Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Phase change material in glazing windows system:a review

Mina A. Nsaif [a*], **Monier Baccar** [a], **Jalal M. Jalil** [b]
[a] Mechanical Engineering Dept., Ecole National ingenious Sfax-ENIS, Tunisia.
[b] Electromechanical Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: mina-abdulkareem-nsaif.alshareefi@enis.tn

HIGHLIGHTS

- The research provides a comprehensive review of PCM composite as an insulator in double and triple windows.
- The implementation of composite PCM is found to enable a significant decrease in inside surface temperature.
- The study highlights the effectiveness of blinds as an efficient means of controlling the amount of daylight.

ARTICLE INFO

Handling editor: Sattar Aljabair

Keywords:
Triple-glazed window
PCM
Phase Change Materials
Thermal insulation
Latent heat
CFD

ABSTRACT

As far as thermal insulation is concerned, phase change materials (PCM) have a very good potential to be excellent insulation materials due to their thermal properties like low thermal conductivity and high latent heat. The researchers started to incorporate the walls and windows with PCM to reduce the internal surface temperature and indoor temperature of the room. This paper focuses on double and triple-glazed windows' thermal performance, different filling insulation materials, ventilation windows, and thermochromic glazing. In addition, a detailed discussion on the effect of changing the thickness and the thermal characteristics of the PCM and its influence on the internal surface temperature, temperature time lag, and other parameters such as total energy transmitted and indoor temperature. Previous studies have shown that including PCM in triple-glazed windows decreases the temperature of the inner surface by 2.7 °C and 5.5 °C compared to double-glazed windows with PCM and triple-glazed windows. Utilizing ventilation during summer nights saves 46% on cooling energy. By using two different PCM melting temperatures, the maximum interior and surface temperatures are reduced by 6 °C. The integrated PCM blind system prevented the room occupants from being exposed to direct sunlight. Finally, additional recommendations were made based on the identified research needs.

1. Introduction

Present-day frameworks are expected to fulfill expanding requests for upgraded supportability, green economy, astute execution, and broadened life span. These desires different improvements in cutting-edge and brilliant materials, planning, assembling, and portrayal methods. One of these clever materials is PCM, which can change its state from fluid to gas and solid when it endures cooling or heat [1-3]. In the time of phase changing, the heat is released or absorbed normally to let temperature vacillation so warm properties free from development materials are adjusted. PCMs stand out enough to be noticed and it is a broadly acknowledged method for saving energy and making a green climate [4-6]. Common foundations, similar to structures, extensions, and asphalts, frequently go through temperature distinction during their whole help lives, including the various temperatures inside and outside, summer and winter, constantly, building and working. These distinctions frequently present adverse consequences on primary execution where additional energy-consuming ways are utilized to facilitate the issues. Taking the structure room for instance, occupants utilize a climate control system to safeguard the scarcely mediocre indoor temperature in the late spring and warm the room in the colder time of year bringing about a huge utilization of power. The intensity of motion through the houses is a significant explanation for causing awkward indoor temperatures [7]. Heat protection and protection are accomplished by the heat protection layer in many structures which is an ordinary and well-known technique [8]. PCMs consolidated in walls, roofs, and indoor coatings can redistribute energy in a proper way that transmits heat moving and limits the temperature vacillation range [9]. promoting huge energy saving [10-12] Momentarily, PCMs can reestablish and deliver warm mass by phase change while enduring temperature vacillation, which is valuable to further develop energy proficiency and lessen energy utilization [6,13,14].

http://doi.org/10.30684/etj.2023.138089.1381
Received 07 February 2023; Received in revised form 23 April 2023; Accepted 05 May 2023; Available online 16 August 2023
2412-0758/University of Technology-Iraq, Baghdad, Iraq

2. Pcm in double and triple glazing window

Li et al. [15], suggested a design of PCM equipped with a triple window, whose external cavity is stuffed with PCM to take care of the issue of the sent-out heat into the room from PCM during a summer night, Exploratory frameworks of two reference windows twofold coated window with PCM and triple windows. The results reveal that the (TW+PCM) performs well in terms of decreasing temperature fluctuations inside and lowering energy usage. Liu et al. [16], created a model for assessing the thermal performance of a non-ventilated DW+PCM. They then experimentally validated the model, as illustrated in Figure 1. The study's findings demonstrated the model's capability to effectively address the interconnected heat transfer concerns between phase change and solar heat transfer within the double glazing unit featuring PCM. Liu et al. [17], examined numerically in winter the thermal efficiency of double glazing filled with various thicknesses of PCM also, Additionally, three PCMs with distinct melting temperatures were examined. The solar transmittance, total transmitted energy, transmitted solar energy, and interior temperature of (DGUs) are all significantly affected by thickness for all three PCMs. Hashim and Hoshi [18] examined the effect of replacing single-pane windows with double-pane ones on the amount of energy saved by homes and buildings in July and August at various hours of 3, 6, 9, 12, 15, 18, 21, and 24 p.m. A useful and sensible review was directed. When there is air between the panels, aspect ratios of 30, 15, and 10 are used and when argon gas is present, aspect ratios of 10 were practically examined. The results of the experiments showed that using double glass with air as a medium for heat transfer between the two panels could result in less heat being transferred than using single glass. Li et al. [19], suggested a setup of (TW) filled with PCM and the numerical model to take care of the issues of heat being released to the room in the release time of PCM on summer's night as well as the phenomenon of overheating from the totally melted PCM cannot be ignored. The setup shows a kindly activity, under the conditions of winter. The setup can avoid the phenomenon of overheating successfully and has worthwhile execution on heat conservation and protection. Jalil and Salih [20] conducted a numerical study to determine how changing the paraffin wax's thermal properties affected the performance of a paraffin-doped (DW) in Baghdad's summer climate (33.3°N, 44.4°E) as shown in Figure 2. To address the conduction and phase change issues in the wax. A FORTRAN-built computer program combined the enthalpy method with a finite difference. The obtained results indicate that increasing the PCM's density, thickness, and latent heat would improve the unit's performance by reducing the double-glazed windows (TDF) and increasing the (TTL). Jalil and Salih [21], examined the performance of theoretically and experimentally of paraffin wax with DW to evaluate the enhancement in the comfort and thermal efficiency of a room in Iraq. The Navier-Stokes equations in the room are solved using the finite volume method, and the conduction problem is solved using the finite difference and enthalpy method. A sandwich panel-constructed room with a south-facing window was built. To confirm the viability of the prototype two unique kinds of windows were utilized. The first is a standard single-pane window with a thickness of 6 millimeters, while the second one is a double-pane window with a 17 millimeters thickness and is stuffed with wax from paraffin. In addition, three scenarios are taken into consideration based on the room's and window's locations in the building, on the floors (ground, first, and ceiling). Bolteya et al. [22], compared experimentally a PCM (RT28HC) glazed unit's thermal efficiency to that of an air-filled unit in a dry arid region using Fluent Software, as shown in Figure 3 they looked at the TTL, internal temperature, liquid fraction, and total transmitted energy to see how thicknesses of PCM affected the thermal efficiency of (DGU).

Ravasio et al. [23], analyzed the thermal performance of a TW+PCM's in comparison to that of a conventional (TW + air). The examination was completed for the long periods of various seasons utilizing three sorts of paraffin (5,10, and 15) that have a variety of melting points in Arctic region climatic conditions. Wei et al. [24], examined numerically the PCM-filled multilayer performance of the glazing unit in terms of energy conservation and dynamic coupled heat transfer. The heat transfer calculation is used for evaluating energy efficiency conservation and a transient coupled heat transfer model that takes into account solar radiation transfer, phase change, and conduction within the glazing unit. It has been discovered that the thermal insulation benefits of the PCM-filled multilayer glazing unit make it an excellent option for transparent envelopes in the building industry. King et al. [25], compared DGUs with a PCM's thermal performance to that of a standard DW in an experimental setting. The results showed that, during the day, the transmittance was good enough to let in enough light into the room. Additionally, the PCM significantly reduced temperature fluctuations, the temperature of the inner glass, and window energy consumption. Rodriguez-Ake et al. [26], presented conjugate heat transfer in (TG) in order to identify the width of the air gap that enhances the thermal performance in a warm climate. The Widths of Air-gap are 6, 10, 14, 18, and 22 mm, each glass is 4 mm thick, and it is 80 cm high. The TG's thermal behavior was evaluated using hourly climatic data from the warmest and coldest days in Spain. When compared to (DG) and (SG), discovered that a 10 mm air gap can reduce the hourly heat flux to the indoors by as much as 17.7 and 38.7 percent on the warmest day respectively. Additionally, the TG has daily electricity, total heat flux, costs, and CO_2 emissions that are up to 40 percent lower than those of the SG. As a result, it has been suggested a TAG to enhance the windows' thermal performance in Merida, Yucatan's weather. Zhang et al. [27] conceived of a novel kind of dynamic rotating PCM window (DPCMW). A vacuum glass layer and a PCM layer made up the window. The relative positions of the vacuum glass and PCM layers could be changed over time by the DPCMW Consequently, the direction of the heat flux could be altered to lessen the building load.

The outcomes demonstrate that the exhibition of the novel kind of dynamic rotating PCM window in both summer and winter outperforms a static PCM window. Shuwei et al. [28], investigated the behavior of PCM with DW under fire. The thermal deformation temperature of the glass with the PCM layer reaching the fire surface under four fixed boundary circumstances, as well as the reaching limit temperature time at the edge, are delayed by 55 and 5 seconds, respectively, in comparison to the hollow glass unit. A summary of the researches in this section is shown in the Table 1.

