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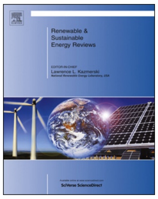

# Latent heat storage in building elements: A systematic review on properties and contextual performance factors

A. Mavrigiannaki [a], E. Ampatzi [b,*]

[a] Welsh School of Architecture, Cardiff University, UK
[b] Welsh School of Architecture, Cardiff University, Bute Building, King Edward VII Avenue, Cardiff, CF10 3NB, UK

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## ABSTRACT

A systematic review of latent heat storage in building elements was conducted to establish the current knowledge base and reveal key design and performance factors that could be used to define technologies available for immediate implementation and for specific applications. All relevant literature published by April 2014 was critically evaluated and a data extraction procedure was used to organise, analyse and report design and performance parameters of Phase Change Material (PCM) elements. The review of a total of 120 papers revealed that published information on these aspects is diverse and in many cases insufficient. The diversity of test conditions and variety of reported values indicate that physical properties and performance data concerning materials and complete PCM elements are not directly comparable. Therefore matching technologies and applications for specific climates and building typologies is not possible solely through published information. However evidence was collected which shows that, with appropriate design, PCM elements can contribute to reducing loads and achieving energy savings in buildings, while securing a comfortable indoor environment. Key design factors to this end were found to be the climate and target season, the design of appropriate controls for active and passive systems used in combination with the PCM elements and cost-related factors. The review also mapped the research foci to date, revealing the range of variations previously examined and potential research gaps worth pursuing in the future.

## Contents

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*Abbreviations:* FSPCM, Form stable PCM; GHG, Greenhouse Gas; HDPE, High Density Polyethylene; LCA, Life Cycle Analysis; LHS, Latent Heat Storage; PCFW, Phase Change Frame-wall; PCM, Phase Change Material; R&D, Research and Development; SSPCM, Shape Stable PCM; TGU, Triple Glass Unit; TIM, Transparent Insulation material; VIP, Vacuum Isolated Panel

* Corresponding author.
*E-mail address:* ampatzie@cf.ac.uk (E. Ampatzi).

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## 1. Introduction

A strong potential in reducing current levels of energy consumption and Greenhouse Gas Emissions, especially those related to heating and cooling, has been recognised for the building sector [1]. A key challenge to this end is to reduce energy consumption and emissions from space conditioning without compromising thermal comfort needs. Current policy [1] supports the use of high insulation levels that are seen as effective in significantly reducing energy use in buildings [2]. However the dynamic behaviour of thermal mass and its positive contribution to delaying heat fluxes and regulating temperature fluctuations has been recognised [3–7] in contrast to the rigid thermal performance of lightweight and highly insulated building envelopes.

Latent Heat Storage (LHS) technologies that use Phase Change Materials (PCM) impregnated in lightweight building elements are considered as an interesting alternative to sensible storage in heavyweight constructions [8], with a theoretical volumetric storage density of up to 15 times higher than traditional storage materials [9]. The enhanced storage capacity of these materials is due to their latent heat storage ability i.e. they can undergo a phase change (e.g. melting/solidification) and therefore exchange more heat with the environment than through solely their sensible heat storage capacity. Attention is drawn to LHS-enhanced building fabric as current construction trends demand speed and ease of assembly and thus favour lightweight constructions [10].

Research on LHS technologies ranges from PCM material development to experimental storage applications and from system modelling to design guidelines. There is also R&D work undertaken for integration of PCM in building services [9,11–13]. However research in the subject is still fragmented and the actual potential held by these technologies in improving thermal conditions and reducing heating and cooling needs in existing and new buildings is not well understood. The aim of this study is to review published evidence, establish the current knowledge base and reveal key design factors for these technologies. The main objective is to examine whether current knowledge can be used to define technologies available for immediate implementation and technologies suitable for specific applications i.e. enable the matching of existing and emerging needs with technologies available.

A number of relevant past reviews has been identified; [8] had a focus on load shifting applications, [14] on PCM integrated into wall elements, [15] and [16] on materials, techniques for embedding PCM into building elements and resulting thermal behaviours. [17] reviewed selected studies on passive and active storage modes of building integrated PCMs. The more recent [18,19] and [20] have reviewed more broadly PCM integration processes, methods for measuring physical properties of finished elements, simulation tools and future research potentials. This study is different from these preceding reviews in that it encompasses and critically evaluates all relevant literature to date, whilst also addressing data quality and availability issues. To achieve that it employs a systematic (structured) review procedure as explained below.

