Peer-reviewed version available at *Energies* **2018**, *11*, 111; doi:10.3390/en11010111

Review Paper

PCMs in transparent building envelope: a SWOT analysis

Ilaria Vigna[1], Lorenza Bianco[1], Francesco Goia [2,*] and Valentina Serra [2,*]

[1] Energy Department, Polytechnic University of Turin, Italy
[2] Department of Architecture and Technology, Norwegian University of Science and Technology, Norway
* Correspondence: francesco.goia@ntnu.no; Tel.: +47-45027437

Abstract: Building envelope 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 building scale and (iii) modulate the light transmission to avoid glare effects. Starting from a literature review of experimental works, this research identifies the main possible integration of PCM in transparent/translucent building envelope components (in glazing, in shutters and in multilayer façade system) drawing a global picture potentials and limitations of these technologies. Transparent envelopes with PCMs have been classified from the simplest "zero" technology, which integrates the PCM into the double glass unit (DGU), to more complex solutions – with different numbers of cavities of the glass (TGU), different position of 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 are resumed in a SWOT (strengths, weakness, opportunities and threats) analysis table to underline strengths and weaknesses of transparent building envelope components with PCMs, and to indicate opportunities and threats for future research and building application.

Keywords: Phase Change Materials (PCMs); PCM-filled window; transparent building envelope; Thermal energy storage (TES); glazing; SWOT analysis; review; experimental

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1. Introduction

1.1 Background

During the last decades, the research activities to enhance energy efficiency in buildings have led to the development of new functional strategies, technologies, and materials. The façade and the building envelope in general, is probably one of the most investigated element of construction, being the place where a large part of the energy exchange between the indoor and the outdoor environment occurs, as well as the place where solar energy harvesting can take place.

Among the large spectrum of technologies and systems to increase the energy performance of the building, phase change materials (PCMs) are undoubtedly a key element in R&D, and several applications of PCMs in the building envelope have been proposed. PCMs are materials that exhibits a phase change (usually the solid-to-liquid transition in building applications) within a desired temperature range, suitable to exploit the latent heat of the phase change for thermal energy storage purpose. Different analysis on the state of the art of PCM in buildings application were published between 1998 and 2016 [1–8]. Most often PCM are employed in opaque building envelope components [4]. However, applications of PCM in transparent building components have also been proposed, and has seen a grown focus in the last 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 manage better the direct solar gain (that

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can cause overheating problems) and to minimize the heat loss, thanks to the buffer effect provided by the PCM layer, while still allowing the exploitation of the visible part of the solar radiation for daylighting. Such an effect is 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 the latent heat) the large part 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.

The performance and effectiveness of the PCM glazing concept is however something complicated to predict and may sometimes shows positive and negative sides. It 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 thought additional devices).

Furthermore, applications in different climates or in different building types might lead to substantially different outcomes. Moreover, complexity arises also from the fact that these systems influences 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 in one domain could be not as well performing when the other domain is concerned.

In terms of building energy performance, the PCM glazing concept is asked (as other state-of-the-art transparent building envelope components) to assure a good performance in terms of reduction of transmission heat loss (i.e. to have low values of thermal transmittance), to offer a (possibly dynamic) control of solar irradiance transmission (i.e. to have 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 daylight uniformity ratio) [11]. Furthermore, when it comes to thermal and visual comfort, the integration of PCM in transparent components should assure suitable surface temperature values (to avoid general and local thermal discomfort conditions), and to reduce the risk of glare discomfort for the occupants.

1.2 Aim of the paper

In this paper, a review, classification, and detailed analysis of different PCM glazing concepts appeared in the scientific literature in between 1998 and 2017 is presented. The aim of this work is, first of all, to provide an up-to-date classification and state of the art of PCM glazing concepts, and therefore to include the latest development in the field since the most recent review for these technologies [9,10] have been published. Moreover, based on 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, following 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. For each research activity, the main achievements, strengths, weaknesses, opportunities, and threats are synthetically highlighted.

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

2. Literature review at a glance

In total, the literature review was based on 29 articles published between 1997 and 2017 related to experimental analysis of PCM in transparent building envelope components. The analyzed works were published in peer review journals and conference papers accessible on-line. A simple analyzing the paper's features leads to the following synthetic picture on the PCM in glazing (view also Figure 1):

- the geographical distribution of the studies;
- the most investigated PCM typologies are paraffin wax (59%) [12–28] and salt hydrates (24%) [20,25,29–33], while only one study analyzed the performance of bio PCM (3%) [25];
- the characterization of technologies has been conducted mostly in outdoor test cells (55%) [16–27,31,34–37] and through laboratory analysis (52%) [12–15,17,29–33,35,37–40], while some other studies have been carried out by coupling modeling activity with experimental activity (41%) [12,14,15,18,20,27–30,33,36,37];
- the parameters investigated for the performance characterization of PCM transparent building envelope components are more related to thermal performance (69%) [15,18–28,30–36,38] and lighting performance (38%) [12–14,17,26,29,35–37,39,40] while energy performance was evaluated by 31% [15,16,19,25,26,33,36,37,39] of the studies;
- only very few analysis have been carried out to evaluate the thermal (14%) [18,26,33,41] and visual (21%) [16,18,20,26,28,41] comfort performance related to the application of the technology at the room level;
- in all the papers the analysis of the PCM transparent systems has been investigated at component scale, while only few works extend the analysis at building/system scale (17%) [17,18,33,35,41].

