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Review

Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis

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Abstract: Building envelopes can play a crucial role in building improvement efficiency, and the adoption of Phase Change Materials (PCMs), coupled with transparent elements, may: (i) allow a better control of the heat flows from/to the outdoor environment, (ii) increase the exploitation of solar energy at a building scale and (iii) modulate light transmission in order to prevent glare effects. Starting from a literature review, focused on experimental works, this research identifies the main possible integrations of PCMs in transparent/translucent building envelope components (in glazing, in shutters and in multilayer façade system) in order to draw a global picture of the potential and limitations of these technologies. Transparent envelopes with PCMs have been classified from the simplest "zero" technology, which integrates the PCM in a double glass unit (DGU), to more complex solutions—with a different number of glass cavities (triple glazed unit TGU), different positions of the PCM layer (internal/external shutter), and in combination with other materials (TIM, aerogel, prismatic solar reflector, PCM curtain controlled by an electric pump). The results of the analysis have been summarised in a Strengths, Weakness, Opportunities and Threats (SWOT) analysis table to underline the strengths and weaknesses of transparent building envelope components with PCMs, and to indicate opportunities and threats for future research and building applications.

Keywords: phase change materials (PCMs); PCM-filled window; transparent building envelope; Thermal energy storage (TES); glazing; SWOT analysis; review; experimental

1. Introduction

1.1. Background

Over the last few decades, research activities conducted to enhance the energy efficiency of buildings have led to the development of new functional strategies, technologies and materials. The façade, and the building envelope in general, are probably two of the most frequently investigated construction elements, as this is where most of the energy exchange between the indoor and the outdoor environment occurs, as well as where solar energy harvesting can take place.

Among the large variety of technologies and systems that can be used to increase the energy performance of a building, phase change materials (PCMs) are undoubtedly one of the key elements in R&D, and several applications of PCMs to the building envelope have been proposed (e.g., a commercially available transparent technology system with an integrated prismatic solar reflector and a cavity filled with PCM has been developed by GlassX (Zurich, Switzerland).

PCMs are materials that exhibit a phase change (usually a solid-to-liquid transition in building applications) over a desired temperature range, and which are able to exploit the latent heat of the

phase change for thermal energy storage purposes. Different analyses on the state of the art of PCM in building applications were published between 1998 and 2016 [1–8]. PCMs are generally employed in opaque building envelope components [4]. However, applications of PCM to transparent building components have also been proposed, and have undergone a grown focus in the last few years [9,10].

The main aim of the adoption of PCMs in transparent systems is to increase the thermal inertia of glazed components and to improve the overall performance of glazed components, in terms of energy and comfort. In other words, the goal of this concept is to better manage the direct solar gain (which can cause overheating problems) and to minimize the heat loss, thanks to the buffer effect provided by the PCM layer, while still allowing the visible part of solar radiation to be exploited for daylighting. Such an effect is only possible because of the optical properties of many PCMs, which show partial transparency to electromagnetic radiation within the solar range. The PCM layer is used to absorb and store (thanks to latent heat) most of the short-wavelength infrared (SW-IR) radiation, near infrared (NIR) radiation and part of the visible (VIS) radiation, and to let part of the VIS radiation enter the indoor environment in order to provide daylighting.

However, the performance and effectiveness of the PCM glazing concept are somewhat complicated to predict, and may sometimes show positive aspects and sometimes negative ones. This depends on different features of the system (i.e., the technology of the assembly), on the material itself (i.e., the type of PCM) and, more in general, on how the system is related to the building energy concept, and how it is managed (i.e., whether the component acts as a fully passive system or is actively controlled through additional devices).

Furthermore, applications in different climates or in different building types might lead to substantially different outcomes. Moreover, complexity also arises from the fact that these systems influence different domains of the building energy and indoor environmental performance (i.e., both thermal and visual environment), and that a concept or solution that might be suitable for one domain might not perform so well as far as the other domain is concerned.

In terms of building energy performance, the PCM glazing concept (like other state-of-the-art transparent building envelope components) is called upon to assure a good performance in terms of reduction of transmission heat loss (i.e., to obtain low values of thermal transmittance), to offer a (possibly dynamic) control of solar irradiance transmission (i.e., to obtain variable values of solar factor), and to allow a good exploitation of daylight to be achieved (i.e., to contribute to high values of daylighting autonomy and the daylight uniformity ratio) [11]. Furthermore, when it comes to thermal and visual comfort, the integration of PCM in transparent components should be able to assure suitable surface temperature values (to avoid general and local thermal discomfort conditions), and reduce the risk of glare discomfort for the occupants.

1.2. Aim of the Paper

A review, classification and detailed analysis of different PCM glazing concepts that appeared in the scientific literature between 1998 and 2018 are presented in this paper. The first aim of this work is to provide an up-to-date classification and state of the art of PCM glazing concepts, and then to include the latest development in the field since the most recent reviews on these technologies [9,10] have been published. Moreover, on the basis of the first-hand experience of the authors, and on the findings from the search in the scientific literature, the paper presents a critical analysis of the performance of the different systems, adopting the structure of the well-known SWOT analysis (Strengths, Weaknesses Opportunities, Threats). The analysis of the state of the art is presented through tables, where each research activity on or technology for the integration of PCM in transparent envelope components is listed. The main achievements, strengths, weaknesses, opportunities, and threats of each research activity are highlighted synthetically.

The scope of this SWOT analysis in particular was to crystalize the knowledge so far achieved on PCM glazing concepts and to identify necessary developments in R&D in order to further improve the performance of the systems investigated so far.

2. Literature Review at a Glance

The literature review was based on a total of 30 papers, published between 1997 and 2018, related to experimental analyses of PCMs in transparent building envelope components. The analysed works were published in peer review journals and conference papers. The review analysis was restricted to only experimental research which presented the results of experimental in-field campaigns and to laboratory tests carried out on transparent technology prototypes with PCM. The investigated features are represented in Figure 1 and the percentages refer to the total number of studies, that is, 30 (thus representing 100%):

- in the "Geographical distribution of the studies" chart, each bar expresses the number of studies conducted for each country;
- in the "Climatic distribution of the studies", "PCM typology", "Type of analysis" and "Type of experimental characterisation" charts, each bar expresses, in percentage, the number of studies which considered the feature described in each row;
- the "PCM encapsulation" pie chart reports, in percentage, the distribution of the analysed articles, according to the typology of the containers.