## 2. Methodology

The systematic review presented here builds on a well-established methodology originating from the health and social sciences [21–22]. This methodology is applied here, not only to assure the comprehensiveness of the research, but also to guide the filtering of information identified. However the added value in systematic reviews is the transparency of the methodology used which allows reproducibility and thus creates a precedent for future reviews to build upon. Two electronic databases have been used in this study, *Web of Science* and *Scopus*, chosen for their prevalence in the subject area. Both databases provide abstract and citation information on peer-reviewed papers in the area of physical sciences [23–25].

### 2.1. Search and data selection

A systematic review uses clearly defined search criteria that are justified by the scope and orientation of the research [21,26]. The present review is concerned with LHS, having a focus on PCM integration in building elements. The keywords, operators and nesting combinations used for the searches in the two databases were as follows:

A. A generic set: TITLE (“thermal energy storage” OR “energy storage” OR “thermal energy” OR “heat storage” OR “thermal storage” OR “phase change material*” OR PCM) AND TOPIC (latent) AND TOPIC (application or system).
B. A focused set: TITLE ONLY (“phase change” or PCM) AND (wall*, roof, floor, panel, window, tile, curtain, shutter, building).

The search was deliberately broad, to allow all relevant publications indexed in the two databases to be identified. The first – generic – set search (A) was performed in September 2013 (Web of Science). The focused set search includes publications available online up to April 2014 (Web of Science + Scopus). The searches were followed by manual text screening that completed the selection process. The preliminary search revealed that a little more than 1/3 of the tracked literature was related to LHS applications in buildings. Around 1/6th of these was on PCMs integration in building elements and was selected for review, along with the results that came out of the second search set. Fig. 1 depicts a summary of the search process. A further filtering, using criteria for data quality and availability was performed (explained further below).

### 2.2. Data extraction

Following guidance for systematic reviews [21,26], a data extraction method was developed. In [27] evaluation criteria for thermal energy storage implementation have been proposed. Using these suggestions as a starting point, a list of parameters critical for successful design, implementation and performance of LHS building elements was formed. These parameters, organised in groups, are shown in Table 1 while in Table 2 a sample of the data extraction table is provided.

## 3. Results

### 3.1. Data availability and mapping

The search process tracked 140 studies to be reviewed. These covered a variety of building elements; more popular being walls (Fig. 2). Following the review, 20 papers were identified as inappropriate for data extraction and were excluded from the analysis. Reason for exclusion was lack of most or all data required for extraction [28–40]. For papers [41–47] that a more recent version was found the review included only the latest version [48–53].

Fig. 3 presents data availability in the 120 papers considered, revealing that very few papers offered data for extraction for all aspects reviewed. In some instances data availability was determined by the actual focus of the research. Very few papers were concerned with the role of internal (incidental) gains, and those were mostly dealing with simulation analyses [54–66]. A paper