This synthetic analysis on the literature permits to highlight the international interest on the subject of PCMs in glazing and to draw the current main research lines on the subject.

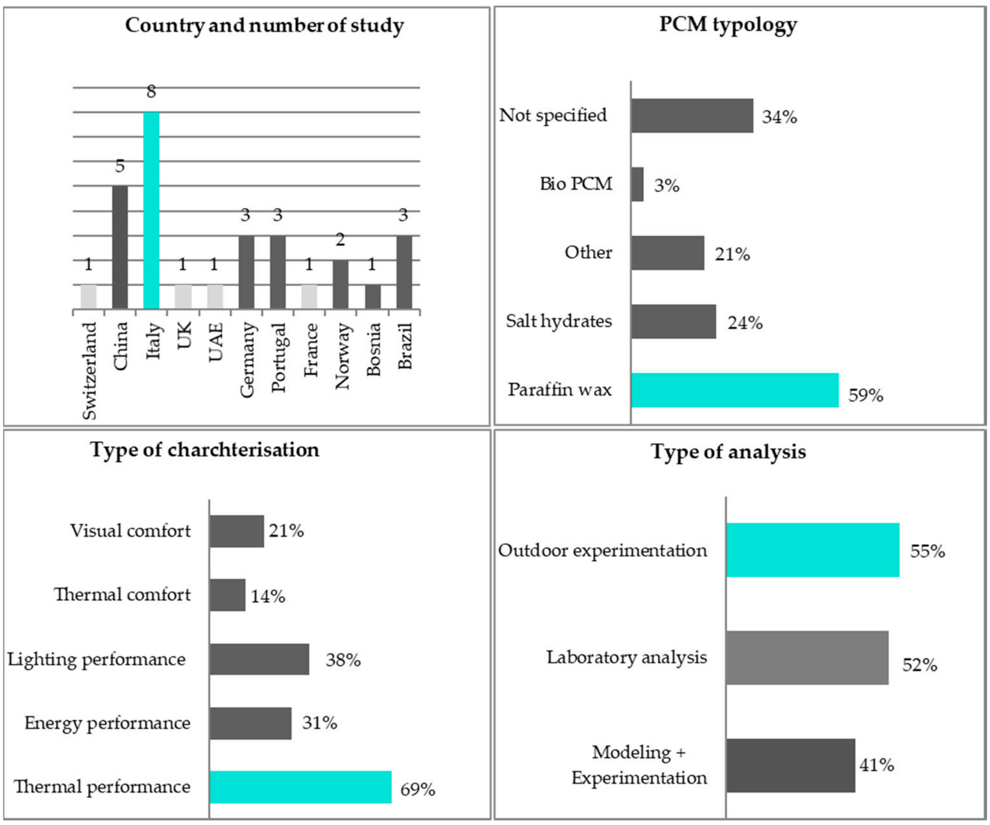


Figure 1. Analysis on the published papers.

3. PCMs in transparent building envelope: the technology classification

The papers related to the integration of PCM in transparent building envelope are classified according to the types of technology explored. In order to improve the energy efficiency of the glazing areas and transparent/translucent areas, PCM integration is possible in three main applications:

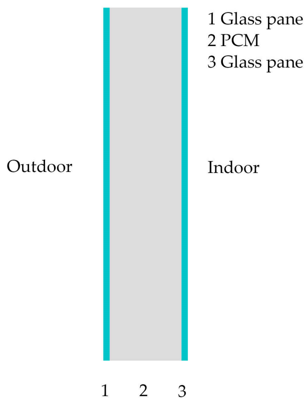
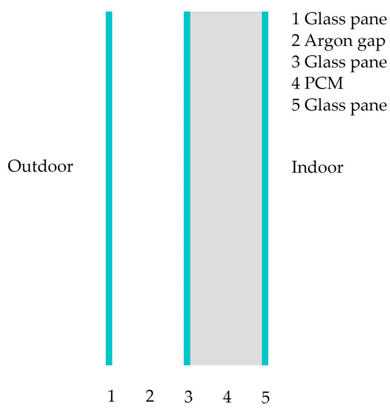
1. in the glazing, in order to directly enhance the heat capacity and thermal inertia of fenestration;
2. in the shutter, acting as an energy buffer positioned inside or outside the traditional window;
3. in façade system to interact in a multilayer technology with other insulating materials and solar control devices.

Each building application can be subdivided in different technological systems (Table 1), starting from the simplest "zero" technology which integrates the PCM into the DGU to more complex solutions, by varying the number of cavities of the glass (TGU), the position of 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 analyzed on the basis of the following classification (Table 1) in this paper:

- **Technology number 0,** glazing basic technology: integration of the PCM in DGU glazing,
- **Technology number 1,** glazing advanced 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.

