials for building applications. Energy. 2019; 186: 115792.
220. Al Yasiri Q, Szabó M. Experimental evaluation of the optimal position of a macroencapsulated phase change material incorporated composite roof under hot climate conditions. Sustain Energy Technol Assess. 2021; 45: 101121.

221. Al Yasiri Q, Szabó M. Energetic and thermal comfort assessment of phase change material passively incorporated building envelope in severe hot climate: An experimental study. Appl Energy. 2022; 314: 118957.
222. Elmarghany MR, Radwan A, Shouman MA, Khater AA, Salem MS, Abdelrehim O. Year-long energy analysis of building brick filled with phase change materials. J Energy Storage. 2022; 50: 104605.
223. Sarcinella A, de Aguiar JL, Jesus C, Frigione M. Thermal properties of PEG-based form-stable phase change materials (PCMs) incorporated in mortars for energy efficiency of buildings. J Energy Storage. 2023; 67: 107545.
224. Yang Y, Pang Y, Liu Y, Guo H. Preparation and thermal properties of polyethylene glycol/expanded graphite as novel form-stable phase change material for indoor energy saving. Mater Lett. 2018; 216: 220-223.
225. Karaipekli A, Sarı A. Development and thermal performance of pumice/organic PCM/gypsum composite plasters for thermal energy storage in buildings. Sol Energy Mater Sol Cells. 2016; 149: 19-28.
226. Ji R, Li X, Lv C. Synthesis and evaluation of phase change material suitable for energy-saving and carbon reduction of building envelopes. Energy Build. 2023; 278: 112603.
227. Li C, Wen X, Cai W, Yu H, Liu D. Phase change material for passive cooling in building envelopes: A comprehensive review. J Build Eng. 2022; 65: 105763.
228. Rahiminejad M, Khovalyg D. Numerical and experimental study of the dynamic thermal resistance of ventilated air-spaces behind passive and active façades. Build Environ. 2022; 225: 109616.
229. Rahiminejad M, Khovalyg D. Experimental study of the hydrodynamic and thermal performances of ventilated wall structures. Build Environ. 2023; 233: 110114.
230. Wang Q, Zhang G, Wu Q, Li W, Shi L. A combined wall and roof solar chimney in one building. Energy. 2022; 240: 122480.
231. Borodulin VY, Nizovtsev MI. Modeling heat and moisture transfer of building facades thermally insulated by the panels with ventilated channels. J Build Eng. 2021; 40: 102391.
232. De Masi RF, Ruggiero S, Vanoli GP. Hygro-thermal performance of an opaque ventilated façade with recycled materials during wintertime. Energy Build. 2021; 245: 110994.
233. Colombo M, Salvalai G, Brutti D, Depaolini CR. Mechanical, thermal and durability performance characterization of novel acrylic solid surface cladding panels in a multidisciplinary test-chain. J Build Eng. 2023; 69: 106251.
234. Pujadas Gispert E, Alsailani M, van Dijk KC, Rozema AD, ten Hoope JP, Korevaar CC, et al. Design, construction, and thermal performance evaluation of an innovative bio-based ventilated façade. Front Archit Res. 2020; 9: 681-696.
235. Brozovsky J, Nocente A, Rüther P. Modelling and validation of hygrothermal conditions in the air gap behind wood cladding and BIPV in the building envelope. Build Environ. 2023; 228: 109917.