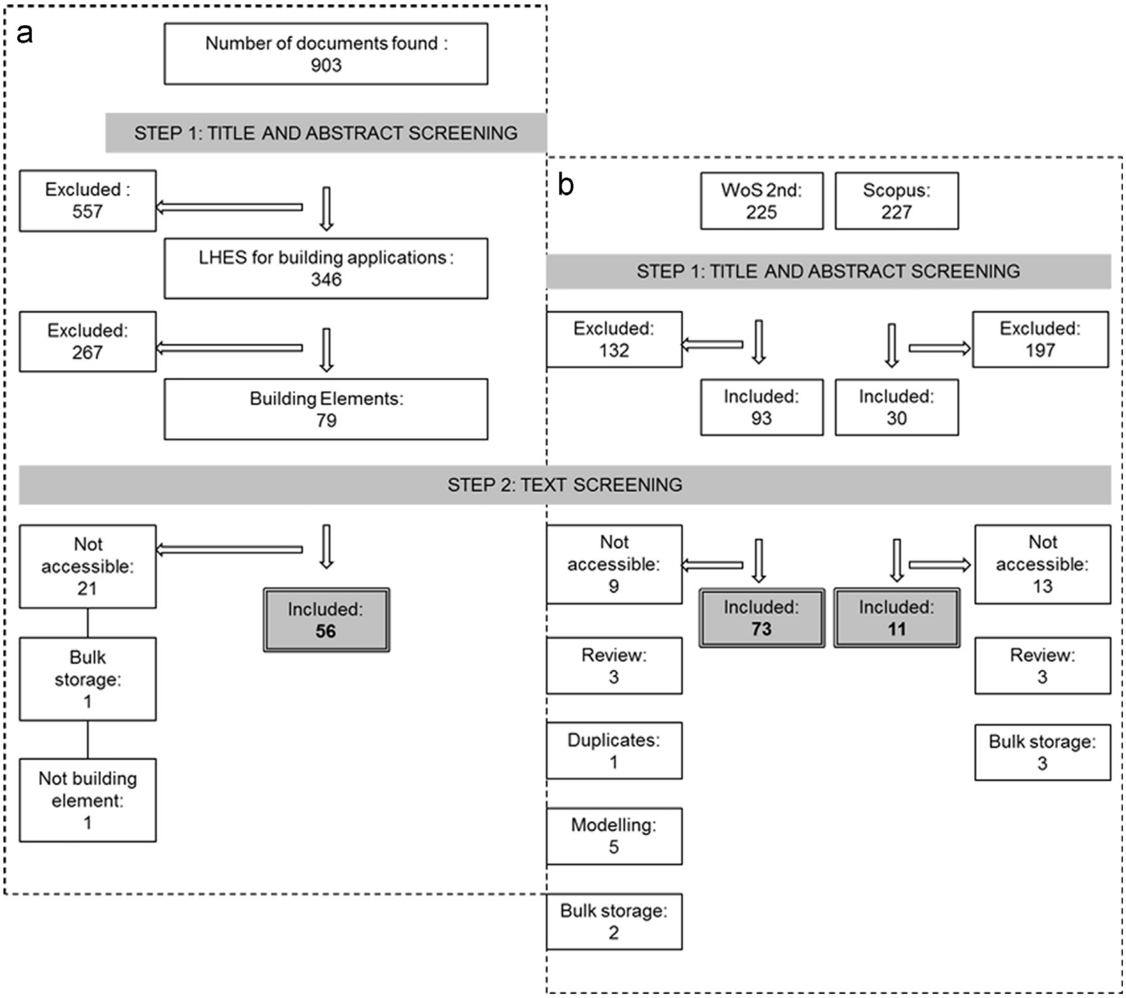

**Fig. 1.** Summary of search process; (a) generic keyword set and (b) focused keyword set.

**Table 1**
Groups of examined parameters.

| Group name | Parameters |
|---|---|
| **Context and application** | Element – application – climate – season – auxiliary system – control – internal gains |
| **Element attributes** | PCM type – PCM amount – thickness |
| **Thermal properties** (material or finished element) | Energy density – thermal capacity – specific heat capacity – conductivity – temperature range – super-cooling – storage duration – discharge time |
| **Element performance** | LHS effect – surface temperature – room temperature fluctuation |
| **Implementation aspects** | Cost – environmental risk – health/safety – lifetime – finishing |
| **Test conditions** | Method of investigation – method verification |

discussing numerical modelling of a PCM-enhanced building element deliberately ignored any gains from occupants or appliances, focusing on the heat flow within the studied element [67]. [68] discussed in particular the role that the occupancy pattern could play in defining an optimum melting temperature and [57] saw internal gains as crucial in determining the element's ability in fully meeting the cooling load. In studies using experimental test rigs, occupancy or appliance use was not considered. However some authors report energy demand reductions, meaning that energy load estimations had been made, considering or not incidental gains [69–72].

Information about the element studiedand its proposed application could be extracted from all papers, being the focal point and either the reason or the main conclusion of each study respectively. Season and climate are widely reported being closely linked to the application type, i.e heating or cooling, or the choice of PCM material. Most of the studies could provide data on PCM type and element thickness and half of the studies provided data on amount of PCM. Thickness, describes the thickness of a single board mixed with PCM or the thickness of a PCM layer within a sandwich (or sandwich-type) panel or a multilayer element. PCM amount has been usually reported in cases of PCM impregnation into a board, given in PCM-weight-percentage (wt%) and related to mechanical strength considerations [51,73]. It was mainly parametric studies, examining optimum melting temperature ranges, rather than specific PCM material or board types, that did not provide data on amount of PCM [74–76].