For each category, sub-categories have been identified and the working principle 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_ glazing basic technology: integration of the PCM in DGU glazing			
0		Integration of the PCM in a double glazing unit (DGU+ PCM)	Thermal inertia improvement
1_ glazing advanced technology: integration of the PCM in TGU glazing			
1		Integration of the PCM in a triple glazing unit (TGU+ PCM)	Thermal inertia improvement

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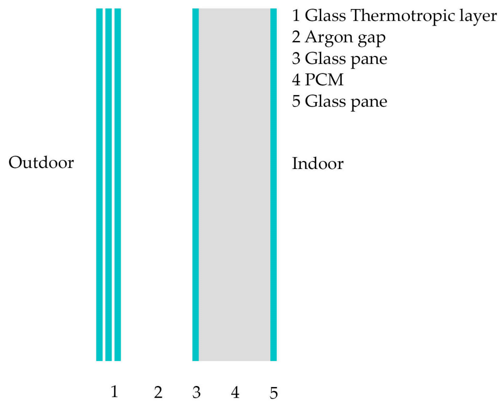
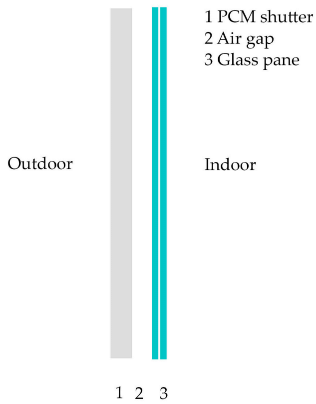
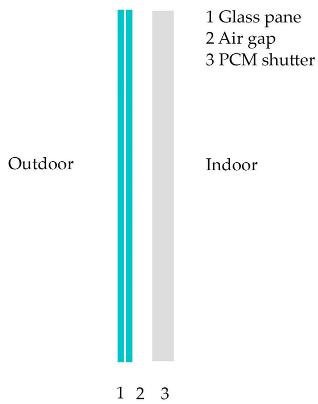
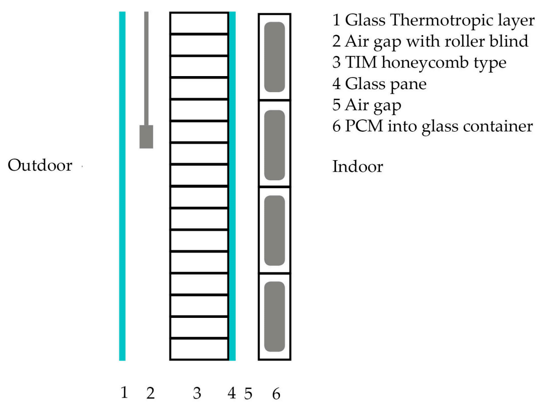
Technology	Sketch	Description	Concept
1a		Integration of the PCM in a triple glazing unit with a control system (TGU+ PCM+TT)	Better control on the charge phase of PCM
2_ shutter technology: integration of the PCM in the shutter			
2a		PCM external shutter	Time shift of incoming peak loads; glare reduction
2b		PCM internal shutter	Solar energy storage in winter; window internal surface temperature reduction in summer
3_façade system: integration of the PCM in the façade			
3a		TIM + PCM	Selective optical transmittance of solar radiation; thermal inertia improvement of the glazing system

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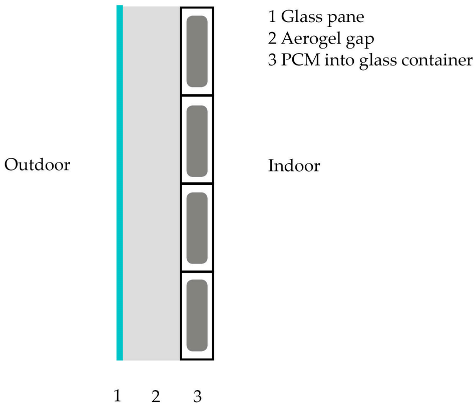
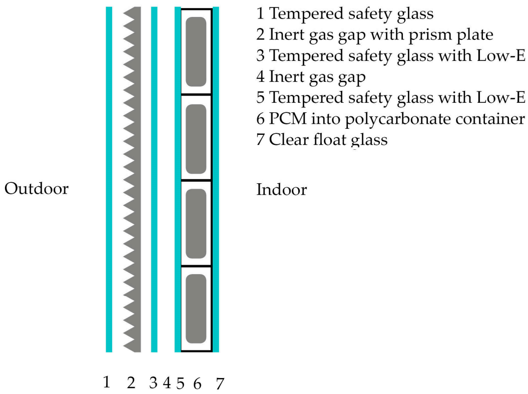
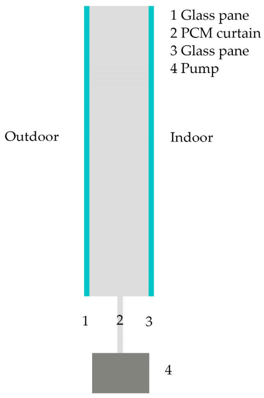
<table>
<tr><th>Technology</th><th>Sketch</th><th>Description</th><th>Concept</th></tr>
<tr><td>3b</td><td>
</td><td>Aerogel + PCM</td><td>Superinsulation and heat storage, U value increase</td></tr>
<tr><td>3c</td><td>
</td><td>Prismatic solar reflector</td><td>Light control, heat storage and thermal inertia improvement</td></tr>
<tr><td>3d</td><td>
</td><td>Double glass with PCM curtain controlled by an electric pump</td><td>Light control, heat gains control</td></tr>
</table>

4. SWOT analysis

4.1 Strenghts and weaknesses of PCM glazing systems

From the analysis of the literature papers briefly presented in paragraph 2 it is developed the SWOT analysis in the following paragraphs. Following the classification of transparent technologies given in paragraph 3 hereafter it is presented potentials and limitations of:

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

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4.1.1. Potentials and limitations of the glazing basic technology: integration of the PCM in DGU glazing

The basic technology integrating the PCM in transparent building envelope is 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 firstly introduced around twenty years ago by *Manz* [29].