Figure 1: Small-Scale Test Facility [16]

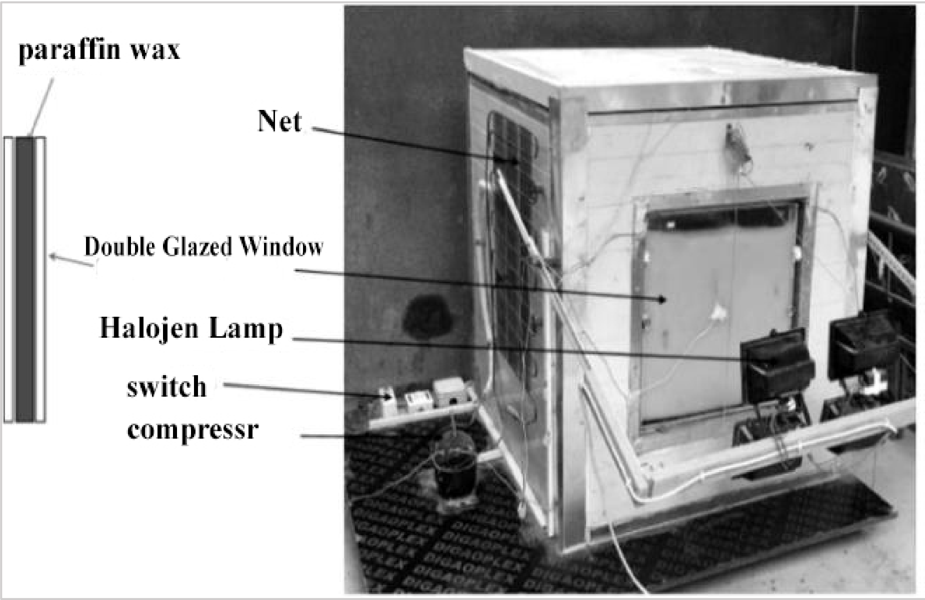


Figure 2: The Double- Glaze Window with Sandwich Panel Room [20]

Figure 3: Experimental Setup (A) Façade Filled with PCM (B) Façade Filled with Air [22]

Table 1: Summary of results (PCM in Double and Triple Glazing Window)

Descriptions System	Climate zones	Area of the cavity of PCM or air (mm)	Results	Ref.
Thermal insulation performance was compared between the (TW + PCM) and reference windows (DW + PCM) and (TW) respectively.	- Sunny, rainy summer.	14 mm	The peak temperature on the inner surface of (PCM +TW) compared with (PCM+DW) and TW, reduces by 2.7^{o}C and 5.5 ^{o}C respectively. The heat transported into the room through the (PCM +TW) is reduced by 16.6% and 28%, respectively, when compared to the (PCM +DW) and TW.	[15]
In order to examine the thermal characteristics of a double glazing unit filled with phase change material (PCM), the researchers developed a comprehensive model that accounted for the interconnected processes of phase change, radiation, and conduction.	Winter season	-----	1) The researchers successfully resolved the intertwined heat transfer issue between phase change and solar heat transfer within the PCM-filled double glazing unit. 2) The variation between the numerical results and experimental results primarily stemmed from the influence of the initial temperature in the PCM-filled double glazing facades during the experiment.	[16]
(DW + PCM) thermal performance was examined in relation to PCM thickness and three PCMs with varying melting temperatures.	Winter season	8 mm, 12 mm, 16 mm, 20 mm, 30 mm and 50 mm	The temperature of the interior surface rises by 158.7% as the PCM thickness rises from 4mm to 50mm; There is a 1091.1% decrease in total transmitted energy; 86.1% less solar energy is transmitted.	[17]
The impact of replacing single-pane windows with double-pane ones on the amount of energy saved for cooling Iraqi homes and buildings	Hot Iraq	-	Decreased the quantity of heat transmitted compared to a single glass by (45%-78%), (54%-85%), and (58%-88%) for three aspect ratios. In contrast, argon was (60% -91%).	[18]
Experiments confirmed and established the physical and mathematical models of dynamic heat transfers known as TW, DW, and PCM.	Summer and winter weatherc onditions .	-	The TDF are 0.75 and 0.63 on a typical sunny summer day, respectively. When compared to DW+PCM and (TW), the energy utilization of TW+PCM is decreased by 21.30 percent and 32.80 percent, respectively, on a typical sunny summer day.	[19]
Determine numerically how the performance of a DW filled with paraffin wax is affected by the various thermal properties of the wax.	Hot environ mental.	-	Increasing the PCM's density from 650 g/m^3 to 1800 g/m^3 can increases (TTL) from 1.5 h to 3.5 h, and also, reduces (TDF) from 1.3 to 0.6. TDF and TTL are 1.6 and 1.5 hours when the latent heat value is 120 KJ/Kg, respectively, and 0.2 and 3.5 hours when the latent heat value is 250 KJ/Kg. Increasing the double-glazed window's thickness would decrease the temperature of the internal surface	[20]
Thermal insulation performance was compared between DW which is filled with paraffin wax and a single window made of glass for the ceiling, first floor, and ground floor	Summer season.	17 mm	The temperature of the ground floor is 8^{o}C, the first floor is 6^{o}C, and the ceiling is 5^{o}C.	[21]
Thermal insulation performance was compared between PCM glazing, the reference was filled with air, the other was filled with PCM (RT28HC) and was studying various PCM thicknesses	Dry arid region.	12 mm	The DGU internal surface temperature decreased by 7.6 °C when using PCM instead of air Recommended thicknesses of PCM up to only 30 mm in dry regions.	[22]
Investigated the use of PCMs in the cavity of TW to cut down on heat loss and, as a result, reduce the amount of energy needed to heat a building.	Four seasons.	-	Thermal performance was improved during the summer by incorporating a PCM into the triple-glazing cavity; The kind of paraffin affected the thermal performance chosen in the spring and autumn. PCM integration had no effect on glass windows' winter thermal performance.	[23]

Table 1: Continued

A PCM-filled glazing unit structure was proposed to decrease the energy amount used in buildings and increase thermal comfort.	Summer season	-	When compared to a standard glazing unit, the PCM-filled glazing unit has energy savings rates of 14.55 percent for DW, 33.89 percent for TW, and 50.71 percent for four glazing units, respectively.	[24]
The thermal insulation ability of a DW was investigated under two conditions: a window with and without PCM.	Cold weather.	12 mm	Decrease the interior temperature variation from (21 to 11) degrees Celsius. It also decreased the interior peak temperature by 9 degrees Celsius. The inner glass temperature was lessened by 8.5 with the help of PCM and it reduced the energy consumption by 3.76%.	[25]
The conjugate heat transfer in a (TG) is provided in order to estimate the air-gap width that enhances its thermal performance.	Cold, warm day.	Hc ¼ 6, 10, 14, 18, and 22 mm	When compared to DG and SG, TG's indoor surface temperature drops by up to 0.65 and 4.9 ºC, respectively; in comparison to the DG and SG, it rises to 3 and 7.8ºC on the coldest day, respectively.	[26]
The DPCMW's insulation performance was compared to the SPCMW's, and the effects of various parameters on the Cfa climate's energy-saving performance were examined.	Summer and Winter season.	6, 9, 12, 15, and 18 mm	In the winter, the DPCMW reduces the SPCMW's cooling load by 93.79 percent and the DPCMW's heating load by 12.40 percent. Compared to the SPCMW, The DPCMW decreases the yearly load on buildings by 28.70%. The ideal phase transition temperature is 23-25°C, and the thickness of the PCM layer has a positive impact on energy savings. The optimal temperature range for the phase transition is 19–25°C.	[27]
The thermal-structural coupling properties under fire conditions were obtained by numerical modeling of the rupture behavior.	-	6 mm	The results indicate DW with PCM has superior fire resistance than regular DW.	[28]

3. Different filling insulation materials

Li et al. [29] simulated numerically the nanoparticle diameter and volume fraction's effect on the temperature differential between the inside of the glass and the outside environment., as well as the amount of energy consumed by Nano-PCM with glazed windows on representative days of various seasons. The inner glass surface's temperature rises with increasing nanoparticle concentration and falls with increasing nanoparticle size. Depending on the season, the degree to which the concentration and size of nanoparticles affect the temperature profile varies. Berardi and Soudian [30] examined the efficacy of using PCMs to retrofit high-rise apartments with WWRs of 80 percent for windows to walls. To provide year-round thermal energy storage, Two PCM compounds with melting temperatures of 21.7 and 25ºC are used to create a new composite PCM system. The composite system was installed on the walls and ceiling of one of the two test cells, which served as a baseline for the other. The test cell appears to have performed better in the results limiting the composite PCM system's ability to reduce surface and peak indoor temperatures. The inclusion of two distinct melting points in a single system, which enabled high latent heat storage capacity in a thin layer, is the composite PCM system's greatest advantage in this study. It is an unobtrusive addition with a thickness of only 2 cm and is suitable for renovation projects that can store a lot of heat. Zhang et al. [31], proposed a heat transfer model with two-dimensional to mathematically explore the impact of improving PCM with various types of nanoparticles on the warm execution of coating windows at various times of the year. The addition of nanoparticles has the potential to speed up PCM's rate of phase change, expedite the solidification and melting processes, and extend the amount of time that the PCM remains liquid. Liu et al. [32], investigated the protection execution of (VG) and protected window of glazing unit in triple glazing water stream. When applied to a window with water flow in an area that is cooled by air, the insulation properties of protected glazing and vacuum glazing are found to be comparable. The additional water stream reduces the surface temperature of the glazing quite effectively. Zhang et al. [33], analyzed numerically 10 different glazing layouts' energy efficiency in China's extreme cold. In addition, the thermal behavior of silica aerogel or PCM-filled glass windows was compared to that of conventional air-filled glass windows. What's more, to guarantee proficient working and limit the intensity misfortune through the window with PCM in the serious cold environment, three designs of the triple-glazing chosen for enhancement and loaded up with PCM and silica aerogel were assessed in view of the silica aerogel layer's thickness, the glass's optical properties and the PCM's softening mark. Kaushik et al. [34], used a Nano-Disbanded PCM to test the heat transfer properties of a DW system. The results were compared to those of a window with PCM and a standard DW, by dispersing a nano-silica ($SiO2$) fraction of 1.0 vol within the technical grade paraffin. Xinpeng et al. [35], established the energy-saving, economy, thermal comfort, and daylighting assessment system for glazed windows with hybrid Nano-PCM. To investigate the optical and thermal performance of glazed units, a simulation model was created. The findings indicate that the incorporation of hybrid Nano-PCM has a beneficial effect on energy and cost savings. A summary of the researches in this section is shown in the Table 2.