Energy density information, in kJ/m², was scarcely reported. Furthermore as with most extracted data concerning thermal properties, information on energy density and thermal capacity (in kJ/kg) was found to be inconsistently reported, often without differentiating the sensible to the latent component. The temperature or temperature range where the phase change occurs was reported in most cases. For studies that did not discuss storage duration, this review assumes it was diurnal. However two studies discussed the potential of storing heat seasonally, utilising the incomplete melting/solidification effects of PCMs during different seasons [47,77]. Performance related aspects i.e. surface

**Table 2**
Form of table for data extraction (extract of).

| Application | PCM | Thickness | Thermal capacity | LHS effect | Cost | Environmental risk |
|---|---|---|---|---|---|---|
| Heating, cooling, load shifting, demand limiting etc. | Paraffin, fatty acids etc. | Thickness of PCM element or PCM layer in element | Storage capacity in kJ/kg | Temperature fluctuation, energy saving etc. | Investment, payback etc. | Sustainability aspects, energy efficiency etc. |

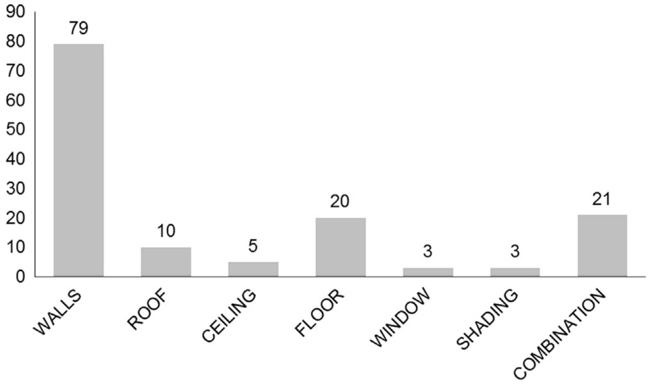

**Fig. 2.** Number of papers on each subject in the 140 papers.

temperature, room temperature swing and the LHS effects were also sought for extraction. The term 'LHS effect' describes any positive result from introducing PCM in building elements i.e. improvement of heat storage capacity, percentage of heat flux reduction, effect on human comfort, energy saving and load shifting potential. For time-varying quantities, an indication of the month or the hour of day that the temperatures represented was recorded accordingly. The LHS effect was studied alongside surface and room temperatures. This is because a promising element might not be able to achieve comfortable temperatures, as in the case of [78].

Mostly in recent studies insights into implementation aspects have been provided i.e. manufacturing, production, installation costs, payback periods, lifetime expectancy, wider environmental benefits, environmental, health and safety risks and final appearance. In some cases the cost of HVAC operation has been discussed, especially in places where off-peak pricing system is applied [58,79–84]. Four studies [58,85–87] have looked at predicted payback, and one [58] provided an economic comparison to ordinary materials that can achieve similar performance. The review identified lack of data on installation and maintenance costs. Lifetime is represented by the number of cycles that the element would undergo without showing deterioration of its thermal performance. Most information regarding this parameter could be extracted from studies that performed sample testing with repeated heating/cooling cycles. These experimental sequences are more rapid than in real time cycles and provide an indication of the minimum number of days that the element can perform satisfactorily [79]. Three of the reviewed studies elaborated on life cycle assessment (LCA) of PCM enhanced elements [50,85,88]. On health and safety risks the only information available was about PCM toxicity or flammability. Specifically [57] indicated that fire safety of the proposed PCM panels and compliance with fire regulations should be noted.

Considerations to do with finishing options like paints, wallpapers and plasters can be relevant to designers and occupants and thus were included in the data extraction. When a PCM is considered as a layer within a multi-layer element, such as a masonry wall, then typical finishing options were assumed for the review. More data on this parameter was obtained from studies on floor elements, where the finishing material was clearly stated [58,89–92]. In the case of PCM-gypsum boards, no information regarding compatibility with finishing materials was traced. It is likely that this factor is omitted in recent studies due to it being extensively examined in very early studies on the same subject, as suggested in [93]. This might indicate that it isno longer of further concern. Nonetheless two studies [52,94] discussed that the performance of a PCM-enhanced element depends on the convective heat transfer ability. Consequently, the surface orientation and coverage by furnishings could reduce the element's effective performing area. To what extend this could be a drawback is subject to future analysis but, apparently, implementation of PCM-elements in real spaces will also have to include interior design considerations.

Fig. 4 presents a categorisation of the methods of investigation traced in the literature, including single element studies, test cells, indoor chambers, computer simulations, outdoor cabins, parametric studies and method combinations. This categorisation was seen as important for extraction and analysis, given that the method largely determines the data used for, or resulting from, each investigation. The breadth of research methods employed is evident here. It is noticeable in Fig. 4 that the studies which could not have provided an approximation or measurement about the indoor temperature swing are those examining single elements and those performing LCA. These studies correspond to a total of 28 papers and represent approximately 2/3 of the missing data on indoor temperature swing. Similarly data relevant to internal gains and indoor temperature swings were available in most studies performing room simulations.