So far literature, presents different experimental studies on the integration of PCM in glazing unit [12–15,28,30,34,42,43]. Real scale prototypes of the technology (DGU+PCM), were used to collect data during measurement [25–26,28] and the assembly and the construction of these prototypes were carried out in house laboratory. Experimental tests have been carried out in an outdoor test cell and the energy performance of the PCM system has been analyzed 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 an extensive experimental campaign, 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 have been investigated also by numerical simulation software [15,28,30,44]. The semi-transparent property of a glazing roof containing PCM and the effect of zenith angle on the thermal performance have been only numerically analyzed by *Liu et al*. [45].

The effect of PCM thickness and PCM melting temperatures on thermal performance of double glazing unit during winter have been numerically and experimentally investigated by *Liu et al.* [36].

Furthermore, some results concerning laboratory characterization [12,14,17,43] and numerical investigations [24] have been published to determine the optical properties of the technologies for PCM in solid and liquid state. The use of large integrating sphere equipment [13,17] has been necessary to obtain reliable results due to the highly scattering property of the system when the PCM is in solid state. Transmittance, reflectance and absorptance spectra have been measured at different incident beam angles for components with different PCM layer thickness. *Durakovic and Torlak* [28] carried out laboratory and natural environment experimental activity to collect data and to validate numerical model on a DGU with PCM in order to optimize the PCM layer thickness in the cavity.

The PCMs typologies tested are commercially available paraffin based with different nominal melting temperatures [12,15,16,28], salt hydrates [42] and eutectics [30].

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

- to reduce the cooling load [15,16,28,30,42];
- 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 [16];
- to improve the poor thermal inertia of the glazing system [12,28,36];
- to collect and store solar energy at a building scale - reduction in the “mismatch” between the heating demand and the availability of solar radiation during winter time-[16];
- to better control the visible solar radiation and reduce the glare risk -improved exploitation of daylighting and visual comfort- [13,14,17];
- a “mitigation” of the internal glass surface temperatures, which leads to an improvement of thermal comfort [18].

On one hand the improvements in terms of energy performance and visible control using the DGU+PCM are assessed during different seasons –summer, winter, mid-season [13,16,18,42] on the other hand some threats and weaknesses are reported. Further investigations of thermally massive glazed units and the optimization process to control the transition of the PCM is needed [12,16,18], by choosing a proper melting temperature range according to boundary conditions in order to avoid too fast melting in summer or incomplete melting during winter.

Moving to the building scale, Bionda et al. [46] developed a simulation tool to evaluate the energy saving potentiality of translucent window with PCM. Results showed that the application of the basic technology (DGU+PCM) can lead to both cooling and heating reduction, respectively between 1%-9% and 7%- 10%. A further positive impact was highlighted on the thermal comfort with a reduction of the number of hours with overheating.

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As a general comment, it is possible to state that the Technology Readiness Level (TRL), can be assessed between 4 and 6, meaning that the technologies are in the validation phase in laboratory and in a significant environment. Still some steps forward need to be done to reach the TRL 9.

In Table 2 are reported the works concerning the basic technology DGU+ PCM. For each work, the main achievements, strengths, weaknesses, opportunities and threats are synthetically highlighted.

4.1.2. Potentials and limitations of the glazing 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 with 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 glazing position;
- the PCM layer thickness;
- the interaction with insulating materials;
- the interaction with solar control device in order to control daylighting.

The following research case studies analyses potentials and limitations of transparent advanced technologies containing phase change materials.

The technology integrating Phase Change Material in triple glazing unit (TGU) has been studied by *Goia et al.* through an experimental [19] and a numerical analysis [47] in order to assess thermo-physical behavior of the component, by varying the position of the PCM layer in the inner or outer cavity of a triple glazing and obtain a better buffer performance –U value, thermal inertia- compared to the DGU technology.

The physical-mathematical model has been developed to test the effect of variation of the position of PCM layer in inner-outer cavity of the TGU on the energy performance of the component, while the real scale prototypes have been realized to analyze the influence of the Thermotropic glass (TT) on solar energy transmission control.

All tested PCMs are paraffin based with different melting temperatures of 25, 30 and 35°C in order to identifythe best range during 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 PCM melting process using a TT layer.

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

The experimental research of *Li et al.* [24] is 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, in sunny days the system effectively avoided overheating risk and reduced heat transferred into the room, while in rainy days the TGU+PCM component played a good performance on reducing the temperature fluctuation of the interior surface and the heat entered the room, but it was unsatisfactory in reducing the peak heat flux of the interior surface and delaying the peak temperature.

In Table 3 are reported the works concerning the advanced technology TGU+ PCM. For each work, the main achievements, strengths, weaknesses, opportunities and threats are synthetically highlighted.