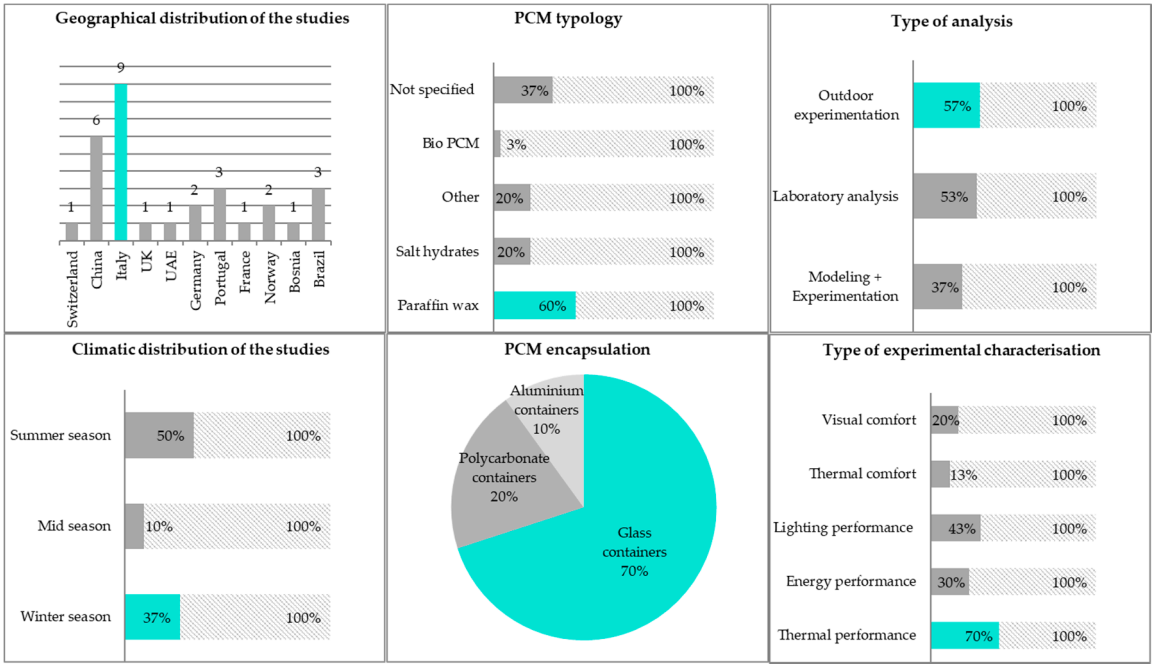


Figure 1. Analysis of the papers that presented experimental activities on PCM glazing systems.

A simple analysis of the paper features has led to the following synthetic picture of PCMs in glazing (see also Figure 1):

- the geographical distribution of the studies, which also provides an indication of the climatic conditions of the study;
- the climatic/seasonal distribution of the studies: winter season (37%) [12–22], mid-season (10%) [14,15,20] and summer (50%) [13–17,20,23–31] season periods;
- the most investigated PCM typologies, that have been found to be paraffin wax (60%) [14–16,18,19,22,23,25–35] and salt hydrates (20%) [12,13,16,17,28,36,37], while only one study analysed the performance of bio PCMs (3%) [28];

- in all the papers, the PCM had been macro-encapsulated in containers, that is, glass containers (70%) [12–15,20–25,27,30–35,38–41], polycarbonate containers (20%) [16,17,19,28,36,42] and aluminium containers (10%) [18,26,29];
- the technologies had predominantly been characterised in outdoor test cells (57%) [14,15,17–22,24–27,29,31,35] and through laboratory analysis (53%) [12,13,17,20,23,32–42], while some other studies had been carried out by coupling a modelling activity with an experimental activity (37%) [12–14,16,21,23,29,30,32,34,37,40];
- the parameters investigated for the performance characterization of PCM transparent building envelope components have been found to be related above all to thermal performance (70%) [13,14,16–27,29–31,36,37,41,42] and lighting performance (43%) [12,20–22,31–35,38–41], while 30% of the studies evaluated energy performance [15,21–23,25,28,31,37,38];
- very few analysis had been carried out to evaluate the thermal (13%) [14,17,22,31,37] and visual (20%) [14,15,17,22,30] comfort performances related to the application of the technology at a room level;
- in all the papers, the analysis of the PCM transparent systems had been investigated at a component scale, while only a few works had extended the analysis to a building/system scale (13%) [14,17,20,35,37].

This synthetic analysis on the literature has made it possible to highlight the international interest in the subject of PCMs in glazing and to outline the main current research lines on the subject.

3. PCMs in Transparent Building Envelopes: A Technology Classification

The papers related to the integration of PCMs in transparent building envelopes have been classified according to the type of technology that had been considered. In order to improve the energy efficiency of the glazing areas and transparent/translucent areas, PCMs can be integrated in three main ways:

(1) in the glazing, in order to directly enhance the heat capacity and thermal inertia of fenestration;
(2) in the shutters, where they act as an energy buffer, and can be positioned either inside or outside a traditional window;
(3) in façade systems, to interact with other insulating materials and solar control devices in a multilayer technology.

Each building application can be subdivided into different technological systems (Table 1), starting from the simplest "zero" technology, which integrates the PCM in a DGU, to more complex solutions, which can involve varying the number of glass cavities (TGU), the position of the PCM layer (internal/external shutter) and the interaction with other materials (TIM, aerogel, prismatic solar reflector, PCM curtain controlled by an electric pump). The technological systems have been analysed on the basis of the following classification (Table 1) in this paper:

- *Technology number 0*, basic glazing technology: integration of the PCM in DGU glazing;
- *Technology number 1*, advanced glazing technology: integration of the PCM in TGU glazing;
- *Technology number 2*, shutter technology: integration of the PCM in the shutter;
- *Technology number 3*, façade system: integration of the PCM in the façade.

Sub-categories have been identified for each category, and the working principle used to integrate the PCM in the glazing has been indicated (Table 1).

Table 1. Technologies integrating PCM in transparent envelopes.

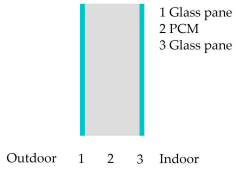
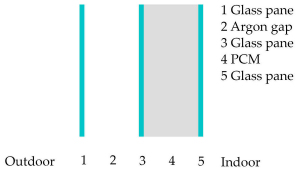
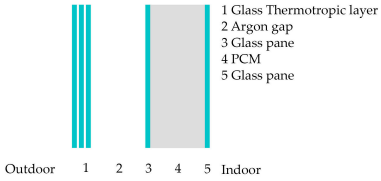
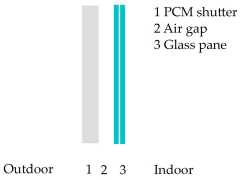
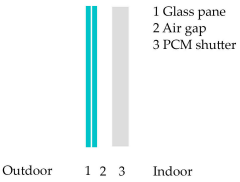
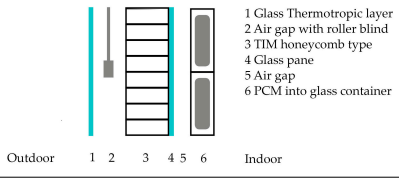
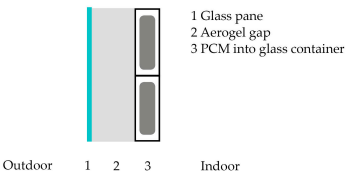
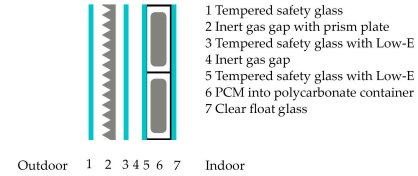
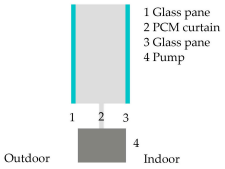
Technology	Sketch	Description	Concept
0_ basic glazing technology: integration of the PCM in DGU glazing			
0		Integration of the PCM in a double glazing unit (DGU + PCM)	Solar control modulation and thermal inertia improvement
1_ advanced glazing technology: integration of the PCM in TGU glazing			
1		Integration of the PCM in a triple glazing unit (TGU + PCM)	Solar control modulation, thermal resistance and thermal inertia improvement
1a		Integration of the PCM in a triple glazing unit with a control system (TGU + PCM + TT)	Better control of the PCM charge phase
2_ shutter technology: integration of the PCM in a shutter			
2a		PCM external shutter	Time shift of incoming peak loads; glare reduction
2b		PCM internal shutter	Solar energy storage in winter; internal window surface temperature reduction in summer
3_ façade system: integration of the PCM in a façade			
3a		TIM + PCM	Selective optical transmittance of solar radiation; improvement in the thermal inertia of the glazing system
3b		Aerogel + PCM	Superinsulation and heat storage, increase in the U value