Table 2: Summary of Results (Different Filling Insulation Materials)

Climate Zones	Material Type	Descriptions System	Results and Conclusions	Ref.
Summer and Winter season.	Nano-PCM.	The warm protection execution of glazed windows with Nano-PCM was explored and was examining the impact of volume division and molecule distance across the glazed window.	Energy consumption was reduced by up to 4.0%.In the summer, the temperature difference between the inside environment and the glass surface is mostly between 1 and 4°C in the fall, between 5 and 10°C, and in the winter, between 14 and 16°C. A nanoparticle diameter of 100 nm and a concentration of one percent yield the lowest energy consumption. For summer, autumn, and winter, energy consumption can be reduced by up to 5%, 2%, and 4%, respectively.	[29]
Fall and summer months	Two different melting temperatures of PCM. (21.7 °C and 25 °C).	The insulation performance of a composite system that was proposed as a retrofit for high-rise residential buildings to store annual thermal energy.	Reducing maximum indoor and surface temperatures by as much as 6 °C.	[30]
Summer and Winter seasons	Pure paraffin Al_2O_3-paraffin TiO_2-paraffin ZnO-paraffin	Examine the effect of nanoparticles on the thermal performance of a PCM-filled double-glazed window.	Al_2O_3's interior surface peak temperatures rise by 0.19 K, while TiO_2's and ZnO's decrease by 0.82 K and 0.36 K, respectively.	[31]
Cooling season.	Water	The thermal insulation performance of a triple-glazed water flow window is evaluated. Two kinds of insulation glazing, namely (VG) and (IGU) are taken into consideration.	Inner glazing can see a reduction of as much as 4.81°C, while outer glazing can see a reduction of 10°C. The (VWFW) and (TWFW) daily thermal efficiency ranges are 24.69 – 45.95 percent and 21.9–36.13 percent, respectively.	[32]
Severe cold	Air paraffin silica aerogel.	Ten distinct glass windows that were either integrated with PCM or silica aerogel were proposed and compared to conventional glass windows.	When compared to traditional triple-glazed windows, the rate of energy savings is found to be 56.67 percent.	[33]
-	Nano-disbanded with PCM	Three window configurations were used to evaluate the double-glazing window's thermal insulation performance: with no PCM (plain, with PCM, and with Nano-disbanded with PCM window).	The temperature of the internal glass was decreased by 11°C and 8.5°C, respectively.A decrease in temperature of 9.5°C and 5.5°C, respectively, in the interior space.	[34]
Summer	Al_2O_3-CuO hybrid Nano-PCMs	Prepared a new type of CuO-Al_2O_3 hybrid Nano-PCM.	The natural lighting index and thermal comfort index rise when the Al_2O_3 ratio increases below 0.001% volume fraction. The highest average interior natural light. is 361.89 lx, with a maximum temperature difference of 9.31 °C. The optimum overall performance for the window is attained with a CuO: Al_2O_3 ratio of 4:6 in terms of energy consumption, energy savings, daylighting, and economic aspects.	[35]

4. Ventilated glazing window system

Gracia et al. [36], examined experimentally the thermal efficiency of a ventilated (DSF) with PCM in its air channel during the heating season in the Mediterranean environment. During the winter, in Pigherd de Lleida (Spain), two identical house-like cubicles were monitored. One of them had a south wall containing PCM and a ventilated facade. Mechanical or natural ventilation options are available for the ventilated facade. As a result, three distinct tests were carried out: conditions of free-floating, controlled temperature, and demand profile According to the findings of the experiments, the utilization of the ventilated facade in conjunction with PCM has a major impact on the overall structure's thermal behavior. Wang et al. [37], proposed a better zonal methodology with a unique optical model of the venetian blind and a model of wind current organization to demonstrate the mechanical ventilated (DSF) in cold winter and warm summer zone both increment ventilation rate and support point can diminish the internal glass temperature and intensity gains through the DSF, however, the reduction range is more noteworthy by expanding the slat angle. Liu et al. [38], conducted a study to investigate 15 different ventilated window typologies with various pane configurations and glazing types in four European countries (United Kingdom, Denmark, France, and Germany), as depicted in Figure 4.

The main objective was to determine the most suitable typology considering energy balance and its impact on thermal comfort. The study's findings showcase the energy and comfort performance of the different ventilated window typologies, providing optimal choices for the climates in these four European countries.The typologies equipped with solar control or Low-emissivity (Low-e) coatings, as well as those featuring double glazing on the outside, exhibited better performance in terms of either minimizing energy consumption or optimizing thermal comfort. Hu et al. [39], proposed a (PCMVW) system for precooling and preheating ventilation to save energy in buildings. Using different control strategies, it is incorporated into a night cooling application and solar energy storage application. The PCM-VW's thermal and energy performance as shown in Figure 5 in comparison to two other ventilation systems using the validated model and it demonstrates that the PCMVW can significantly reduce the amount of energy required for cooling and heating applications in both summer and winter. The developed summer night control plan Utilizing between-glass reflection shading, using VW self-cooling to ventilate the room while in the mode of ventilation pre-cooling, and heating with VW air to prevent overcooling are all cooling applications. Utilizing between-glass absorption blinds, making use of VW's hot air, self-cooling VW and bypass ventilation are the developed control strategies for solar energy storage systems. Hu et al. [40], introduced a phase change material enhanced ventilated window (PCMVW) designed to serve both ventilation pre-cooling and pre-heating purposes, as depicted in Figure 6. In this setup, a PCM heat exchanger is utilized as a heat sink during ventilation pre-cooling and as thermal energy storage during ventilation pre-heating.To evaluate the performance of the PCMVW, the researchers conducted a night cooling experiment and a solar energy storage experiment.

They also carried out a self-cooling experiment using a ventilated window (VW) for overheating protection. The experimental results revealed that during ventilation pre-cooling with the PCM heat exchanger, the room's inlet air temperature was, on average, 1.4 °C lower for 7 hours during the daytime compared to the normal VW. Additionally, the PCMVW achieved an average energy saving of 0.7 MJ/day compared to a normal VW. However, it was noted that the cooling capacity of the PCMVW had limitations without advanced blinds control and system operation control. Regarding ventilation pre-heating application, the PCM contributed to raising the VW's inlet air temperature by 2.0 °C for 12 hours. This led to an average energy saving of 1.6 MJ/day compared to a normal VW. Prabhakar et al. [41], optimized PCM melting temperature of buildings in different environmental conditions utilizing an optimization based on simulation and combined with free cooling activity. It was tracked down that accusing PCM of night ventilation, particularly while utilizing some particular control procedures of regular ventilation worked by outside windows opened outcomes in impressive cooling energy reserve funds. However, in these climate conditions, coupling PCM with natural ventilation improved energy savings. Combining the PCM with natural ventilation increased its effectiveness, however, the advantages were comparable to those of using natural ventilation on its own. Tao et al. [42], compared Low-E glazing to standard clear glazing when employing (NVDSF), considering the impact of spectrum optical characteristics, ambient conditions, and configurations. When clear glass is replaced with Low-E glass, the ventilation rate increases by 13%, according to the results. However, the ventilation performance is influenced by the spectral optical properties of Low-E glazing, where a higher absorptivity is better for natural ventilation. A summary of the researches in this section is shown in the Table 3.