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4.1.3. Potentials and limitations of shutter technology: integration of the PCM in the shutter

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

Internal PCM sun protection studies [20,27,31,48] settle the problem of overheating of the screen positioned on the inner side during summer period: in the case of incoming solar radiation, the blind can only heat up to the melting temperature of the PCM that starts to absorb heat and stored it as latent heat. A further increase in temperature cannot occur until the PCM is completely melted. The PCM thus decreases the blind surface temperature as well as the g-value of the system. Furthermore the possibility to increase thermal inertia of the glazing during winter [20–22,31,49] could be achieved thanks to the insulation properties of the PCM layer and the possibility to take advantage of the heat stored during the day on the release phase of the material.

The concept of moving the PCM layer in external shutters [23,25,50] has been proposed to optimize the technology performance during summer period, by absorbing incident solar radiation before it enters in 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.* [25] verified the influence of the color of the polycarbonate panel and the behavior of different PCMs typologies on the performance of the shading component; furthermore, a qualitative analysis of PCM phase transition pointed out the strong discontinuity in appearance that can limit the application of transparent PCM-filled components in architecture.

In Table 4 are reported the works concerning the technologies of PCM shutters. For each work the main achievements, strengths, weaknesses, opportunities and threats are synthetically highlighted. The tested PCMs are: paraffin based and salt hydrates.

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

- heat gains reduction;
- internal surface temperature reduction;
- thermal comfort enhancement;
- peak cooling loads 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 incoming daylight and problems of leakage; furthermore, the melting temperature range of PCM should be carefully chosen in order to avoid too fast melting in external shutters and on the other hand the incomplete melting of PCM in internal components.

Future improvements concern the visual comfort of the element, by enhancing the appearance quality of the shading during melting phase and the possibility to integrate ventilation systems to improve the discharging process of PCM.

4.1.4. Potentials and limitations of façade system: integration of the PCM in the façade

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

The heat storage capacity of hydrate salts combined with the insulation property of Transparent Insulation Material (TIM) was studied through an experimental investigation by *Manz* [29] and the storage capacity of this passive technology are promising. Nevertheless, the solid phase of PCM lead to heat and light gains reduction and the encapsulation into glass containers could represent a threat from a safety point of view.

The combination of PCM and aerogel in a system façade has been prototyped by *Berthou* [35] to achieve the aims of superinsulation, heat storage and daylighting. The results of laboratory and in situ experimentations show that the translucent layer of silica aerogel has a filtering role for solar radiation and interact with the PCM to reduce heat loss. The application of this façade system has a positive role during winter season, even if the choice of PCM melting temperature should be adequate in order to allow the phase change of the material even in low solar radiation days.

The novel Responsive Building Element concept proposed by *Iennarella et al.* [51] consists of three glazings dynamically combined to minimize the energy consumption for lighting and HVAC systems: a low-E selective glass coupled with two active layers (with an automated motion), one with an 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 located in Turin and the annual energy consumption (for cooling, heating and lighting) was numerically assessed for different configurations, changing the orientation of the sample room and the thicknesses of the active layers. Results showed that the module allowed a significant improvement in annual primary energy performances compared to a traditional transparent façade and the advantage of using the RBE was particularly evident for south, west and east orientation, whilst less for the north orientation because of the weak activation of the PCM in summer.

The commercially available façade system with prismatic solar control have been studied using large scale measurements [32,38] and simulation [33]. The purpose of thermal inertia enhancement through PCM activation could be reached only by choosing low melting temperature of PCM and by ensuring a long-time interval between consequent cycles. Further improvements have to be done in order to enhance daylighting and to reduce the artificial lighting.

The transparent façade system developed by *Ismail et al.* [37,39,40] is a double glass unit containing a PCM moving curtain controlled by an electric pump; experimental investigations using spectrophotometry indicate a considerable reduction in the infrared and ultraviolet radiations while preserving good visibility and the use of colored PCM, in particular the green one, 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 been recently numerically investigated by *Goia et al*.[52] and the results show that this technology can significantly reduce the indoor cooling load and increase conversion efficiency from solar energy to electrical energy.

In Table 5 are reported the works concerning the technologies of PCM integrated in façade systems. For each work the main achievements, strengths, weaknesses, opportunities and threats are synthetically highlighted.

Table 2. SWOT analysis of PCM in DGU glazing.

0_ glazing basic 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 B. Durakovic and al., 2017 [28]	Paraffin wax	Impact of PCM on window thermal performance	Thermal performance improvement (lower interior surface temperature and overheating delay) and building energy demand reduction	Instantaneous jump of heat gain once the PCM is completely melted.		