Studies that used a mathematical model – either for element study or for simulations – report on whether it is a verified model or whether it is validated in comparison to data existing in literature [60,61,84,95–98]. Studies that used two methods of investigation reported agreement between results [69,48–49,57–58,63,74,78,90,99–116]. Agreement between results is usually reported as a phrase "good agreement" or "reasonable agreement" and rarely with numerical comparisons. Often the need for future work was discussed [48,57,67–68,70,73,77,79,82,84–85,93–94,100,104,106–107,110–111,117–129] with an aim to include omitted parameters or to extend their investigations e.g. from test cell to macro-scale investigation.

### 3.2. Properties and performance factors

In the following sections the results of this systematic review are presented using the same structure as that used for data extraction. Results for walls, roofs and floors are presented together, whereas results for windows and shading devices are presented separately as they represent a small but distinct part of the reviewed literature. The discussion reveals that research on LHS fabric solutions is fragmented and the data resulting from it cannot lead to generalisable conclusions for these technologies. For completeness, any conclusions that can be drawn from the data are presented below, even if these are specific to a specific context or building type, or even tied to a particular research experiment.

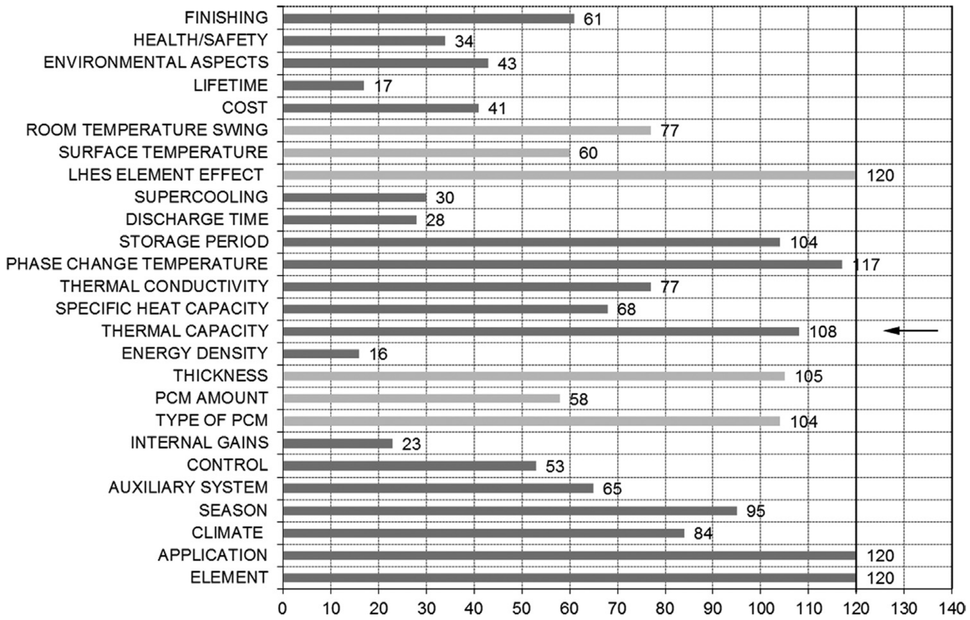

**Fig. 3.** Number of papers that provided data for each parameter.

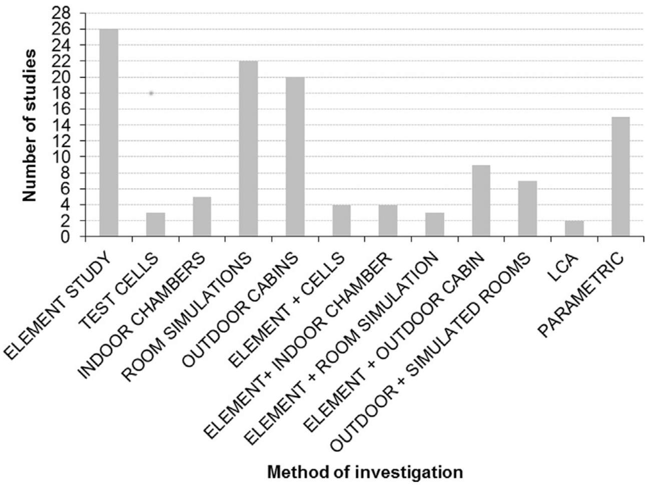

**Fig. 4.** Methods of investigation identified in the 120 papers.

### *3.2.1. Context and application*

Table 3 presents the building parts and the type of PCM elements that have been examined to date. On wall elements, most of the available data concern panels and primarily gypsum wallboards. The second more popular category is brick walls and composite wall constructions, such as TIM-façade and TROMBE walls. In TIM-facades and TROMBE walls, the PCM layer is used as the "collector panel" of the composite wall in order to increase the passive solar heating potential [48,67,71,100,119,130]. An auxiliary system has been described for most cases along with the designed or proposed control. Specifically [82] studied the performance of a LHS-enhanced building using two different control modes and concluded to the optimum control for achieving best energy cost savings. The study highlights the critical role that controls can play in utilising effectively LHS element's thermal properties. Other studies have suggested the need for applying night ventilation, either natural or mechanical (free cooling concept), to aid PCM discharge [55,85,93,106,120]. In TROMBE wall studies attention is drawn to strategies for reducing radiative heat loss [48,71,119].

A number of studies discuss applications of PCM impregnated elements on flat and sloped roofs [53,72,109–110,126,131]. Ceilings incorporating a tube system that circulates a heat transfer fluid (water), have been described in [56] and [57], while in [97] PCM cylinder macro-capsules embedded in a hollow core slab are discussed. With regard to floor-integrated LHS, data have been collected from simulated spaces and some outdoor monitored cabins. Such radiant floor constructions (see Fig. 5) have been studied for their ability to achieve heating energy savings when incorporating a PCM layer [58,83,113,132–133]. Apart from heating, there have also been studies (see Fig. 6) investigating the cooling potential of PCM embedded into floors [90,92,112,134]. Also, two PCM-floors have been monitored in outdoor experimental rooms for their passive solar heating potential [89,127].