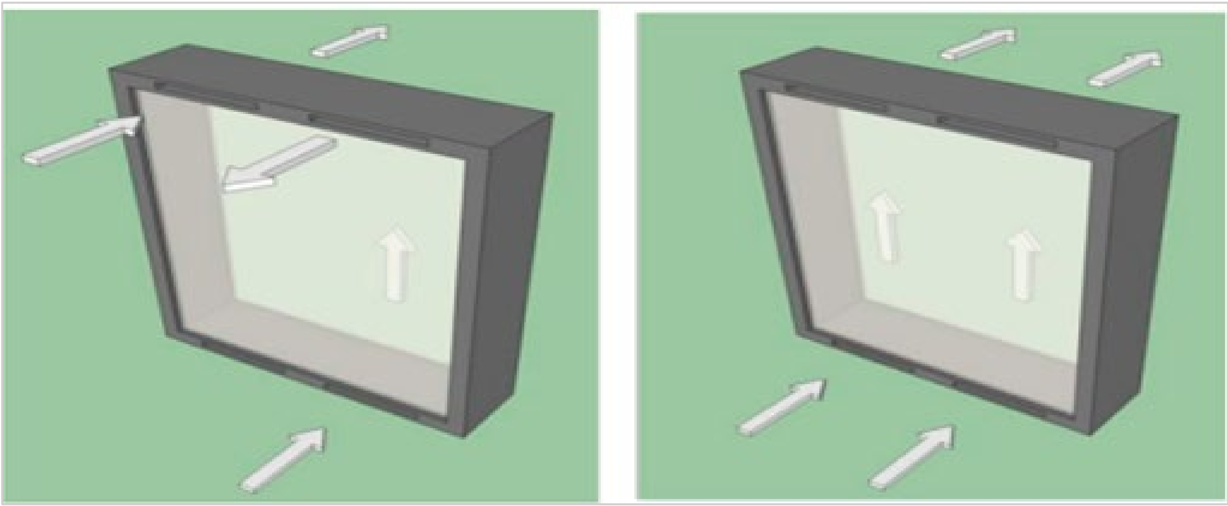


Figure 4: Illustration of the ventilation concepts: Cooling mode (left) and Heating mode (right) [38]

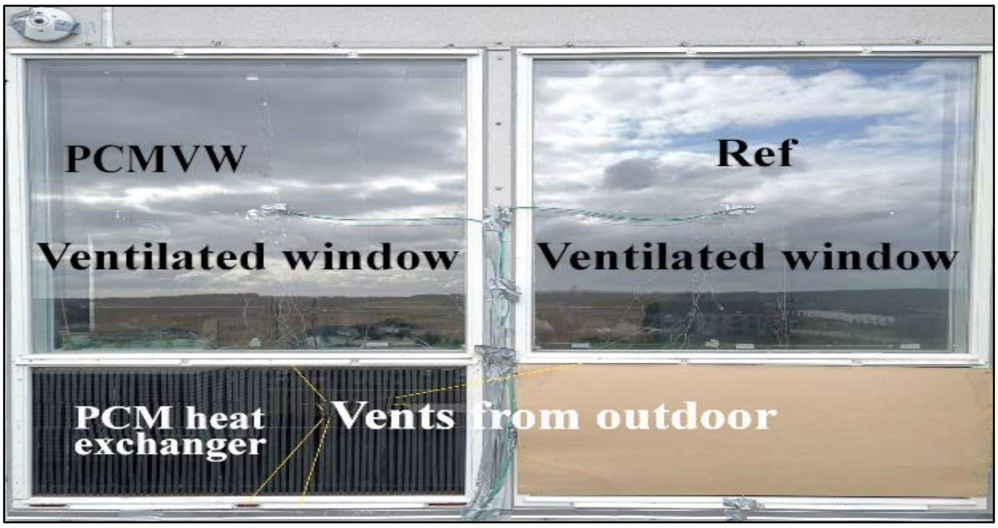


Figure 5: The Reference Window in The Right, The PCMVW In the Left [39]

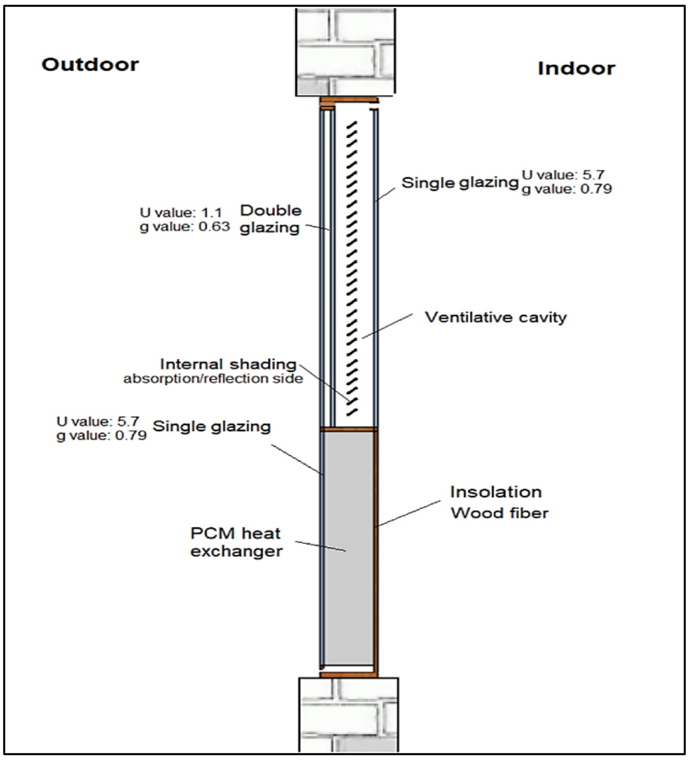


Figure 6: The overview of the VW + PCM model [40]

Table 3: Summary of results (Ventilated Glazing Window System)

Climate Zones	Descriptions System	Results and Conclusions	Ref.
Winter	An experimental examination of the thermal behavior of was presented for a ventilated facade's air cavity filled with macro-encapsulated PCM.	Under free-floating conditions, the utilization of this ventilated facade enhances the cubicle's overall thermal performance, whereas the oscillation of the outside temperature causes daily drops in the reference cubicle's indoor temperature. In severe winter conditions, raises daily temperature by 9°C to 18°C.	[36]
Cold winter hot summer China's zone	A new airflow network model and an improved zonal approach utilizing a dynamic venetian blind optical model.	The difference in temperature between outer and inner cavities is 4.4 and 2.0°C. The inner glass experiences a temperature decrease of 1.5°C when the slat angle is varied from 0° to 60°. When the slat angle is varied from 0° to 60°, heat gains can be reduced by 63%.	[37]

Table 3: Continued

-----	The study focuses on the examination of 15 distinct window typologies, encompassing variations in glazing type, glazing position, coating position, and cavity width, among others. The investigation considers two different ventilation concepts, namely the heating mode and cooling mode. The researchers conducted calculations to assess the energy demand and thermal comfort aspects, including the internal surface temperature and inlet air temperature of the window typologies, under diverse weather conditions in four European countries.	The study reveals that the preferred position for single glazing is on the internal side of the window. While this placement only marginally improves energy consumption compared to external placement, it significantly enhances the performance of the inlet air temperature. Thus, positioning the single glazing internally leads to more favorable results in terms of maintaining desirable inlet air temperature levels.	[38]
Summer and winter.	Compared between (no VW, no PCM), (VW, no PCM), and (VW, PCM).	Cooling on summer nights saves 46% and 27% of cooling energy in room 1 and 51% and 38% in room two. The PCM-VW reduces the energy of heating in room 1 by 29%, 48%, and 28%, respectively, for solar energy storage applications.The room with southwest-facing windows saves 62.3% of energy using the developed control strategy, while the room with northeast-facing windows saves 58.2%.The room with windows in the southwest saves 9.4% of energy using the developed control strategy, while the room with windows facing northeast saves 4%.	[39]
Summer and winter.	the researchers conducted an experimental study on a phase change material enhanced ventilated window (PCMVW). They investigated its thermal and energy performance in two different applications: ventilation pre-cooling and ventilation pre-heating. The experiments aimed to assess how the PCMVW performed in these scenarios and its potential benefits in terms of cooling and heating applications.	The results of the night cooling experiment demonstrated that when the PCM heat exchanger was employed, the room's inlet air temperature was, on average, 1.4°C lower for a duration of 7.0 hours compared to the normal ventilated window (VW). Additionally, the PCMVW achieved an average ventilation energy saving of 0.7 MJ/day during the tested period in comparison to a normal VW. However, it was noted that the pre-cooling effect of the PCMVW had limitations. On the other hand, the solar energy storage experiment indicated that the PCM heat exchanger was effective in increasing the VW's inlet air temperature by 2.0°C over a period of 12.0 hours. This enhancement led to an average ventilation energy saving of 1.6 MJ/day when compared to a normal VW.	[40]
Hot weather.	Investigated the relationship between PCM technology and natural ventilation.	By combining a PCM passive system with night ventilation, PCM's efficiency went up from 3.32 percent to 25.62 percent. When PCM was used with temperature-controlled ventilation, it increased to 40%.	[41]
-	Compared to ordinary glazing and low-E glazing in the utilization of (NVDSF).	At all solar intensities (50-1000W/m^2) and incident angles (100-800), the natural ventilation rate is approximately 13% higher with NVDSF.The NVDSF execution is preferred under solar intensities bigger than 600 W/m^2.The rate of ventilation increments until a vent level of 0.4 m. The best cavity gap is then found to be between 0.15 and 0.3 meters.	[42]

5. PCM blind system in glazing window system

Alawadhi et al. [43] studied using the finite element approach to limit solar heat absorption via windows in buildings by utilizing PCM in the shutter rather than foam. The high fusion latent heat of PCM may be employed to limit heat gain in the blinds by absorbing heat gain before it enters the interior area. The suggested PCM shutter system's thermal efficacy is measured by comparing the gain at the interior space to the heat gain of the foam shutter during normal working hours. The effect of various design parameters, such as the shutter's PCM type and quantity, is evaluated through a parametric study. Silva et al. [44], presented the outcomes of a summertime experiment using a window shutter that contained PCM. The blind prototype was tested in an outdoor cell with two compartments positioned side by side and orientated south.