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Technology 0 F. Goia et al., 2013 [18]	Paraffin wax	Evaluation of the thermal comfort performance during different seasons	Shading and buffering effect of the PCM improve indoor thermal conditions and prevent glare effect	Not significant comfort improvement on cloudy days (low incident solar irradiation); overheating risk during summer		Few commercial transparent PCM products can be found on the market and there is little quantification of their real advantages in terms of energy efficiency and indoor environmental comfort.
Technology 0 F. Goia et al, 2014 [16]	Paraffin wax	Thermal benefits of a PCM glazed unit compared with a traditional double glass	Total daily energy gains reduction. Smooth and 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 control strategies of indoor air temperature	Transition temperatures of PCM can be chosen freely on 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 by preserving privacy when PCM has a translucent aspect (solid phase)	The integration of PCM in traditional DGU may determine an increase in the price of the final product (impact in the production cost of the glazed unit)
Technology 0 B.L. Gowreesunker et al., 2013 [12]	Paraffin wax	Characterization of the optical and thermal aspects of a PCM glazed unit compared with a reference	Thermal mass improvement of the transparent envelope	During rapid changes in temperature or phase of the PCM, the transmittance spectra are unstable; changeability of visual aspect	Change in transparency of PCM as design issue	Not accurate results of function assumed by default model possessed by existing simulation tools
Technology 0 L. Jain et al., 2009 [34]	Commercial grade PCM (purity 99.3%)	Effects of ambient temperature, solar radiation and thickness of a DGU PCM	Significant drop of PCM transmittance passing from 4 mm to 30 mm			

		component on solar transmittance	of the component; PCM has higher transmittance than water for the thickness of 15 mm.			
Technology 0 S.Li et al., 2013 [42]	Salt hydrates	Evaluation of the surface temperature fluctuations	Smooth of temperature fluctuations in sunny days of summer	Indoor surface temperatures of the system are higher than the reference during summer; heat gains reduction in winter		Problem in simulation of phase interface tracking
Technology 0 S. Li et al, 2014, [30]	Glauber's salt	Effects of DGU PCM on building energy consumption in summer and winter.	In sunny summer day, reduction of incoming heat and peak temperature on the interior surface of the DGU PCM compared to a reference; decrease of annual energy consumption of air conditioning system and heating system	Lack of stable satisfactory thermal performance of the PCM window		High cost and unsatisfactory annual energy saving effects of other commercially available tested transparent technologies (thermochromi c windows, electrochromic glass, windows with semi-conductor solar cells and low-E film)
Technology 0 C. Liu et al., 2017 [36]		Effects of PCM thickness and melting temperature on thermal performance of double glazing unit	During winter, the thickness of PCM layer of DGU PCM system positively influences the system performances by means of an increase of interior temperature, decrease of total transmitted energy and transmitted solar energy			
Technology 0 K. Zhong et al., 2015	Paraffin wax	Effects of PCM thermophysical parameters on dynamic	Shifting in peak load of air conditioning system; heat	Slight increase of solar heat gain of the system		High cost and unsatisfactory annual energy saving effects

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[26]		heat transfer characteristics of the PCM window	transfer reduction during sunny summer; load shifting effect and thermal insulation effect of PCM glazing improves with the increasing latent heat of fusion.	compared to the reference, in presence of low solar radiation; heat transfer increasein rainy summer days		of other commercially available tested transparent technologies (thermochromic window, electrochromic glass, window with semi-conductor solar cells and low-E film)

338 **Table 3.** SWOT analysis of PCM in TGU glazing.

1_ glazing advanced 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 S. Li et al., 2016 [24]	Paraffin wax MG29	Evaluation of the thermal performance and energy saving potential of a TGU+PCM during summer days	In sunny days, PCM in outer chamber of the system effectively reduces peak temperatures on the interior surface and incoming heat compared to reference	In rainy days, the system is unsatisfactory in reducing peak heat flux and delaying the peak temperature on the interior surface	Possibility to adjust and shift the peak load of air conditioning system, also reducing its energy consumption	
Technology 1a F. Goia et al., 2014, L. Bianco et al., 2017 [19,26]	Paraffin wax	Evaluation of the effect of the position of PCM layer (inner-outer cavity of the TGU) on thermo-physical performance during summer	TT layer prevent the complete melting of PCM in inner cavity; solar gain and peak indoor surface temperature reduction during daytime	Complete exploitation of the latent heat of fusion of PCM in the outer cavity with a consequent increase of transmitted irradiance; in case of high solar irradiation, PCM in the outermost cavity negatively affects the thermo-physical behavior of the system	Further investigation of the system behavior inserting PCM with different transition temperatures; enhance renewable energy exploitation at a building scale by both using solar energy in a more efficient way and reducing the time mismatch between solar energy availability and heating/cooling energy demand	The limited effect of the thermotropic layer given a small variation in the optical properties

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340 **Table 4.** SWOT analysis of PCM in shutter.

2_ shutter technology: integration of the PCM in the shutter S: Strengths, W: Weaknesses, O: Opportunities, T:Threats						
Ref.	**PCM**	**Aims**	**S**	**W**	**O**	**T**
Technology 2a A. Komerska et al., 2015 [23]	Paraffin wax	Evaluation of the thermal performance of the polycarbonate shutter containing PCM in mid-season (solid phase)	Total daily solar heat gains reduction, internal surface temperature reduction; preservation of high illuminance level. Improvements of the thermal resistance of the system shutter and window	Absence of melting process during the whole period of measurements; during cloudy days, performance decrease of the system; negative effect of solar heat gains reduction in winter		
Technology 2a L. Bianco et al. 2017 [25]	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 color of the polycarbonate panels and the behaviour of different PCMs typologies	Good potentiality of the technology to reduce the cooling daily energy compared to the reference. Internal surface temperature of the glazing with PCM shutter reduction compared to reference. Thermal inertia improvement of the dynamic window with heat fluxes time peak shift.	For sol-air temperature higher than 26 °C, performance decrease in total heat flux reduction of the PCM systems, compared to the reference; discontinuity in appearance during the melting phase of PCM;	Future research developments to make the system more adaptive and performing during summer and to extend its use also in winter and intermediate season may consist in the coupling of different panels (of different colors and 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	Little scientific evidence in literature in relation to the durability of the bio PCM; sealing problem of the material in polycarbonate; the discontinuity in appearance of the PCM can limit the architectural application of transparent component containing PCM