In most studies looking at combinations of PCM integration to the building fabric a combination of wall and ceiling or roof element has been examined [61,62,65,77,114,115,128,161–163]. Only a few studies examine coverage of all internal surfaces with a PCM layer [59,96,129] and these usually follow up on preliminary single-element studies. For example a renovated office where Energain® panels were applied as interior lining on walls and ceilings to improve the building's thermal inertial was presented by [161]. Energain® panels have been previously studied by the same research group under various test conditions [103,120,141]. Initial results of the office monitoring showed an increased number of hours during which internal conditions are within the thermal comfort range due to the addition of a PCM layer to the otherwise lightweight construction.

In [115] a PCM-enhancedceiling was studied following a previous investigation on PCM-enhanced plaster tested solely on walls. The combined effect (walls and ceiling) was found to be effective in reducing the maximum room temperature by 4 °C, with night ventilation used to aid solidification of the PCM-plaster. PCM-plasterboards used on walls and ceilings were also studied by [77]. Simulation results showed that solar energy stored passively at the end of the heating season can be discharged after summer, at the beginning of the new heating season. This seasonal storage effect can reduce the heating energy demand at the beginning of the heating season by 90%. The authors do not however discuss any possible negative or neutral effects on cooling during summer months when the system is operating at a saturated status.

As seen in Table 3, the SSPCM (Shape Stable PCM) is a widely examined PCM element type. SSPCM consists of microencapsulated

**Table 3**
Building parts and types of PCM elements studied to date.

| **Wall** | **Roof** | **Ceiling** | **Floor** | **Combination** |
|---|---|---|---|---|
| Gypsum board [93,69,79,135,99,117,73,49,54,51,136,118,52,137,74,138,139] | 2 stainless steel panels [109,156] | PCM embedded piping [56] | PCM tiles [89,50] | Gypsum board [84,77,65,160] |
| TIM-PCM intelligent façade [67,100] | | Sheet steel tray containing PCM/gypsum composite [57] | Concrete floor [127,113,112,157] | DuPont™ Energain™ Panels [161] |
| TROMBE [119,48,71,140,130] | Concrete slab [126,110] | | FSPCM [58] | Sandwich panel [128] |
| PVC panel filled with PCM and coupled to a VIP [101] | | | SSPCM [133,158,91] | SSPCM [162,63,62,61,96,60,129] |
| DuPont™ Energain™ panels [94,85,103,141,120,121,142] | Trapezoidal metal sheet [111] | Hollow core ceiling slabs filled with PCM cylinders [97] | Piped radiant floor with a steel matrix to improve thermal conductivity [90] | |
| Sandwich [102,70,122] | Reinforced cement concrete roof with PCM [53] | TABS with PCM [124,125] | Radiant floor with water pipes embedded in concrete slab and two PCM layers (cooling/heating) [92] | Concrete mixed with Micro-encapsulated PCM [163,164] |
| Structural insulated panels [81] | | | | |
| Honeycomb panels [55,104,143] | PV-PCM roof [72] | | Under-floor electric heating system [132,159] | PVC panel filled with PCM and coupled to a VIP [78] |
| PCFW [144] | | | | Gypsum plaster [115] |
| Panel composed of microencapsulated paraffin and not-expanded polyurethane as binding [145] | Slope roof with PCM panel below insulation layer [131] | | Radiant floor with water pipes embedded in concrete slab [83] | CSM panels [88] |
| PCM Integrated copper foam panels with ventilation holes [123] | | | OA floor [134] | SSPCM + gypsum board [164] |
| SSPCM [75,76,82,146,147] | | | | |
| Bricks filled with PCM [148,105,98,149,150] | | | | |
| PCM layer in masonry wall [151,152,107,71,68] | | | | |
| Concrete mixed with PCM [108] | | | | |
| Hollow glass brick [106] | | | | |
| Ventilated facade with fins filled with PCM [97] | | | | |
| PCM-enhanced cellulose insulation [153] | | | | |
| Macro-encapsulated PCM panel on concrete wall [87,154] | | | | |
| BioPCM25™ [155] | | | | |