Table 1. *Cont.*

Technology	Sketch	Description	Concept
3c		Prismatic solar reflector	Light control, heat storage and improvement in the thermal inertia
3d		Double glass with PCM curtain controlled by an electric pump	Light control, heat gain control

4. SWOT Analysis

4.1. Strenghts and Weaknesses of PCM Glazing Systems

A SWOT analysis has been developed from the review of the literature papers presented briefly in Section 2 and it is described in the following section. The potential and limitations of the following devices are presented hereafter on the basis of the classification of the transparent technologies given in Section 3:

- the basic glazing technology (Section 4.1.1);
- the advanced glazing technologies: integration of the PCM in TGU glazing (Section 4.1.2);
- the shutter technology: integration of the PCM in the shutter (Section 4.1.3);
- the façade system: integration of the PCM in the façade (Section 4.1.4).

It's important to underline that the main outcomes (strengths, weaknesses, opportunities, and threats) for each solution are here synthetically summarised as found in the original paper, without any interpretation or added consideration by the Authors of this Review.

4.1.1. Basic Technology: Integration of the PCM in DGU Glazing

The basic technology in which the PCM is integrated in transparent building envelopes involves a double-glazing unit (DGU), where the cavity between the two glass panes is filled with PCM instead of a gas. This type of technology was first introduced about twenty years ago by Manz [12].

So far, the literature has presented different experimental studies on the integration of PCM in glazing units [13,23,24,30,32–34,41,43,44]. Real-scale prototypes of the technology (DGU + PCM) were used to collect data during measurements [25,26,28], and the assembly and the construction of these prototypes were carried out in house laboratories. Experimental tests were performed in outdoor test cells, and the energy performance of the PCM system were analysed and compared with a conventional fenestration. The surface temperatures, transmitted irradiances, heat fluxes and comfort performance of both the PCM glazing and the reference fenestration were measured during extensive experimental campaigns, in order to assess the energy performance of the technology under different boundary conditions. Starting from experimental results, the effects of thermo-physical parameters on the dynamic heat transfer performance of PCM were also investigated by means of numerical simulation softwares [13,23,30,43–45]. The semi-transparent property of a glazing roof containing PCM and the effect of zenith angle on the thermal performance were only analysed numerically by Liu et al. [46,47].

The effect of the PCM thickness and PCM melting temperatures on the thermal performance of double glazing units have been numerically and experimentally investigated by Liu et al. [21,41].

Furthermore, some results concerning laboratory characterizations [32,34,35,44] and numerical investigations [24] were published to determine the optical properties of the technologies for PCMs in solid and liquid states. The use of large integrating sphere equipment [33,35] has been necessary to obtain reliable results, due to the high scattering property of the system when the PCM is in a solid state. Transmittance, reflectance and absorbance spectra have been measured at different incident beam angles for components with different PCM layer thicknesses. Durakovic and Torlak [30] carried out laboratory and natural environment experimental activities to collect data and to validate a numerical model on a DGU with PCM in order to optimize the PCM layer thickness in the cavity.

The tested PCM typologies are commercially available paraffin-based ones with different nominal melting temperatures [15,23,30,32] and eutectics [13].

The results of the studies highlighted the potential of the technologies:

- to reduce the cooling load [13,15,23,30,43];
- to exploit the time shift of the cooling load—a well-designed project will ensure that the external temperature will start to decline before total melting of the enclosed PCM [15];
- to improve the poor thermal inertia of the glazing system [21,30,32,41];
- to collect and store solar energy at a building scale—a reduction in the "mismatch" between the heating demand and the availability of solar radiation during winter time-[15];
- to better control the visible solar radiation and reduce the glare risk—an improved exploitation of daylighting-[33–35];
- a "mitigation" of the internal glass surface temperatures, which leads to an improvement in the thermal comfort [14].

On one hand, the improvements, in terms of energy performance and visible control, that can be obtained using DGU + PCM were assessed during different seasons—summer, winter, mid-season [14,15,33,43], while, on the other hand, some threats and weaknesses were reported. However, further investigations of thermally massive glazed units and the optimization process used to control the transition of the PCM are still needed [14,15,32]. This can be achieved by choosing a proper melting temperature range on the basis of the considered boundary conditions in order to avoid too fast melting in summer or incomplete melting during winter.

Moving to the building scale, Bionda et al. [48] developed a simulation tool to evaluate the energy saving potentiality of translucent windows with PCM. The results showed that the application of the basic technology (DGU + PCM) can lead to both cooling and heating reductions, of between 1–9% and 7–10%, respectively. A further positive impact on thermal comfort was highlighted, with a reduction in the number of hours of overheating.

As a general comment, it is possible to state that the Technology Readiness Level (TRL) can be assessed as being between 4 and 6, which means that the technologies are in the validation phase in laboratories and in a significant environment. However, some steps still need to be taken to reach TRL 9.

The works concerning the basic technology DGU + PCM technology are reported in Table 2. The main achievements, strengths, weaknesses, opportunities and threats are synthetically highlighted.

Table 2. SWOT analysis of PCM in DGU glazing.