The temperature of the air inside, the weather outside, and the heat flux through the interior wall partition were all monitored and analyzed. The external air temperature ranges from 13 ℃ to 25 ℃ during the experiment, and the average solar radiation measured is 237 W/m^2 to 306 W/m^2. Silva et al. [45], presented and discussed an experiment using a full-scale outdoor test cell with two compartments that are next to each other. The south-facing facade features a window shutter, a window protection system, and a glazed area. It was put to the test and compared two windows shutters that were similar, one with PCMs and the other without reference compartment throughout the course of the experiment, the relative humidity ranged from 75% to 95%, and the temperature of the outside air ranged from 4.5 to 14℃ with a highest thermal amplitude of 9.5 ℃. The maximum value reached was 310 W/m^2 and between 25W/m^2 and 110W/m^2, the daily average solar radiation was present. Li et al. [46], enhanced and tested a system of novel laminated composite PCM blinds with a large capacity for thermal energy storage in a typical (DSF) building. During the summertime period that was monitored, the findings demonstrated that the integrated PCM blind system might maintain a DSF average air temperature of less than 35 ℃ without significantly increasing the temperature compared to the surrounding temperature. Heat transfer into the building was reduced because the inner skin of the DSF had a surface temperature that was lower than the exterior skin's by about 2.9 ℃. Thermally, the PCM blind outperformed an ordinary aluminum blind by utilizing validated numerical models. Li et al. [47] focused on numerical and experimental evaluations of the integrated PCM blind system's thermal performance in DSF buildings.

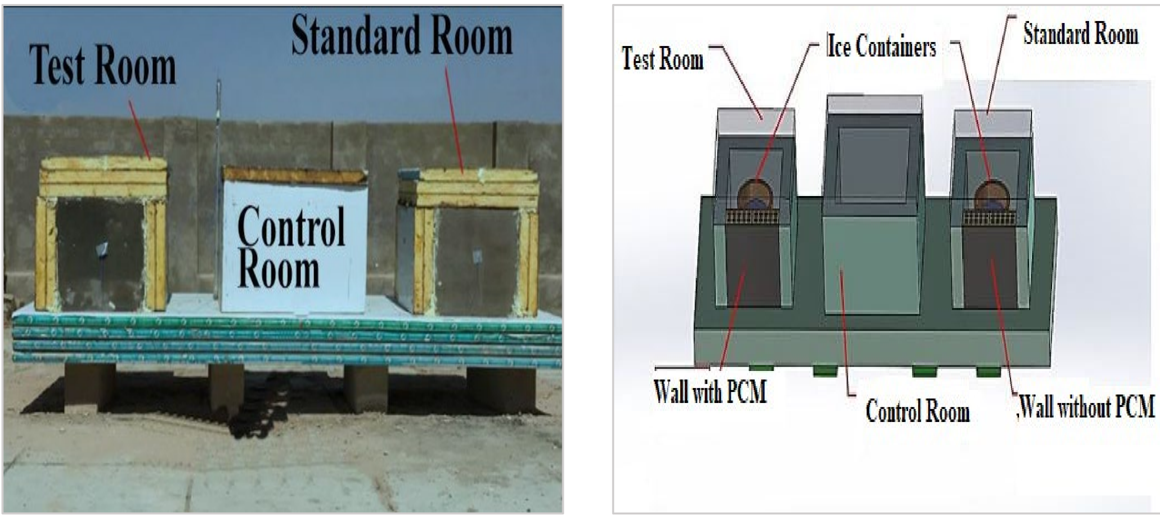
Experimental data were utilized to validate the numerical models in a DSF test facility that was integrated with the prototype that was created. The Heat flow and temperature profiles combined with the proposed PCM blind system and aluminum blind were modeled and compared using the (CFD) approach. Further theoretical evaluations revealed that the PCM blind is capable of both reducing the temperature of the air and absorbing more heat gain in DSF when compared to the standard aluminum blind. A summary of the researches in this section is shown in the Table 4.

Table 4: Summary of results (PCM Blind System in Glazing Window System)

Descriptions System	Results and Conclusions	Ref.
A PCM-filled window shutter is being studied as a means of lowering the amount of heat that enters buildings	When a P116 PCM shutter with a thickness of 0.03 m is used, heat gain through windows can be reduced by 23.29 %.	[43]
Analyzed and demonstrated the PCM’s thermal performance incorporated window blind in an experimental chamber during the summer climate.	The PCM window shutter can's compartment opens warm managing the limit of the indoor temperature around 18% - 22%. The greatest and least temperature tops diminished by 6% and 11%, individually. In addition to raising indoor temperature the PCM-equipped compartment took 45 minutes longer to reach the min temperature peak and 60 minutes longer to attain the highest possible temperature than the reference compartment (no PCM).	[44]
At full scale, the experimental performance of a window blind made of PCM was tested.	The PCM shuttered compartment has a max indoor temperature of 37.2 ℃, which is 16.6 ℃ lower than the reference compartment's indoor air temperature when comparing the indoor temperature over time, the decrease in temperature can reach 90% when the indoor air temperature rises, and up to 35% when they fall. The difference between the two compartments for the highest indoor air temperature peak is between 30% and 40%.	[45]
*Thermal insulation performance was theoretically and experimentally compared between (DSFs) blind systems with and without PCM	During the day, the interior glass skin's surface temperature was between 1.0 and 2.9℃ lower than the outside glass skin's surface temperature. Based on simulation results, PCM blind is more effective at lowering the average temperature of the DSF cavity air by 2.2 ℃, or about 5.5%.	[46]
An integrated PCM blind system's thermal performance was evaluated theoretically and experimentally.	During the day, the interior glass skin's surface temperature was between 1.0 and 2.9 ℃ lower than the external ones. The integrated system can keep the average temperature of the cavity air below 36 degrees Celsius during the day without significantly increasing it compared to the surrounding temperature.	[47]

6. PCM in building

Li et al. [48], compared the thermal mass of a glazed roof with PCM to that of a standard roof using experiments. various PCM layer thicknesses, PCM melting temperatures, and glazed roof slopes were tested to see how they affected the thermal environment's energy usage and dissatisfaction rate inside the building. The interior surface temperature of a glazed roof can be effectively reduced by raising the PCM's melting temperature, but the rate of dissatisfaction with the indoor thermal environment is only slightly affected. The peak temperature of the internal surface of the indoor chamber and glazed roof decreases when the thickness of the PCM layer is increased, as does the rate of dissatisfaction, energy consumption, and peak temperature enhancement when the slope of the glazed roof is increased. Li et al. [49], developed a one-dimensional photothermal model using the finite difference approach that takes into consideration phase-dependent thermophysical parameters as well as spectrum-dependent optical features. This model is used to study heat transfer through paraffin-glazed units. It was discovered that the heat transfer process can be accurately simulated using a 4-band spectrum. The outcomes showed that an unseemly choice of liquefying temperature or thickness of the paraffin layer might nullify the energy-saving point. When the melting temperature of paraffin is between 18 and 26 °C and the recommended paraffin layer thicknesses are between 6 and 12 mm, taking into account the transmitted energy, the paraffin-containing glazed window has a better photothermal performance for the climatic conditions that were studied. Jiang et al. [50], investigated the energy usage of different windows based on the thermal performance analysis of the glass and frames in a rural residence with a severe cold climate. To investigate the energy consumption of nine (WWR) groups, four glass types, four frame materials, and three frame configurations, there are three steps. The findings indicate that the most comprehensive plan is the single mullion, single transom type with triple pane glass, and PCM frame. The layout, which has a huge south window and a modest north window saves energy in order to meet lighting performance requirements and the structure and height of the building. It saves around 20% more energy than the first one. The design of windows and the use of a PCM frame in extremely cold environments are the subjects of the proposed conclusions. Abbas et al. [51], analyzed and looked into a numerical and experimental study of inserting capsules of PCM providing insulation into the hollow bricks that comprise a wall. Two identical rooms of a novel plug-and-play wall system were designed and constructed to test two southern walls with and without PCM in natural outdoor conditions. The findings indicate that the inner surface wall and room temperature will both decrease as a result of PCM encapsulation in the treated wall. From the reduction in the inner temperature of the PCM wall, it can be concluded that the utilization of PCM capsules will lead to an increase in the stored heat in the PCM wall more than that stored in the wall without PCM, and that will cause a reduction in the heat gain entering the room. Abbas et al. [52], planned and manufactured a test model comprises of two indistinguishable cubical rooms to test the wall in the case with and without PCM in a characteristic open-air condition in Iraq throughout the late spring as shown in Figure 7. The findings indicate that the PCM will lower the temperature of the test wall's inner side and the test room for the PCM capsules in the inner row, while the use of the capsules in the outer row will reduce the both temperatures of the inner surface and room. Therefore, the best location for PCM is in the inner row. Zu-An et al. [53], evaluated the influence laws and efficacy of various PCM on the thermal performance of walls in summer and winter by using a validated numerical model. The findings indicate that: (1) A single layer of PCM operates well in one season, but a double layer of PCM is the greatest choice all year. (2) The efficiency of double-layer PCM is directly connected to the difference in temperature between indoors and outside, which is greater in the summer than in the winter. A summary of the researches in this section is shown in the Table 5.