paraffin dispersed in High Density Polyethylene (HDPE) or other supporting materials (polyethylene and styrene-butadiene-styrene comopolymere, graphite foam). Applied to walls, ceilings and floors as interior lining, SSPCM technologies (Fig. 7) have resulted to 10% heating energy savings [129]. In addition, SSPCM on walls and ceilings coupled with night ventilation have been shown to reduce the need for auxiliary cooling during summer days and save up to 76% of daytime cooling [61–62]. A number of parametric studies have examined SSPCM [63,76–76,91,132,159]. The application of SSPCM as interior lining on all interior surfaces was studied in [96] and as a floor element in [91]. The performance of SSPCM was found by both studies to be dependent on the convective heat transfer coefficient, whilst the thermal conductivity of the element had an insignificant effect on resulting indoor temperatures. [91] presented optimised values of latent heat around 120 kJ/kg and thickness at 20 mm. These values have been confirmed and/or adopted by other parametric studies [63,75–76]. The same authors suggested that thin PCM layers applied over large surfaces are preferable than thicker layers applied to smaller areas [96]. A similar argument has also been presented by [127] about PCM-concrete floors.

Focusing on convective heat transfer effects, [94] observed that the inner convective heat transfer coefficient is higher for PCM walls in comparison to conventional walls. Both [94] and [96] agree that the convective heat transfer coefficient values given in guidance or calculated through the equations do not represent the performance of PCM building fabric elements, due to the enhanced energy exchange effects between the element and the volume of air. More specifically, guidance gives a value of $\approx 2\ \mathrm{W/m^2\,K}$, while [96] suggested values between $5.62\ \mathrm{W/m^2\,K}$ and $8.72\ \mathrm{W/m^2\,K}$ and [94] reported measured experimental values at $4.43\ \mathrm{W/m^2\,K}$. Also, it has been commented that high values like $10\ \mathrm{W/m^2\,K}$ can only be achieved with forced convection [94]. The dual role of ventilation in aiding the discharge process not only by cooling the element but also by enhancing convection has also been discussed [66,94].

In [52] the thermal behaviour of PCM-gypsum board, when used as partition wall or lining, was studied. The board's storage capacity was found to be higher when it was used as partition wall rather than as lining. This effect was accredited to the dual-side energy exchange with the environment in the case of a partition wall. However in the reviewed literature, rarely PCM wallboards or panels have been mentioned as partition walls (Table 4). In Table 4 all reported positions for the placement of PCM boards or other PCM layers in wall constructions are given. The term PCM layer has been used in the literature to describe PCM panels such as SSPCM or PCM panel constructions that encompass a PCM layer. The term has even been used theoretically without describing a specific construction, differentiating the subject of study from PCM-boards which are clearly described as gypsum boards impregnated with PCM. The terminology used by the authors has been preserved in this review.

In the case of TIM facades a PCM layer is placed behind the wall system facing the conditioned space [67,100]. In TROMBE walls the PCM layer has replaced the traditional storage wall [48,71,119]. In masonry walls it has been used as filling in bricks, as a layer after outer brick leaf or as middle layer [105,107,148]. Gypsum and other PCM-panels are also placed as interior lining of external walls or as internal partitions [69,118]. Overall, PCM layers have been considered as interior lining in temperate and continental climates, as middle layers in all types of climates and after the outer brick leaf or as brick filing in temperate and hot climates.