0_ Basic Glazing Technology: Integration of the PCM in DGU Glazing S: Strengths, W: Weaknesses, O: Opportunities, T: Threats						
Ref.	**PCM**	**Aims**	**S**	**W**	**O**	**T**
Technology 0 Durakovic et al., 2017 [30]	Paraffin wax	Impact of PCM on the thermal performance of windows	Improvement in the thermal performance (lower interior surface temperature and overheating delay) and reduction in the building energy demand	Instantaneous jump in the heat gain once the PCM has melted completely.		
Technology 0 Goia et al., 2013 [14]	Paraffin wax	Evaluation of the thermal comfort performance during different seasons	Shading and buffering effects of the PCM improve the indoor thermal conditions and prevent glare effects	No significant comfort improvement on cloudy days (low incident solar irradiation); overheating risk during summer		Few commercial PCM glazing on the market, and limited quantification of their real advantages in terms of energy efficiency and indoor environmental comfort.
Technology 0 Goia et al, 2014 [15]	Paraffin wax	Thermal benefits of a PCM glazed unit compared with traditional double glass	Reduction in the total daily energy gains. Smooth shift of solar gains in summer.	Partial phase change process in winter, decrease in the solar free gains; overheating risk during summer; required integration of the system with indoor air temperature control strategies	The transition temperatures of PCM can be chosen freely over a wide range of values and thus a relatively high degree of tuning is assured to suit different conditions; Integration of PCM in transparent elements allows daylighting to be exploited while preserving privacy (when PCM is in solid phase)	The integration of PCM in a traditional DGU could determine an increase in the price of the final product (impact on the production costs of the glazed unit)
Technology 0 Gowreesunker et al., 2013 [32]	Paraffin wax	Characterization of the optical and thermal aspects of a PCM glazed unit compared with a reference unit	Improvement in the thermal mass of the transparent envelope	The transmittance spectra are unstable during rapid changes in temperature or the phase of the PCM; changeability of the visual aspects	Change in transparency of PCM as a design issue	Some default modelling of phase change in some simulation tools not based on the effective-heat capacity method may lead to inaccurate results
Technology 0 Liu et al., 2017 [21,41]		Effects of PCM thickness and melting temperature on the thermal performance of double glazing units	During winter, the thickness of the PCM layer of a DGU PCM system positively influences the performances of the system as a result of an increase in the interior temperature, and of a decrease in the total transmitted energy and transmitted solar energy	Weak optical performance of the technology filled with PCM		
Technology 0 Zhong et al., 2015 [26]	Paraffin wax	Effects of the thermophysical PCM parameters on the dynamic heat transfer characteristics of a PCM window	Shifts in the peak load of an air conditioning system; heat transfer reduction during a sunny summer; load shift effect and thermal insulation effect of PCM glazing improves with the increasing latent heat of fusion.	Slight increase in the solar heat gain of the system compared to the reference system, in the presence of low solar radiation; heat transfer increase on rainy summer days		High costs and unsatisfactory annual energy saving effects of other commercially available tested transparent technologies (thermochromic window, electrochromic glass, window with semi-conductor solar cells and low-E film)

4.1.2. Advanced Technology: Integration of the PCM in TGU Glazing

The adoption of Phase Change Materials, in combination with advanced technologies, has been investigated in order to improve the weaknesses of the basic technology through the interaction of the PCM layer with more complex transparent envelopes through a multilayer structure.

The parameters investigated in order to assess the optimal configuration of a PCM transparent technology are:

- the location of the PCM compared to the position of the glazing;
- the PCM layer thickness;
- the interaction of the PCM with insulating materials;
- the interaction of the PCM with solar control devices in order to control daylighting.

The following research case studies analysed the potential and limitations of transparent advanced technologies containing phase change materials.

Goia et al. [25] and Bianco et al. [22,31] studied the technology that integrates Phase Change Material in triple glazing units (TGU) through experimental and a numerical analysis [49] in order to assess the thermo-physical behaviour of the components, by varying the position of the PCM layer in the inner or outer cavity of a triple glazing, and they obtained a better buffer performance—U value and thermal inertia—compared to the DGU technology.

They developed a physical-mathematical model to test the effect of variations in the position of a PCM layer in the inner-outer cavity of the TGU on the energy performance of the components, while real-scale prototypes were set up to analyse the influence of Thermotropic glass (TT) on solar energy transmission control. All the tested PCMs were paraffin based, with different melting temperatures of 25, 30 and 35 °C, in order to identify the best range during the summer period.

The results of this research highlight the potentials of this technology:

- solar gain reduction during daytime;
- heat storage within the paraffin layer;
- IR radiation absorption;
- heat flux peak shift;
- better control of the PCM melting process using a TT layer.

The main limitations are connected to the limited active control over the release of energy in summer and the drastic reduction in solar free gains during winter.

The experimental research of Li et al. [27] was focused on the dynamic thermal performance and energy saving performance of a triple-pane window with the outer cavity filled with PCM (paraffin type) during summer days. Compared to a DGU + PCM, the system effectively avoided overheating risks and reduced heat transfer to the room on sunny days, while the TGU + PCM component showed a good performance on reducing the temperature fluctuation of the interior surface and the heat entered the room on rainy days, but it was unsatisfactory in reducing the peak heat flux of the interior surface and delaying the peak temperature. The works concerning the advanced TGU + PCM technology are reported in Table 3.

Table 3. SWOT analysis of PCM in TGU glazing.

1_ Advanced Glazing Technology: Integration of the PCM in TGU Glazing S: Strengths, W: Weaknesses, O: Opportunities, T: Threats						
Ref.	**PCM**	**Aims**	**S**	**W**	**O**	**T**
Technology 1 Li et al., 2016 [27]	Paraffin wax MG29	Evaluation of the thermal performance and energy saving potential of a TGU + PCM during summer days	On sunny days, PCM in the outer chamber of a system effectively reduced peak temperatures on the interior surface and incoming heat, compared to a reference system	On rainy days, the system is unable to satisfactorily reduce the peak heat flux and delay the peak temperature on the inner surface	Possibility of adjusting and shifting the peak load of an air conditioning system, and of reducing its energy consumption	
Technology 1a Goia et al., 2014, Bianco et al., 2017 [22,25,31]	Paraffin wax	Evaluation of the effect of the position of a PCM layer (inner-outer cavity of the TGU) on the thermo-physical performance of the technology system	An TT layer prevented the complete melting of PCM in an inner cavity; reduction in the solar gain and peak indoor surface temperature during daytime	Complete exploitation of the latent heat of fusion of PCM in an outer cavity with a consequent increase in the transmitted irradiance; in the case of high solar irradiation, PCM in the outermost cavity negatively affects the thermo-physical behaviour of a system	Further investigation of the behaviour of a system inserting PCM with different transition temperatures; enhancement solar energy use and reduction of the time mismatch between solar energy availability and heating/cooling energy demand	Limited effect of the thermotropic layer considering the small variations in the optical properties

4.1.3. Shutter Technology: Integration of PCMs in Shutters

The concept of PCM integration in shutter systems was first developed in order to shift the potential of thermal storage and a surface temperature decrease-internal shutter-and solar-light control and a peak solar radiation reduction-external shutter-to another element positioned in front of the glazing.

Internal PCM sun protection studies [16,17,29,50] dealt with the problem of the overheating of a screen positioned on the inner side during the summer period: in the case of incoming solar radiation, the blind can only heat up to the melting temperature of the PCM, which then starts to absorb heat and store it as latent heat. A further increase in temperature cannot occur until the PCM has melted completely. The PCM thus decreases the blind surface temperature as well as the g-value of the system. Furthermore, the possibility of increasing the thermal inertia of the glazing during winter [16–18,26,51] could be achieved, thanks to the insulation properties of the PCM layer and to the possibility of taking advantage of the heat stored during the day for the release phase of the material.

The concept of moving the PCM layer to external shutters [19,28,52] was proposed to optimize the technology performance during the summer period, by absorbing incident solar radiation before it enters indoor spaces and exploiting the latent heat storage process of PCM to shift the peak values of heat fluxes and surface temperatures.

The experimental analysis carried out by Bianco et al. [28] verified the influence of the colour of the polycarbonate panel and the behaviour of different PCMs typologies on the performance of shading components; furthermore, a qualitative analysis of the PCM phase transition pointed out the strong discontinuity in appearance that can limit the application of transparent PCM-filled components in architecture.

The works concerning the technologies of PCM shutters are reported in Table 4. The tested PCMs are paraffin-based ones and salt hydrates.

The results of the studies highlight the potential of the technologies:

- heat gain reduction;
- internal surface temperature reduction;
- thermal comfort enhancement;
- peak cooling load reduction;
- glare risk reduction;
- thermal inertia enhancement and heat loss reduction in winter.