(A) **(B)**

Figure 7: Test Model of PCM capsules as insulation materials inserted into a hollow brick wall (A: Manufactured Test Model, B: Schematic Test Model) [52]

Table 5: Summary of Results (PCM in Building)

Descriptions System	Results and Conclusions	Ref.
In order to find out how the melting temperature of PCM thickness and roof slope affect the thermal performance of a glazed roof with PCM and indoor thermal comfort under genuine climatic circumstances.	The peak temperature decreases by approximately 16.3 °C, the time lag increases to approximately 40 minutes, and the energy consumption decreases by 47.5% when PCM is used with a melting temperature of 32 °C. Increasing the thickness of the PCM layer from 6 to 9 mm, energy consumption is reduced by 23%. The impact on energy consumption is lessened by an additional 16 mm increase in PCM layer thickness. The glazed roof's indoor peak temperature is 7.7 °C higher than the roof's 10 °C peak temperature at 30 °C of inclination.	[48]
The non-gray properties of glass and the liquid and solid phases of paraffin were taken into account when developing a model for paraffin-containing glazed windows.	The summer-appropriate paraffin with a melting temperature of 18–26 °C can provide a better condition for all of the taken into account parameters. In addition, the paraffin layer has a thickness of 6-12 mm.	[49]
The thermal transmittance and usage of energy of 4 distinct inner design temperatures (14, 16, 18, and 20 °C) are compared using original single glass and 3 varieties of multilayer glass windows.	The TW is recommended in extremely cold areas because it uses the least amount of energy at various indoor temperatures, saves 14.1–16.0 percent of energy, and decreases slightly with temperature. Window frame II + PSFP (plastic-steel frame + PCM) is the most effective and comprehensive thermal insulation scheme, able to save 12.2% more energy than the original design.	[50]
Find out how the use of PCM capsules as isolation will be integrated and affects the room's and wall's thermal performance.	Reduction of approximately 4.7°C in the PCM room's inner surface (TW) relative to the wall without any PCM. On the day of the examination, The PCM can minimize the TLL by 23.84 percent. Extending the delay by two hours.	[51]
The usage of PCM as a thermal protection material had been tentatively investigated in two models.	A decrease of approximately 2.7 °C in the inner surface TW-A. A decrease of approximately 2.7 °C in the air temperature of test room A.A decrease of approximately 1.9 °C in the inner surface TW-B. A decrease of approximately 1.9 °C in the air temperature of test room B.	[52]
A numerical model of the melting solidifying heat transfer process was built and verified as well.	When (ΔT) is narrower, the PCM usage increases under other relevant parameters; for example, T = 6 °C (27-33 °C, 12-18 °C) for double-layer PCM. Meanwhile, when the thickness and latent heat of PCM surpass 10 mm (5 mm+5 mm) and 125 kJ/kg, respectively, the efficacy achieves saturation When compared to the reference wall (without PCM), the optimized PCM may lower the attenuation rate by 84.6%/84.3%, delay time by 5 h/4.86h, and max and average heat flux by 58.2%/36.4% and 22.1%/19.4%, respectively.	[53]

7. Thermochromic with PCM glazing windows system

Soudian et al. [54], characterized the new cementitious plaster's optical and thermal properties to control thermal and solar loads. Cement plaster, thermochromic paint TC, and PCM were incorporated into a product made for use on exterior facades to dynamically control solar radiation and thermal stresses on the exterior of buildings. The samples' thermal conductivity, infrared emittance, and solar reflectance were measured. Jin et al. [55], analyzed numerically the possibility of combining 2 materials into a system of single adaptive glazing to save energy. PCM-integrated thermochromic triple glazing units were found to perform better than standard DGUs by limiting overall heat gain by as much as 32% or 40%, respectively., on sunny and cloudy summer days. However, they are prone to blocking more pleasant solar radiation in the winter, making them less effective than standard double-glazing units. Imghoure et al. [56], proposed a brand-new smart configuration with two PCM to improve buildings' energy efficiency. By controlling and adjusting how solar radiation is absorbed and reflected, it is based on the construction of adaptive exterior walls that can adapt to changing climate conditions. The findings demonstrate that, in the summer and winter, the effects of external climate conditions can be minimized with a configuration that includes two PCM with distinct melting temperatures. Ma et al. [57], conducted a parametric study to evaluate the implementation potential of novel windows in the severe cold region and presented a novel glazing window coupled with solid-solid PCM. The innovative window's energy performance is numerically examined under a variety of optical and thermal PCM characteristics to offer design strategies for the PCM parameters used in the innovative window. In the case of 10% property variations, the findings demonstrate that the building energy efficiency is significantly affected by PCM properties like latent heat, melting temperature, absorption coefficient, and refractive index. Ji and Li [58] evaluated the energy efficiency of thermochromic coatings with PCM (TC-PCM) systems in five distinct climate zones. According to simulation results, the yearly energy consumption of TC-PCM systems in Shanghai's climate characteristics decreases by 42.9 kWh/m^2 in comparison to traditional PCM systems (TR-PCM), resulting in an energy savings rate of up to 39.9%. This is because PCMs' phase change cycle performance could be improved by TC-PCM systems' adaptive solar absorptance, thereby lowering the amount of energy needed for heating and cooling. A summary of the researches in this section is shown in the table 6. Some studies use the PCM as thermal storage. [59-67].

Table 6: Summary of Results (Thermochromic with PCM Glazing Windows System)

Descriptions System	Results and Conclusions	Ref.
This study looked into whether a novel cementitious plaster made of PCMs and TC paint could be used as a finish material for exterior facades to control solar and thermal loads in different seasons.	According to the findings, the application of TC paint to the cement plaster surface resulted in a 23% increase in solar reflectance.	[51]
Double and triple glazing units included PCM and thermochromic glazing.	The overall heat gain is lowered by 32% on sunny days and 40% on cloudy days, respectively. In the winter, G5 and G6 perform worse than standard double glazing with a low-E coating, primarily because the majority of the time, PCM remains in its solid condition., preventing the desired solar radiation from entering the building. G6 may perform better than G1 on a sunny day with a lot of solar incident radiation if the phase-change temperature of the chosen PCM is lower than RT27.	[52]
The investigated materials are a PCM and a (TC). The thermal behavior of those materials when combined is simulated for walls.	The results demonstrate that using W-doped VO2 can lower the surface temperature of an indoor space in the summer, while this solution has no significant impact on the indoor temperature in the winter when compared to a reference case.	[53]
It is proposed to incorporate solid-solid PCM and silica aerogel into an innovative glazing window.	The innovative 4 mm single-glazing window has the potential to achieve a maximum energy savings of 18.22 percent for the building that houses it within the realistic range of PCM properties.	[54]
TC is suggested to further develop the energy proficiency of PCMs by managing sun-oriented radiation impact.	According to simulation results, the demand yearly energy usage for TCPCM systems reduces by 42.9 kWh/m^2, resulting in an energy savings rate of up to 39.9%.TC has a switching temperature of 26 °C and PCMs have a transition temperature of 26 °C, respectively. The TC-PCM system is also shown to have the lowest yearly energy demand.	[55]

8. Conclusion

A comprehensive review of studies on the thermal insulation applications of PCM in glazing window systems is presented in this paper. The evaluation yields the following conclusions:

1) In the first section, PCM in windows with double or triple glazing: When double or triple-glazed windows were filled with PCM, the access temperature due to high solar flux would be absorbed by PCM (latent heat) so the surface temperature will be decreased. Previous studies have shown that including PCM in triple-glazed windows decreases the temperature of the inner surface by 2.7°C and 5.5°C compared to double-glazed windows with PCM and triple-glazed windows.
2) In the second section, which discusses various filling insulation materials such as different nanoparticles with PCM-filled to increase the thermal conductivity. The previous studies have shown that, by using two different PCM melting temperatures, the maximum interior and surface temperatures are reduced by 6°C.
3) In the third section (ventilated glazing window system), the ventilated air at night was used to decrease the temperature of PCM which was obtained during the daytime. Previous studies have shown that utilizing ventilation during summer nights saves 46% on cooling energy.
4) The PCM blind system in the glazing window system is the fourth section. The integrated PCM blind system prevents the room's occupants from being exposed to direct sunlight. Previous studies have shown that the integrated PCM blind system prevented the room occupants from being exposed to direct sunlight.
5) In the sixth section (thermochromic windows using the PCM glazing system), the analysis shows a lot of potential for PCM and thermochromic glazing integration in the glazed facade to save energy in buildings and reduce total heat gain.
6) Nevertheless, studies on triple-glazed windows loaded with PCM or other fillers did not examine how well they performed in Iraqi climates or select the best PCM kind (melting temp) for the region's environment. A many researches have been made on the Iraqi environment and the melting temperature of the PCM was 40°C. A novel glazing method

that involves filling the window's interior surface temp with various insulating materials, including high- and low-melting-temp PCM, blinder with PCM, and nano with PCM, has gained considerable favor recently.