Technology 2b H. Weinläder et al., 2005 [20]	Paraffin wax, Salt hydrates	Effect of variation of PCM typology on thermal – comfort performance	Low heat loss in winter; peak cooling loads reduction 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 concealing measure, e.g. screen-print glazings; investigation of thermal comfort performance	
Technology 2b H.Weinlaeder et al., 2011 [31]	Salt hydrates	Effect of PCM integrated into the blinds of a polycarbonate shutter on thermo-physical performance of office buildings	Reduction of surface temperatures of the interior side of the shutter; g-value of the system reduced during melting process; cooling loads reduction and thermal comfort improvement	Incomplete regeneration of PCM during night; daylighting reduction; overheating risks during night; ventilation system integrated to dissipate stored heat		Steady-state calculations – as usually given in standards – are often not sufficient to describe PCM systems
Technology 2b T.Silva et al., 2015, 2016 [21,22,27]	Paraffin wax	Effect of PCM integrated into the blinds of an aluminium shutter on thermo-physical performance	Indoor maximum temperature peak reduction; heat flux decreased	Fast and complete melting of PCM determines indoor discomfort conditions; introduction of active ventilation system to improve the PCM charging and discharging processes	Thermal inertia improvement using PCM in large glazing areas which dominates current architectural design	Numerical model requires simplifications (the change in volume between solid and liquid phase is not considered,

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343 **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 H.Manz et al, 1997 [29]	Salt hydrates	Characterization of a novel external wall (PCM + TIM) by means of optical experiments on PCM, experiments on a prototype and numerical simulations	Energy losses reduction	Backscattering of the solar radiation in the solid state leading to secrease of solar gains and light transmittance; safety – mechanical destruction of glass container	Investigation of aesthetic/architectural/comfort value of a transparent wall; test durability and reliability of the system;	
Technology 3b Y.Berthou et al., 2015 [35]	Eutectic of fatty acids	Evaluation of passive solar behavior combining super insulation, heat storage and daylighting	U- value improvement, good daylighting performance when PCM is in 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 S.Grynning et al., 2013-2015 [32,38]	Salt hydrates	Definition of thermal behavior and conditions needed for thermal mass activation	Thermal mass activation of PCM even for cold climates	Not uniform melting process; long-time interval between periodic phase change processes must be addressed to ensure the complete achievement of the cycle		
Technology 3c F.Frontini et al., 2013 [33]	Salt hydrates	Influence of the PCM system on comfort and energy demand	Internal air temperature decrease; energy for heating and cooling reduction; thermal mass enhancement	Daylighting reduction		

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Technology 3d K.A.R. Ismail et al., 1997, 2001 [37,39]	Colored PCM	Effect of variation of the PCM thickness on the performance parameters (U-value and g-value)	Filter of the solar radiation; good performance of colored PCM – green and blue	Presence of an electric pump	Investigation of thermal/ visual comfort performance of coloured PCM	Insufficient available properties to simulate the behavior of PCM
Technology 3d K.A.R. Ismail et al., 2002 (43)	Mixture glycol - colored PCM blue and green	Effect of variation of the PCM thickness and color on the thermal-optical parameters	Reduction in transmittance using blue and green PCM		Aesthetic/architectural value of the colored PCM; investigation of thermal comfort performance	One dimensional formulation of the model ignores the effects of the extremities of the panel

4.2 Threats and opportunities of PCM glazing systems

In Table 6 are summarized the main results of the SWOT analysis on all the typologies of technologies analyzed in the paper i.e. glazing, shutter and façade with PCMs. The considerations reported in the table have been elaborated by the authors from the literature analysis of the previous paragraphs.

It is possible to notice that the integration of PCMs in transparent envelope gives strengths to the performance of the technology under the energy, thermal and comfort aspects. Benefits are revealed increasing the thermal mass and the heat storage capacity of the building envelope.

With regards to the weaknesses, most of the points are related mainly to PCMs chemical and thermo-physical properties such as flammability, chemical compatibility, change in volume. A proper climate based design of the transparent system with PCM, needs to be done to define the correct nominal melting temperature of the PCMs to ensure the complete achievement of the cycle of the PCM. At the same time, the benefit of integrating PCMs in glazing is achieved during its change of phase, but this phase is the most critic from other points of views such as the visual transmission and the aesthetic of the system. In fact, during the transition phase the PCM is not homogeneous and consequently influence the appearance of the technology. Furthermore, the external view and the transparency of a glazing system with PCM is achieved only when the PCM is completed melted and so liquid i.e. in an optimized design technology, in the late afternoon when the solar heat gains are lowering. This means that during the rest of the day the dynamic glazing was in transition phase and so not completely transparent and consequently the daylighting was lower.