The main limits of this technology are represented by the reduction of the incoming daylight and problems related to leakage; furthermore, the melting temperature range of PCM should be chosen carefully in order to prevent the material from melting too quickly in the external shutters as well as the incomplete melting of the PCM in the internal components.

Future improvements could be made concerning the visual appearance of the system to improve the architectural integration of the element, by enhancing the appearance quality of the shading during the melting phase and considering the possibility of integrating ventilation systems to improve the PCM discharging process.

Table 4. SWOT analysis of PCM in shutters.

2_ Shutter Technology: Integration of the PCM in the Shutters S: Strengths, W: Weaknesses, O: Opportunities, T: Threats						
Ref.	**PCM**	**Aims**	**S**	**W**	**O**	**T**
Technology 2a A. Komerska et al., 2015 [19]	Paraffin wax	Evaluation of the thermal performance of a polycarbonate shutter containing PCM in a mid-season (solid phase)	Reduction in the total daily solar heat gains and in the internal surface temperature; preservation of high illuminance level. Improvements in the thermal resistance of the shutter and window of the system	Absence of a melting process during the whole measurement period; during cloudy days, performance decrease in the system; negative effect of a solar heat gain reduction in winter		
Technology 2a Bianco et al., 2017 [28]	Paraffin wax, Salt hydrates, bio PCM	Experimental analysis in an outdoor test cell to evaluate the energy performance of the technology and verify the influence of the colour of the polycarbonate panels and the behaviour of different PCM typologies	Good potentiality of the technology to reduce the cooling daily energy compared to the reference system. Reduction in the internal surface temperature of the glazing with a PCM shutter, compared to reference system. Improvement in the thermal inertia of the dynamic window with a time peak shift of the heat fluxes.	Decrease in the performance of the total heat flux reduction of the PCM systems for higher sol-air temperatures than 26 °C, compared to the reference; discontinuity in appearance during the melting phase of the PCM;	Future research developments to make the system more adaptive and better performing during summer, and extending its use to winter and intermediate seasons may require the coupling of different panels (colours, thicknesses) filled with PCM with different melting temperatures and typologies; optimization strategies of light and solar transmittance can be obtained by fluidizing the materials in the panel using slurry PCM	Limited scientific evidence in literature in relation to the durability of bio PCMs; sealing problem of the material in polycarbonate; the observed discontinuity in appearance of PCMs could limit architectural applications of transparent components containing PCM
Technology 2b Weinläder et al., 2005 [16]	Paraffin wax, Salt hydrates	Effect of variations in the PCM typology on the thermal—comfort performance	Low heat loss in winter; reduction in the peak cooling loads in summer; thermal comfort enhancement	Leakage of the containers, inhomogeneous appearance; overheating risk in summer; limited visual contact with the environment	Homogeneous visual performance investigations by means of a concealing measure, e.g., screen-printed glazing; investigation of the thermal comfort performance	
Technology 2b Weinlaeder et al., 2011 [17]	Salt hydrates	Effect of PCM integrated with the blinds of a polycarbonate shutter on the thermo-physical performance of office buildings	Reduction in the surface temperatures of the inner side of the shutter; g-value of the system reduced during the melting process; reduction in the cooling loads and improvement in the thermal comfort	Incomplete regeneration of the PCM during the night; daylighting reduction; overheating risks during the night; ventilation system integrated to dissipate stored heat		Steady-state calculations—such as those that are usually given in standards —are often not sufficient to describe PCM systems
Technology 2b Silva et al., 2015, 2016 [18,26,29]	Paraffin wax	Effect of PCM integrated with the blinds of an aluminium shutter on the thermo-physical performance	Reduction in the maximum indoor peak temperature; decreased heat flux	Fast and complete melting of the PCM determines indoor discomfort conditions; introduction of an active ventilation system to improve the PCM charging and discharging processes	Thermal inertia improvement using PCM in large glazing areas, which currently dominate architectural design	Numerical model requires simplifications (a change in volume between solid and liquid phases is not considered)

4.1.4. Façade System: Integration of the PCM in Façades

The development of façade systems containing PCM has been investigated to improve the thermal inertia of transparent envelope components in order to achieve the typical thermal performances of opaque building elements, but still preserving daylighting.

Manz [12] studied the heat storage capacity of hydrate salts, combined with the insulation property of Transparent Insulation Material (TIM), through an experimental investigation, and the storage capacity of this passive technology was found to be promising. Nevertheless, the solid phase of PCM leads to heat and light gain reductions, and encapsulation in glass containers could represent a threat from a safety point of view.

Berthou [20] prototyped a system in which PCM was combined with aerogel in order to achieve the aims of superinsulation, heat storage and daylighting. The results of laboratory and in situ experimentations showed that the translucent layer of silica aerogel played a filtering role on solar radiation and interacted with the PCM to reduce heat losses. This kind of façade system plays a positive role during the winter season, even though the PCM melting temperature should be chosen carefully in order to allow the phase change of the material to take place, even on low solar radiation days.

The novel Responsive Building Element concept proposed by Iennarella et al. [53] consists of three glazings that have been dynamically combined to minimize the energy consumption for lighting and HVAC systems: a low-E selective glass coupled with two active layers (with automated motion), one with aerogel, to increase the insulation in winter, and one with a PCM to increase the solar control in summer. The system was designed for a sample office room in Turin, and the annual energy consumption (for cooling, heating and lighting) was assessed numerically for different configurations, changing the orientation of the sample room and the thicknesses of the active layers. The obtained results showed that the module allowed a significant improvement to be made in the annual primary energy performances, compared to a traditional transparent façade, and that the advantage of using the RBE was particularly evident for south, west and east facing orientations, but less so for a north facing one because of the limited activation of the PCM in summer.

Commercially available façade systems with prismatic solar control were studied using large scale measurements [36,42] and simulation [37]. The purpose of thermal inertia enhancement, through PCM activation, can only be reached by choosing low melting temperatures of the PCM and by ensuring a long-time interval between consequent cycles. Further improvements still need to be made to enhance daylighting and to reduce artificial lighting.

The transparent façade system developed by Ismail et al. [38–40] is a double glass unit containing a moving PCM curtain controlled by an electric pump. They conducted experimental investigations using spectrophotometry, which indicated a considerable reduction in the infrared and ultraviolet radiations while preserving good visibility, and the use of coloured PCMs, in particular the green ones, seems to be more effective in reducing radiated energy gains.

The particular combination of a PCM layer and a semi-transparent PV module inside the cavity of a double skin façade (DSF) has recently been investigated numerically by Goia et al. [54] and the obtained results show that this technology can significantly reduce the indoor cooling load and increase conversion efficiency from solar energy to electrical energy.

The works concerning the technologies of PCM integrated in façade systems are reported in Table 5.

Table 5. SWOT analysis of PCM in the façade.