List of Abbreviations

PCM	Phase Change Materials
TW	Triple-glazed Window
DW	Double-glazed Window
TW+PCM	Triple-glaze Window + PCM
DW+PCM	Double-glaze Window + PCM
TW+PCM	Triple-glaze Window with PCM
TG	Triple-glass window
SG	Single glass window
DG	Double glass window
TDF	Temperature Decrement Factor
TTL	Temperature-Time Lag
DGUs	Double-Glazing Units
DPCMW	Dynamic rotating PCM Window
SPCMW	Static PCM Window
VG	Vacuum Glazing
IGU	insulated glazing unit
VWFW	VG insulation water flow window (VWFW)
TWFW	IGU insulated water flow window
DSF	Double Skin Façade
PCMVW	PCM-enhanced ventilated window
VW	Ventilated Window
NVDSF	Naturally Ventilated Double-Skin Façade
WWR	Window-to-Wall Ratio
PSFP	Plastic-Steel Frame + PCM
NTW	Wall without PCM
TC	Thermochromic coatings
TC-PCM	Thermochromic Coatings with PCM
CFD	Computational Fluid Dynamics
ΔT	Phase-transition Temperatures Range
LBW	Lightweight Building Walls

Author contributions

Conceptualization, M. Nsaif. M. Baccar and J. Jalil; writing—review and editing, M. Nsaif; supervision, M. Baccar and J. Jalil; project administration, M. Nsaif . All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] H. Akeiber, P. Nejat, M.Z.A. Majid, M.A. Wahid, A review on phase change material (PCM) for sustainable passive cooling in building envelopes, Renew. Sust. Energ. Rev., 60 (2016) 1470-1497. https://doi.org/10.1016/j.rser.2016.03.036

[2] F. Kuznik, D. David, K. Johannes, J.J .Roux, A review on phase change materials integrated in building walls, Renew. Sust. Energ. Rev., 15 (2011) 379–391. https://doi.org/10.1016/j.rser.2010.08.019

[3] R. Abd Razak, A.C.K. Zhe, M.M.A.B. Abdullah, Z .Yahya, S. Junaidi, K. Muhamad, N.A.M. Mortar, Paraffin as a phase change material in concrete for enhancing thermal energy storage, IOP Conf. Ser. Mater. Sci. Eng., 743, 2020, 012012. https://doi.org/10.1088/1757-899X/743/1/012012

[4] E. Rodriguez-Ubinas, L. Ruiz-Valero, S. Vega, Applications of Phase Change Material in highly energy-efficient houses, Energy Build., 50 (2012) 49-62. https://doi.org/10.1016/j.enbuild.2012.03.018

[5] S.M. Hasnain, Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques, Energy Build., 39 (1998) 1127–1138. https://doi.org/10.1016/S0196-8904(98)00025-9

[6] M. Ahangari ,M. Maerefat, An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions, Sustain. Cities Soc., 44 (2019) 120–129. https://doi.org/10.1016/j.scs.2018.09.008

[7] Y.A. Lakhdari, S. Chikh, A. Campo, Analysis of the thermal response of a dual phase change material embedded in a multi-layered building envelope, Appl. Therm. Eng., 179 (2020) 115502. https://doi.org/10.1016/j.applthermaleng.2020.115502

[8] C. Jia, X. Geng, F. Liu, Y. Gao, Thermal Behavior Improvement of Hollow Sintered Bricks integrated with Both Thermal Insulation Material (TIM) and Phase-Change Material (PCM). 2021, Case Stud. Therm. Eng., 25 (2021) 100938. https://doi.org/10.1016/j.csite.2021.100938

[9] C. Arkar , S. Medved, Free cooling of a building using PCM heat storage integrated into the ventilation system, Sol. Energy, 81 (2007) 1078-1087. https://doi.org/10.1016/j.solener.2007.01.010

[10] A. M. Khudhair ,M. M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Conv. Manag., 45 (2004) 263-275. https://doi.org/10.1016/S0196-8904(03)00131-6

[11] U.Stritih, V.Butala, Energy saving in building with PCM cold storage, Int. J. Energy Res., 31 (2007) 1532–1544. https://doi.org/10.1002/er.1318

[12] M. Beiranvand, M.R. Mohaghegh, Energy analysis and simulation of PCM enhanced building envelopes in commercial buildings. a case study, Energy Stor., 3 (2021) e246. https://doi.org/10.1002/est2.246

[13] T. Kawaguchi, H. Sakai, N. Sheng, A Kurniawan, Microencapsulation of Zn-Al alloy as a new phase change material for middle-high-temperature thermal energy storage applications, Appl. Energy, 276 (2020) 115487. https://doi.org/10.1016/j.apenergy.2020.115487

[14] A. Dobri, A. Tsiantis, T.D. Papathanasiou, Investigation of transient heat transfer in multi-scale PCM composites using a semi-analytical model, Int. J. Heat Mass Transf., 175 (2021) 121389. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121389

[15] S. Li, G. Sun, K. Zou, X. Zhang, Experimental research on the dynamic thermal performance of a novel triple-pane building window filled with PCM, Sustain. Cities Soc., 27 (2016) 15-22. https://doi.org/10.1016/j.scs.2016.08.014

[16] C. Liu, Y. Zheng, D. Li, H. Qi, X. Liu, A Model to Determine Thermal Performance of a Non-ventilated Double Glazing Unit with PCM and Experimental Validation, Procedia Eng., 157 (2016) 293-300. https://doi.org/10.1016/j.proeng.2016.08.369

[17] C. Liu, Y.Wu, Y. Zhu, D. Li, L. Ma, Experimental investigation of optical and thermal performance of a PCM-glazed unit for building applications, Energy Build., 158 (2018) 794-800. https://doi.org/10.1016/j.enbuild.2017.10.069

[18] W.M. Hashim , H.A. Hoshi, Energy Saving in Power Consumption by Using Double Glazing Windows in Iraq, Eng.Technol. J., 36 (2018) 1002-1007. https://doi.org/10.30684/etj.36.9A.10

[19] S. Li, K. Zou, G. Sun, X. Zhang, Simulation research on the dynamic thermal performance of a novel triple-glazed window filled with PCM, Sustain. Cities Soc., 40 (2018) 266-273. https://doi.org/10.1016/j.scs.2018.01.020

[20] J. M. Jalil ,S. M. Salih., Analysis of Thermal and Insulation Performance of Double-Glazed Window Doped with Paraffin Wax, Eng.Technol. J., 38 (2020) 383-393. https://doi.org/10.30684/etj.v38i3A.448

[21] J. M. Jalil, S. M. Salih., Experimental and numerical investigation of paraffin wax as thermal insulator in a double-glazed window, J. Energy Storage , 35 (2021) 102173, https://doi.org/10.1016/j.est.2020.102173

[22] A.M. Bolteya, M.A. Elsayad, A.M. Belal, Thermal efficiency of PCM filled double glazing units in Egypt, Ain Shams Eng. J., 12 (2021) 1523–1534. https://doi.org/10.1016/j.asej.2020.12.004

[23] L. Ravasio, R.K .Calay, R .Riise, Simplified Thermal Performance Evaluation of a PCM-Filled Triple-Glazed Window under Arctic Climate Conditions, Energies, 14 (2021) 8068.https://doi.org/10.3390/en14238068

[24] L. Wei, G. Li, S.T. Ruan, H. Qi, Dynamic coupled heat transfer and energy conservation performance of multilayer glazing window filled with phase change material in summer day, J. Energy Storage, 49 (2022) 104183. https://doi.org/10.1016/j.est.2022.104183

[25] M.F.L. King, P.N. Rao, A .Sivakumar, V.K. Mamidi, Thermal performance of a double-glazed window integrated with a phase change material (PCM), Mater. Today: Proc., 50 (2022) 1516–1521. https://doi.org/10.1016/j.matpr.2021.09.099

[26] A. Rodriguez-Ake, J. Xamán, I. Hernández-López, Numerical study and thermal evaluation of a triple glass window under Mexican warm climate conditions, Energy, 239 (2022) 122075.https://doi.org/10.1016/j.energy.2021.122075

[27] X. Zhang, Z. Liu, P. Wang, B. Li, Performance evaluation of a novel rotatable dynamic window integrated with a phase change material and a vacuum layer, Energy Conv. Manag., 272 (2022) 116333. https://doi.org/10.1016/j.enconman.2022.116333

[28] S. Wang, C. Zhang, S. Zhang, Y. Zhou, M. Arıcı, Characteristics of PCMs-filled double glazing unit under fire: A detailed thermal structural analysis, J. Build. Eng., 65 (2023) 105672. https://doi.org/10.1016/j.jobe.2022.105672

[29] D. Li, Y. Wu, C. Liu, G. Zhang, M. Arıcı, Energy investigation of glazed windows containing Nano-PCM in different seasons, Energy Convers. Manag., 172 (2018) 119–128. https://doi.org/10.1016/j.enconman.2018.07.015

[30] U. Berardi , S. Soudian, Experimental investigation of latent heat thermal energy storage using PCMs with different melting temperatures for building retrofit, Energy Build., 185 (2019) 180-195. https://doi.org/10.1016/j.enbuild.2018.12.016

[31] G. Zhang, Z. Wang, D. Li, Y. Wu, M .Arıcı, Seasonal thermal performance analysis of glazed window filled with paraffin including various nanoparticles, Int. J. Energy Res., 44 (2020) 3008-3019. https://doi.org/10.1002/er.5129

[32] C. Liu, Y. Lyu, C. Li, J. Li, K. Zhuo, H. Su, Thermal performance testing of triple-glazing water flow window in cooing operation, Sol. Energy, 2018 (2021) 108–116. https://doi.org/10.1016/j.solener.2021.02.048

[33] S. Zhang, W. Hu, D. Li, C. Zhang, M. Arıcı, Ç. Yıldız, Energy efficiency optimization of PCM and aerogel-filled multiple glazing windows, Energy, 222 (2021) 119916. https://doi.org/10.1016/j.energy.2021.119916