The main weaknesses deriving from the integration of PCMs in transparent envelope are related to the technological aspects such as leakage risk and/or difficulty in sealing the PCMs and the increase of the weight of the transparent technologies.

As far as it regards the opportunities it is possible to highlight that PCM in transparent envelope presents several research paths for future development. It is also worth mention that the integration of the PCM needs to overcome technological problems and reach a technological readiness level which makes the integration in real scale building feasible. One of the most interesting opportunity is to work on the regulation of the PCM transition, in order to have a homogenous behavior of the system and also to be able to lead the state of the material and indeed its appearance, liquid or solid, transparent of translucent This scenario could be envisaged with the integration of other materials/system in a more complex façade system.

Amongst the threats, the most significant one is the cost-effective of the system that needs to be justified by the enhanced performances of the façade system in order to make architects use these kinds of solution. The other threats identified can be considered technical ones, which can be overcame researching on the subject.

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Table 6. Summary of the SWOT analysis.

Strengths
• heat gain reduction and time shift in summer
• heat loss reduction in winter
• energy demand reduction
• thermal and visual comfort improvement
• day/night mismatch reduction between solar energy availability and heating demand
• increase in the thermal mass of transparent envelope
• heat storage capacity improvement of building envelope
Weaknesses
• flammability of paraffin based PCM
• chemical incompatibility of PCM with other materials
• change in volume between liquid and solid phase
• necessary time interval between periodic phase change processes to ensure the complete achievement of the cycle for PCM
• the view through the PCM layer is only possible when the PCM is completely liquid
• non-uniform appearance during phase change
• energy efficiency of PCM during its transition phase
• daylight reduction in winter
• increase of solar transmission when PCM is in liquid state
• back scattering effects of PCM in solid state
• the integration of PCM increases the weight of the window
• technological problem in the integration of PCMs in the glazing/shutter/façade for leakage risk
Opportunities
• widespread of highly glazed building envelopes have been exponentially adopted by architects over the last decade
• translucent appearance of PCM in solid state gives the possibility to develop large transparent surface areas able to ensure both privacy and natural daylighting
• several PCM typologies and melting temperatures enhance the opportunity to develop a tailor-made system for specific sites and indoor thermal loads
• transient appearance of PCM during transition phase could be considered as positive feature from an aesthetic/architectural point of view
• research on PCM with natural origin – not toxic, not flammable, 100% recyclable
• responsive elements able to enhance their performance during all the seasons, investigation of more complex systems that couple different layers of PCM with different melting temperatures, typologies and thickness, development of movable/removable devices able to better adapt to boundary conditions
• coloured capsule to contain PCM performance investigation
• investigation of new sealing techniques
Threats
• standard performances are insufficient to give a clear picture of the performance of dynamic components
• commercially available switchable technologies (e.g. electrochromic, gasochromic and thermochromic glasses) are able to ensure variable solar and visible transmission
• lack of user-friendly simulation programs able to investigate PCM technologies behaviour
• in order to enhance the discharging of the system and the solidifying process of the PCM, a careful integration of the component with control strategies of indoor air temperature (cooling system) is necessary to avoid overheating during night
• the market needs to be convinced of the financial payback of the initial investment to increase its uptake

5. Conclusions

Next generation of building envelope needs to be a dynamic filter and to manage heat and mass transfer between indoor and outdoor environment. One of the possible solution to achieve this goal is the integration of the Phase Change Materials (PCMs) able to regulate and to enhance the thermal energy storage of walls and windows. The adoption of PCMs in transparent systems is to improve the performance of glazed components in terms of energy and comfort, enhancing the thermal inertia of the system. Furthermore, PCMs optical properties show partial transparency to electromagnetic radiation within the solar range permitting the exploitation of daylighting.

In this work, a complete critical picture on the experimental papers on transparent building envelope integrating PCMs is given (between 1998 and 2017).

The first step of the research categorized the main possible integration of PCM in transparent building envelope: in the cavity of double or triple glazing, as internal or external shutter system or in a more complex system with other materials, such as façade. For each technology category identified, the research papers published on the subject, related experimental activity, have been analyzed. The results is a SWOT analysis, which points out for each work the main strengths, weakness, opportunities and threads.

Globally, the analysis shows that the main strengths integrating PCM in transparent building envelope are related to an enhancement in terms of performance of the technology under the energy, thermal, and comfort aspects. Benefits are also revealed increasing the thermal mass and the heat storage capacity of the building envelope. Different weaknesses need to be overcome both at the technological and chemical level. In addition, the energy performance should be accurately evaluated also during winter i.e. if the PCMs stay solid, the reduction of solar heat gains could negatively influence on the overall energy balance of the building, and the thermal. Another critic element is visual and thermal behavior of the dynamic envelope during the transition phase of the material, when the PCMs is not completed liquid.

In conclusion, the work defines the opportunities and threads for future building application of transparent building envelope with PCMs, according the results achieved by the different researches. The main outcomes of the work highlight that that still some research on the subject needs to be carried out in order to achieve cost-effective solution and higher technology readiness's level. In addition several opportunities on this dynamic transparent envelope have been identified showing also new research paths.

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