3_Façade System: Integration of the PCM in the Façade S: Strengths, W: Weaknesses, O: Opportunities, T: Threats						
Ref.	**PCM**	**Aims**	**S**	**W**	**O**	**T**
Technology 3a Manz et al, 1997 [12]	Salt hydrates	Characterization of a novel external wall (PCM + TIM) by means of optical experiments on a PCM, experiments on a prototype and numerical simulations	Reduction in the energy losses	Backscattering of the solar radiation in the solid state, which leads to an increase in the solar gains and light transmittance; safety—mechanical destruction of the glass container	Investigation of the aesthetic/architectural/comfort values of a transparent wall; testing the durability and reliability of the system;	
Technology 3b Berthou et al., 2015 [20]	Eutectics of fatty acids	Evaluation of the passive solar behaviour by combining super insulation, heat storage and daylighting	Improvement in the U-value, good daylighting performance when PCM is in a liquid state	Overheating risk in summer; no melting process of PCM in winter and no solidification process in summer	Architectural value of a transparent passive solar wall; investigation of acoustic properties of the system (high-sound absorptivity and lower-than-air velocity of sound propagation)	
Technology 3c Grynning et al., 2013–2015 [36,42]	Salt hydrates	Definition of the thermal behaviour and conditions needed for thermal mass activation	Thermal mass activation of a PCM, even for cold climates	No uniform melting process; long-time interval between periodic phase change processes should be addressed to ensure the complete achievement of the cycle		
Technology 3d Ismail et al., 1997, 2001 [38,40]	Coloured PCM	Effect of variations in the PCM thickness on the performance parameters (U-value and g-value)	Solar radiation filtering; good performance of coloured PCMs—green and blue	Presence of an electric pump	Investigation of the thermal/ visual comfort performance of coloured PCMs	Insufficient number of available properties to simulate the behaviour of PCMs
Technology 3d Ismail et al., 2002 [39]	Glycol mixture—blue and green coloured PCMs	Effect of variations in the PCM thickness and in the colour on the thermal-optical parameters	Reduction in transmittance using blue and green PCMs		Aesthetic/architectural value of the coloured PCM; investigation of the thermal comfort performance	One-dimensional formulation of the model neglected the effects of the extremities of the panel

4.2. Threats and Opportunities of PCM Glazing Systems

The main results of the SWOT analysis pertaining to all the typologies of technologies analysed in the paper i.e., glazing, shutter and façade with PCMs, are summarised in Table 6. The considerations reported in the table have been elaborated by the authors from the literature analysis presented in the previous sections.

It is possible to note that the integration of PCMs in transparent envelopes introduces some positive aspects to the performance of the technology from the energy, thermal and comfort points of view. Benefits have emerged as the thermal mass and the heat storage capacity of the building envelope have increased.

With regards to the weaknesses, most of the points, such as flammability, chemical compatibility and change in volume, are mainly related to the chemical and thermos-physical properties of the PCMs. An appropriate climate-based design of the transparent system with PCM needs to be introduced to define the correct nominal melting temperature of the PCMs in order to ensure the complete achievement of the PCM cycle. At the same time, since the benefit of integrating PCMs in glazing is achieved during its phase change, this phase can be considered the most critical from other points of view, such as those pertaining to visual transmission and the aesthetics of the system. In fact, the PCM is not homogeneous during the transition phase, and consequently influences the appearance of the technology. Furthermore, the external view and the transparency of a glazing system with PCM can only be achieved when the PCM has melted completely, and is therefore in a liquid state i.e., in an optimized design technology, in the late afternoon when the solar heat gains are lower. This means that the dynamic glazing is in a transition phase during the rest of the day and therefore not completely transparent, and the daylighting is consequently lower.

The main weaknesses that arise from the integration of PCMs in transparent envelopes are related to technological aspects, such as leakage risks and/or difficulty in sealing the PCMs as well as an increase in the weight of the transparent technologies.

As far as the opportunities are concerned, it is possible to highlight that PCMs in transparent envelopes present the possibility of several research paths for future development. It is also worth mentioning that the integration of PCMs still needs certain technological problems to be overcome and a technological readiness level to be reached which would make their integration in real scale buildings feasible. One of the most interesting opportunities is that of working on the regulation of PCM transition, in order to obtain homogenous behaviour of the system and also to be able to control the state of the material as well as its appearance, whether liquid or solid, transparent or translucent. This scenario could be envisaged considering the integration of other materials/systems in a more complex façade system. The most significant threat is the cost-effectiveness of the system, which needs to be justified by the enhanced performances of the façade system in order to encourage architects to use these kinds of solutions. The other identified threats can be considered technical ones, which can be overcome through research on the topic.

Table 6. Summary of the SWOT analyses.

Strengths
• solar gain reductions and time shifts of the heat load in summer; • increases in the thermal mass of transparent envelopes; • heat storage capacity improvements of building envelopes; • PCMs in shutter technologies contributes to an improvement of the thermal inertia of window systems; • overall reduction in the energy demand; • thermal comfort improvements during the summer season as a result of the reduction in the indoor surface temperatures during peak conditions; • reduction in the day/night mismatch between the available solar energy and the heating demands; • low maintenance costs of the responsive technologies because no mechanical parts; • lower costs of the window, compared to other responsive technologies e.g., switchable glazed technologies; • easy to dismantle (e.g., PCM can easily be removed and processed separately at the end of its life); • PCM in a solid state is a diffuse medium with relevant scattering effects.
Weaknesses
• flammability of paraffin-based PCMs; • chemical incompatibility of some PCMs with some common materials in glazing systems (e.g., sealants); • PCM changes in volume between the liquid and solid phases; • high embodied energy of some typologies of PCMs; • necessary time interval between two change processes to ensure the full achievement of the PCM cycle; • the view through a PCM layer is only possible when the PCM is completely liquid; • non-uniform appearance during the phase change of a PCM; • daylight reduction when a PCM is in a solid phase; • increased solar transmission when a PCM is in a liquid state; • increased weight of PCM glazed systems; • risk of leakage of PCMs; • the triggering mechanisms that enables energy storage cannot be controlled (e.g., it is not possible to change the transition temperature between winter and summer); • it is difficult to find a configuration that works well in both winter and summer; • the responsive technologies need to be integrated in a whole building energy concept (e.g., the use of night ventilation or other technique to enhance the performance); in order to enhance the discharging of the system and the solidifying process of a PCM, a careful integration of the components with indoor air temperature control strategies (cooling system) is necessary to avoid overheating during the night.