[34] N .Kaushik, P. Saravanakumar, .S Dhanasekhar, Thermal analysis of a double-glazing window using a Nano-Disbanded Phase Changing Material (NDPCM), Mater. Today: Proc., 62 (2022) 1702–1707. https://doi.org/10.1016/j.matpr.2021.11.537

[35] X. Yang, D. Li, R. Yang, Y. Ma, X. Tong, Y. Wu, Comprehensive performance evaluation of double-glazed windows containing hybrid nanoparticle-enhanced phase change material, Appl. Therm. Eng., 223 (2023) 119976. https://doi.org/10.1016/j.applthermaleng.2023.119976

[36] A. De Gracia, L. Navarro, A. Castell, Á. Ruiz-Pardo, Experimental study of a ventilated facade with PCM during winter period, Energy Build., 58 (2013) 324-332. https://doi.org/10.1016/j.enbuild.2012.10.026

[37] Y. Wang, Y. Chen, J. Zhou, Dynamic modeling of the ventilated double skin façade in hot summer and cold winter zone in China, Build. Environ., 106 (2016) 365-377. https://doi.org/10.1016/j.buildenv.2016.07.012

[38] M. Liu, P.K.Heiselberg, O.K. Larsen, L. Mortensen, J. Rose, Investigation of Different Configurations of a Ventilated Window to Optimize Both Energy Efficiency and Thermal Comfort, Energy Procedia, 132 (2017) 478- 483. https://doi.org/10.1016/j.egypro.2017.09.660.

[39] Y. Hu, R. Guo, P.K. Heiselberg, Performance and control strategy development of a PCM enhanced ventilated window system by a combined experimental and numerical study, Renew. Energ., 155 (2020) 134-152. https://doi.org/10.1016/j.renene.2020.03.137

[40] Y. Hu, P.K. Heiselberg, R. Guo, Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study, Energy Build., 214 (2020) 109903. https://doi.org/10.1016/j.enbuild.2020.109903

[41] M. Prabhakar, M. Saffari, A. de Gracia, L.F. Cabeza, Improving the energy efficiency of passive PCM system using controlled natural ventilation, Energy Build., 228 (2020) 110483.https://doi.org/10.1016/j.enbuild.2020.110483

[42] Y. Tao, H. Zhang, D. Huang, C. Fan, J. Tu, L. Shi, Ventilation performance of a naturally ventilated double skin façade with low-e glazing, Energy, 229 (2021) 120706. https://doi.org/10.1016/j.energy.2021.120706

[43] E. M. Alawadhi, Using phase change materials in window shutter to reduce the solar heat gain, Energy Build., 47 (2012) 421-429. https://doi.org/10.1016/j.enbuild.2011.12.009

[44] T. Silva, R. Vicente, F. Rodrigues, A. Samagaio, Performance of a window shutter with phase change material under summer Mediterranean climate conditions, Appl. Therm. Eng., 84 (2015) 246-256. https://doi.org/10.1016/j.applthermaleng.2015.03.059

[45] T. Silva, R. Vicente, F. Rodrigues, A. Samagaio, Development of a window shutter with phase change materials: Full scale outdoor experimental approach, Energy Build., 88 (2015) 110-121. https://doi.org/10.1016/j.enbuild.2014.11.053

[46] Y. Li, J. Darkwa, G. Kokogiannakis, W. Su, Phase change material blind system for double skin façade integration: System development and thermal performance evaluation, Appl. Energy, 252 (2019) 113376. https://doi.org/10.1016/j.apenergy.2019.113376

[47] Y. Li, J. Darkwa, W. Su, Investigation on Thermal Performance of an Integrated Phase Change Material Blind System for Double Skin Façade Buildings, Energy Procedia, 158 (2019) 5116-5123. https://doi.org/10.1016/j.egypro.2019.01.688

[48] D. Li, Y. Wu, G. Zhang, M. Arıcı, C. Liu, F. Wang, Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption, Appl. Energy, 222 (2018) 343–350. https://doi.org/10.1016/j.apenergy.2018.04.015

[49] D. Li, B. Wang, Q. Li, C. Liu, M. Arıcı, Y. Wu, A numerical model to investigate non-gray photothermal characteristics of paraffin-containing glazed windows, Sol. Energy, 194 (2019) 225-238. https://doi.org/10.1016/j.solener.2019.10.073

[50] W. Jiang, B. Liu, X. Zhang, T. Zhang, D. Li, L. Ma, Energy performance of window with PCM frame, Sustain. Energy Technol. Assess., 145 (2021) 101109. https://doi.org/10.1016/j.seta.2021.101109

[51] H. M. Abbas, J.M .Jalil, S.T .Ahmed, Experimental and numerical investigation of PCM capsules as insulation materials inserted into a hollow brick wall, Energy Build., 246 (2021) 111127. https://doi.org/10.1016/j.enbuild.2021.111127

[52] H. Abbas, J.M. Jalil, S.T. Ahmed, Experimental Investigation of The Optimal Location of PCM Capsules in a Hollow Brick Wall, Eng.Technol. J., 39 (2021) 846-858. https://doi.org/10.30684/etj.v39i5A.1980

[53] Z. A. Liu, J. Hou, Y. Chen, Z. Liu, T. Zhang, Q. Zeng, Effectiveness assessment of different kinds/configurations of phase-change materials (PCM) for improving the thermal performance of lightweight building walls in summer and winter, Renew. Energ., 202 (2023) 721-735. https://doi.org/10.1016/j.renene.2022.12.009

[54] S. Soudian, U. Berardi, N. Laschuk, Development and thermal-optical characterization of a cementitious plaster with phase change materials and thermochromic paint, Sol. Energy, 205 (2020) 282-291. https://doi.org/10.1016/j.solener.2020.05.015

[55] Q. Jin, X. Long, R. Liang, Numerical analysis on the thermal performance of PCM-integrated thermochromic glazing systems, Energy Build., 257 (2022) 111734. https://doi.org/10.1016/j.enbuild.2021.111734

[56] O. Imghoure, N. Belouaggadia, M. Ezzine, R. Lbibb, Evaluation of phase change material and thermochromic layers in a "smart wall" in different climates for improving thermal comfort in a building, J.Build. Eng., 56 (2022) 104755. https://doi.org/10.1016/j.jobe.2022.104755

[57] Y. Ma, D. Li, R. Yang, S. Zhang, M. Arıcı, C. Liu, Energy and daylighting performance of a building containing an innovative glazing window with solid-solid phase change material and silica aerogel integration, Energy Conv. Manag., 271 (2022) 116341. https://doi.org/10.1016/j.enconman.2022.116341

[58] R. Ji, X. Li, Numerical analysis on the energy performance of the PCMs-integrated thermochromic coating building envelopes, Build. Environ., 233 (2023) 110113. https://doi.org/10.1016/j.buildenv.2023.110113

[59] A. Oliver, Thermal characterization of gypsum boards with PCM included: Thermal energy storage in buildings through latent heat, J. Energy Build., 48 (2012) 1-7. https://doi.org/10.1016/j.enbuild.2012.01.026

[60] R. S. Oda, S.E. Najim, J.M. Jalil, Experimental Study of Thermal Performance of a Solar Collector Combined with Paraffin Wax as Phase Change Material PCM, Int. J. Eng. Res. Technol., 6 (2017) 108-113.

[61] R. S. Oda, S.E. Najim, J.M. Jalil, The Numerical Investigation of the Solar Collector Evacuated Tube Combined with Thermosyphon and Paraffin Wax as PCM, Int. J. Innov. Res. Sci. Eng. Technol., 6 (2017) 18472-18483. http://dx.doi.org/10.15680/IJIRSET.2017.0609153

[62] A. R. Abdulmunem , J. M. Jalil, Indoor investigation and numerical analysis of PV cells temperature regulation using coupled PCM/Fins, Int. J. Heat Technol., 36 (2018) 1212-1222. https://doi.org/10.18280/ijht.360408

[63] S. M. Salih, J.M. Jalil, S.E. Najim, Double-Pass Solar air Heater (DP-SAH) utilizing Latent Thermal Energy Storage (LTES), IOP Conf. Ser.: Mater. Sci. Eng., 518 (2019) 032038. https://doi.org/10.1088/1757-899X/518/3/032038

[64] B. E. Moon , H. T. Kim, Evaluation of thermal performance through development of a PCM-based thermal storage control system integrated unglazed transpired collector in experimental pig barn, Sol. Energy, 194 (2019) 856-870. https://doi.org/10.1016/j.solener.2019.11.009

[65] K. H. Suffer, J.M. Jalil, H.A. Hasan, Numerical Investigation of PCM Thermal Storage in Water Solar Collector, J. Adv. Res. Fluid Mech. Therm. Sci., 66 (2020) 164-78. https://www.akademiabaru.com/submit/index.php/arfmts/article/view/2816

[66] J. M .Jalil, H. S. Mahdi, A.S. Allawy, Cooling performance investigation of PCM integrated into heat sink with nano particles addition, J. Energy Storage., 55 (2022) 105466.https://doi.org/10.1016/j.est.2022.105466

[67] H. Zhou, J. Cai, T. Zhang, L. Xu, Q. Li, H. Ren, Z. Shi, Performance analysis on the concentrated photovoltaic /thermal air collector with phase change material and vacuum double-glazing for temperature regulation, Renew. Energ., 207 (2023) 27-39. https://doi.org/10.1016/j.renene.2023.03.012