Table 6. *Cont.*

Opportunities
• architects have made an increasingly large use of transparent systems over the last few decades; • the translucent appearance of a PCM in a solid state offers the possibility of developing large transparent surface areas that are able to ensure both privacy and sufficient natural daylighting; • several PCM typologies and melting temperatures enhance the opportunity of developing a tailor-made system for specific sites and indoor thermal loads; • the transient appearance of a PCM during a transition phase could be considered as a positive feature from an aesthetic/architectural point of view; • the improved characteristics of PCMs of a natural origin –non-toxic, non-flammable, 100% recyclable— enhance the possibility of lowering the embodied energy of the material; • coupling different layers of PCM with different melting temperatures, typologies and thicknesses, in movable/removable devices could lead to a better adaptation to the boundary conditions; • the integration of PCMs in coloured containers or with coloured pigments in the PCM could enhance the architectural integration value of PCM technologies; • the integration of existing numerical models into building performance simulation tools; • the investigation of new sealing techniques, in order to solve leakage problems of PCM containers; PCMs that remain solid at a macroscopic level (thus no leakage risk), but exhibit a phase change at a microscopic layer.
Threats
• the TRL of responsive windows is low, and is still at a research level (except for a few commercially available products); • the standard performance metrics are insufficient to offer a clear picture of the performance of the dynamic components, and it is difficult to efficiently explain the effectiveness of these systems to users/clients/professional figures; • the commercial switchable technologies that are currently available (e.g., electrochromic, gaschromic and thermos-chromic glass) are able to ensure variable solar and visible transmission and they allow the user to control the optical properties of a system; • there is a lack of user-friendly simulation tools to investigate PCM glazed technologies; • there is a lack of input data for simulation tools; • misintegration of the system with the building energy concept or a malfunctioning of some control strategies (e.g., non-effective ventilation, not enough temperature swing between day and night,) can determine an impaired performance; • the market needs to be convinced of the financial payback of the initial investment to increase its uptake; • there is a lack of long term assessments of the durability and stability of latent heat; • there is a lack of understanding of the effects of hysteresis and of supercooling (no studies have been carried out in this area); • the performance is very much climate dependent, and as a result the design of the system is more challenging; there is a lack of analyses on the performance from a life-cycle perspective and on comparing it with other solutions (i.e., the performance in operation might be even better, but might not be over the entire life cycle).

5. Conclusions and Suggestions for Future Research Activities

A complete critical picture of the experimental works on the transparent building envelopes that integrate PCMs has been given (between 1998 and 2017) in this work. The first step of the review activity involved categorizing the main possible integrations of PCMs in transparent building envelopes: in the cavity of double or triple glazing units, as an internal or external shutter system, or in a more complex system with other materials, such as on a façade. The research papers published on the subject, related to the experimental activity, have been analysed for each of the previously identified technology categories. The result is a series of SWOT analyses, which have pointed out the main strengths, weakness, opportunities and threats for each work.

The analysis has shown that the main strengths of integrating PCMs in transparent building envelopes are related to an enhancement, in terms of performance, of the technology from the energy, thermal, and comfort points of view. Benefits, which show an increase in the thermal mass and the heat storage capacity of the building envelope, have also been revealed. However, different weaknesses still

need to be overcome, at both the technological and chemical level. In addition, the energy performance should also be evaluated accurately during winter i.e., if the PCMs stay solid, the reduction in solar heat gains could negatively influence the overall energy and thermal balance of a building. Another critical aspect pertains to the visual and thermal behaviour of the dynamic envelope during the transition phase of the material, when the PCM is not completed liquid.

In short, the present work has defined the opportunities and threats for future building applications of transparent building envelopes with PCMs, according the results achieved in the different researches. The main outcomes of the work highlight that some research on the subject still needs to be carried out in order to achieve cost-effective solutions and a higher technology readiness level. Moreover, opportunities for this dynamic transparent envelope have been identified and new research paths have been indicated. Finally, aside from some technological improvements aimed assuring full durability of some technologies (e.g., sealants) and design optimisation, the review activity has also highlighted the need to develop and/or integrate numerical models in building performance simulation tools, as well as performance metrics, and standardised test procedures.

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References

1. Baetens, R.; Jelle, B.P.; Gustavsen, A. Phase change materials for building applications: A state-of-the-art review. *Energy Build.* **2010**, *42*, 1361–1368. [CrossRef]
2. Pomianowski, M.; Heiselberg, P.; Zhang, Y. Review of thermal energy storage technologies based on PCM application in buildings. *Energy Build.* **2013**, *67*, 56–69. [CrossRef]
3. Sharma, A.; Tyagi, V.V.; Chen, C.R.; Buddhi, D. Review on thermal energy storage with phase change materials and applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 318–345. [CrossRef]
4. Wang, X.; Zhang, Y.; Xiao, W.; Zeng, R.; Zhang, Q.; Di, H. Review on thermal performance of phase change energy storage building envelope. *Sci. Bull.* **2009**, *54*, 920–928. [CrossRef]
5. Zhou, D.; Zhao, C.Y.; Tian, Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. *Appl. Energy* **2012**, *92*, 593–605. [CrossRef]
6. Khudhair, A.M.; Farid, M.M. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Convers. Manag.* **2004**, *45*, 263–275. [CrossRef]
7. Tatsidjodoung, P.; Le Pierrès, N.; Luo, L. A review of potential materials for thermal energy storage in building applications. *Renew. Sustain. Energy Rev.* **2013**, *18*, 327–349. [CrossRef]
8. Hasnain, S.M. Review on sustainable thermal energy storage technologies, Part I: Heat storage materials and techniques. *Energy Convers. Manag.* **1998**, *39*, 1127–1138. [CrossRef]
9. 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. [CrossRef]
10. Fokaides, P.A.; Kylili, A.; Kalogirou, S.A. Phase change materials (PCMs) integrated into transparent building elements: A review. *Mater. Renew. Sustain. Energy* **2015**, *4*. [CrossRef]
11. Rezaei, S.D.; 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. [CrossRef]
12. Manz, H.; Egolf, P.; Suter, P.; Goetzberger, A. TIM–PCM external wall system for solar space heating and daylighting. *Sol. Energy* **1997**, *61*, 369–379. [CrossRef]
13. Li, S.; Zhong, K.; Zhou, Y.; Zhang, X. Comparative study on the dynamic heat transfer characteristics of PCM-filled glass window and hollow glass window. *Energy Build.* **2014**, *85*, 483–492. [CrossRef]
14. Goia, F.; Perino, M.; Serra, V. Improving thermal comfort conditions by means of PCM glazing systems. *Energy Build.* **2013**, *60*, 442–452. [CrossRef]

15. Goia, F.; Perino, M.; Serra, V. Experimental analysis of the energy performance of a full-scale PCM glazing prototype. *Sol. Energy* **2014**, *100*, 217–233. [CrossRef]
16. Weinläder, H.; Beck, A.; Fricke, J. PCM-facade-panel for daylighting and room heating. *Sol. Energy* **2005**, *78*, 177–186. [CrossRef]
17. Weinlaeder, H.; Koerner, W.; Heidenfelder, M. Monitoring results of an interior sun protection system with integrated latent heat storage. *Energy Build.* **2011**, *43*, 2468–2475. [CrossRef]
18. Silva, T.; Vicente, R.; Rodrigues, F.; Samagaio, A.; Cardoso, C. Development of a window shutter with phase change materials: Full scale outdoor experimental approach. *Energy Build.* **2015**, *88*, 110–121. [CrossRef]
19. Komerska, A.; Bianco, L.; Serra, V.; Fantucci, S.; Rosiński, M. Experimental analysis of an external dynamic solar shading integrating PCMs: First results. *Energy Procedia* **2015**, *78*, 3452–3457. [CrossRef]
20. Berthou, Y.; Biwole, P.H.; Achard, P.; Sallée, H.; Tantot-Neirac, M.; Jay, F. Full scale experimentation on a new translucent passive solar wall combining silica aerogels and phase change materials. *Sol. Energy* **2015**, *115*, 733–742. [CrossRef]
21. Liu, C.; Wu, Y.; Li, D.; Zhou, Y.; Wang, Z.; Liu, X. Effect of PCM thickness and melting temperature on thermal performance of double glazing units. *J. Build. Eng.* **2017**, *11*, 87–95. [CrossRef]
22. Bianco, L.; Cascone, Y.; Goia, F.; Perino, M.; Serra, V. Responsive glazing systems: Characterisation methods and winter performance. *Sol. Energy* **2017**, *155*, 372–387. [CrossRef]
23. Zhong, K.; Li, S.; Sun, G.; Li, S.; Zhang, X. Simulation study on dynamic heat transfer performance of PCM-filled glass window with different thermophysical parameters of phase change material. *Energy Build.* **2015**, *106*, 87–95. [CrossRef]
24. Jain, L.; Sharma, S.D. Phase Change Materials for Day Lighting and Glazed Insulation in Buildings. *J. Eng. Sci. Technol.* **2009**, *4*, 322–327.
25. Goia, F.; Bianco, L.; Cascone, Y.; Perino, M.; Serra, V. Experimental Analysis of an Advanced Dynamic Glazing Prototype Integrating PCM and Thermotropic Layers. *Energy Procedia* **2014**, *48*, 1272–1281. [CrossRef]
26. Silva, T.; Vicente, R.; Rodrigues, F.; Samagaio, A.; Cardoso, C. Performance of a window shutter with phase change material under summer Mediterranean climate conditions. *Appl. Therm. Eng.* **2015**, *84*, 246–256. [CrossRef]
27. 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. [CrossRef]
28. Bianco, L.; Vigna, I.; Serra, V. Energy assessment of a novel dynamic PCMs based solar shading: Results from an experimental campaign. *Energy Build.* **2017**, *150*, 608–624. [CrossRef]
29. Silva, T.; Vicente, R.; Amaral, C.; Figueiredo, A. Thermal performance of a window shutter containing PCM: Numerical validation and experimental analysis. *Appl. Energy* **2016**, *179*, 64–84. [CrossRef]
30. Durakovic, B.; Torlak, M. Experimental and numerical study of a PCM window model as a thermal energy storage unit. *Int. J. Low-Carbon Technol.* **2016**. [CrossRef]
31. Bianco, L.; Cascone, Y.; Goia, F.; Perino, M.; Serra, V. Responsive glazing systems: Characterisation methods, summer performance and implications on thermal comfort. *Sol. Energy* **2017**, *158*, 819–836. [CrossRef]
32. Gowreesunker, B.L.; Stankovic, S.B.; Tassou, S.A.; Kyriacou, P.A. Experimental and numerical investigations of the optical and thermal aspects of a PCM-glazed unit. *Energy Build.* **2013**, *61*, 239–249. [CrossRef]
33. Goia, F.; Zinzi, M.; Carnielo, E.; Serra, V. Characterization of the optical properties of a PCM glazing system. *Energy Procedia* **2012**, *30*, 428–437. [CrossRef]
34. Li, D.; Zheng, Y.; Li, Z.; Qi, H. Optical properties of a liquid paraffin-filled double glazing unit. *Energy Build.* **2015**, *108*, 381–386. [CrossRef]
35. Goia, F.; Zinzi, M.; Carnielo, E.; Serra, V. Spectral and angular solar properties of a PCM-filled double glazing unit. *Energy Build.* **2015**, *87*, 302–312. [CrossRef]
36. Grynning, S.; Goia, F.; Time, B. Dynamic Thermal Performance of a PCM Window System: Characterization Using Large Scale Measurements. *Energy Procedia* **2015**, *78*, 85–90. [CrossRef]
37. Frontini, F.; Pfafferott, J.; Herkel, S.; Schwarz, D. Building simulation study of a residential double-row house with seasonal PCM-translucent façade. In Proceedings of the CleanTech for Sustainable Buildings: From Nano to Urban Scale, Lausanne, Switzerland, 14–16 September 2011; pp. 99–104.
38. Ismail, K.A.; Henriquez, J. Thermally effective windows with moving phase change material curtains. *Appl. Therm. Eng.* **2001**, *21*, 1909–1923. [CrossRef]

39. Ismail, K.A.; Henríquez, J. Parametric study on composite and PCM glass systems. *Energy Convers. Manag.* **2002**, *43*, 973–993. [CrossRef]
40. Ismail, K.A.; Henriquez, J.R.; Te, D.D.E. PCM Glazing Systems. *Int. J. Energy Res.* **1997**, *21*, 1241–1255. [CrossRef]
41. Liu, C.; Wu, Y.; Zhu, Y.; Li, D.; Ma, L. Experimental investigation of optical and thermal performance of a PCM-glazed unit for building applications. *Energy Build.* **2018**, *158*, 794–800. [CrossRef]
42. Grynning, S.; Goia, F.; Rognvik, E.; Time, B. Possibilities for characterization of a PCM window system using large scale measurements. *Int. J. Sustain. Built Environ.* **2013**, *2*, 56–64. [CrossRef]
43. 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.* **2013**, 1–8. [CrossRef]
44. Li, D.; Ma, T.; Liu, C.; Zheng, Y.; Wang, Z.; Liu, X. Thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material. *Energy Build.* **2016**, *119*, 143–152. [CrossRef]
45. Li, D.; Li, Z.; Zheng, Y.; Liu, C.; Hussein, A.K.; Liu, X. Thermal performance of a PCM-filled double-glazing unit with different thermophysical parameters of PCM. *Sol. Energy* **2016**, *133*, 207–220. [CrossRef]
46. 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**. [CrossRef]
47. Liu, C.; Wu, Y.; Li, D.; Ma, T.; Hussein, A.K.; Zhou, Y. Investigation of thermal and optical performance of a phase change material–filled double-glazing unit. *J. Build. Phys.* **2017**, 174425911770873. [CrossRef]
48. Bionda, D.; Kräuchi, P.; Plüss, I.; Schröcker, M. Simulation of the thermal performance of translucent phase change materials and whole-building energy implications. In Proceedings of the 10th Conference on Advanced Building Skins, Bern, Switzerland, 3–4 November 2015; pp. 673–680.
49. Goia, F. Thermo-physical behaviour and energy performance assessment of PCM glazing system configurations: A numerical analysis. *Front. Archit. Res.* **2012**, *1*, 341–347. [CrossRef]
50. Wang, Q.; Zhao, C.Y. Parametric investigations of using a PCM curtain for energy efficient buildings. *Energy Build.* **2015**, *94*, 33–42. [CrossRef]
51. Soares, N.; Samagaio, A.; Vicente, R.; Costa, J. Numerical simulation of a PCM shutter for buildings space heating during the winter. In Proceedings of the World Renewable Energy Congress 2011 (WREC2011), Linköping, Sweden, 8–13 May 2011; pp. 1797–1804.
52. Alawadhi, E.M. Using phase change materials in window shutter to reduce the solar heat gain. *Energy Build.* **2012**, *47*, 421–429. [CrossRef]
53. Iennarella, S.; Serra, V.; Lo, V.R.M. A novel concept of a responsive transparent façade module: Optimization of energy performance through parametric design. *Energy Procedia* **2015**, *78*, 358–363. [CrossRef]
54. Elarga, H.; Goia, F.; Zarrella, A.; Dal Monte, A.; Benini, E. Thermal and electrical performance of an integrated PV-PCM system in double skin façades: A numerical study. *Sol. Energy* **2016**, *136*, 112–124. [CrossRef]



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