A few studies [84,87,107,121,152,154] have examined the optimum positioning of the PCM layer in the building envelope. All these studies conclude that the optimum position depends on both the climate and the intended application. For some climates double PCM layers have also been proposed for achieving best performance during both heating and cooling periods as reported by [70,84,122,138]. In that case the outer layer has a higher melting temperature than the inner and is active in summer conditions, while the inner is active in winter conditions. The use of double layers was examined for roofs by [109], sandwiched between the top roof slab and the ceiling. This study found that the two layers of PCM, iwith the top having a high melting temperature and the lowerlayer having a melting temperature near the thermal comfort range, can give best results. Double layers have been considered for floor constructions too. Double PCM layers with two different melting temperatures were also studied by [92], one at 38 °C for heating and another at 18 °C for cooling (Fig. 8). [152] studied the options of having PCM before or after the insulation layer. The study also examined the optimum melting temperature for both seasons, with either configuration. It concluded that for the specific climatic context (Csa) no such temperature can be identified. The suggestion made was for a target application (heating or cooling) to be identified or double layers to be considered.

**Fig. 5.** Structure of the under-floor heating system (reproduced here with permission from [132]).

A broad range of climatic types has been examined to date, largely corresponding to the regions where the research was done. For climates with both cooling and heating needs, the aim is to dampen temperature fluctuations, and thus reduce heating and cooling demands [70,84,102,118]. There are a few studies discussing in particular the potential of completely eliminating the need for ‘auxiliary’ heating or cooling systems [54,89,96,100,119,127]. In general, it is observed that the climatic context often influences decisions that are key to the design of the research, such as the positioning of PCM layer, season and application type (heating/cooling), phase change temperature, and consequently PCM type (see also Fig. 10 and Fig. 12).

### 3.2.2. *Element attributes and thermal properties*

The range of thicknesses that have been studied to date, for either PCM-board or PCM-layer, is shown in Fig. 9 (to link the information presented in this figure to the publications reviewed, see also Table 3). The thickness ranges from 0.01 m to 0.095 m for PCM-gypsum boards and from 0.005 m to 0.02 m for PCM panels. A thickness of 0.02 m has also been used as layer in TROMBE, TIM and masonry walls. Regarding PCM floors, the thickness of concrete slabs that have been examined is between 0.05 m and 0.095 m, while for PCM layers added in floor constructions thicknesses between 0.01 m and 0.025 m have been tested. [127] suggested that PCM-concrete mixes in layers thinner than 0.05 can be charged faster. Two studies discussed incomplete solidification issues; [113] reported impediment of complete solidification-and thus discharge of energy-due to excessive amount of PCM in a concrete slab. However even without complete solidification, the concrete-PCM slab studied by [113] was able to maintain appropriate surface temperatures and provide heating during the 16 h that the auxiliary

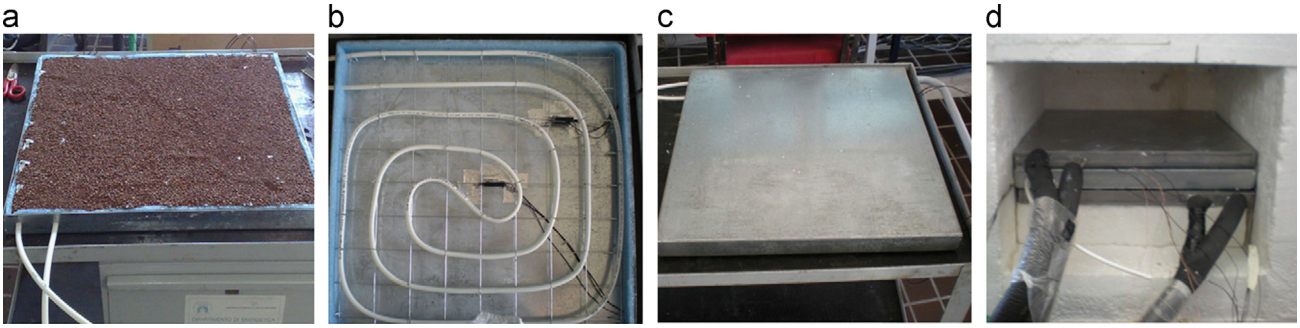

**Fig. 6.** Radiant floor experimental set-up: (a) the metal container with the pipes and the supporting metal net, (b) the specimen filled with the granular PCM, (c) the closed specimen, and (d) the specimen before closing the testing chamber (reproduced here with permission from [90]).

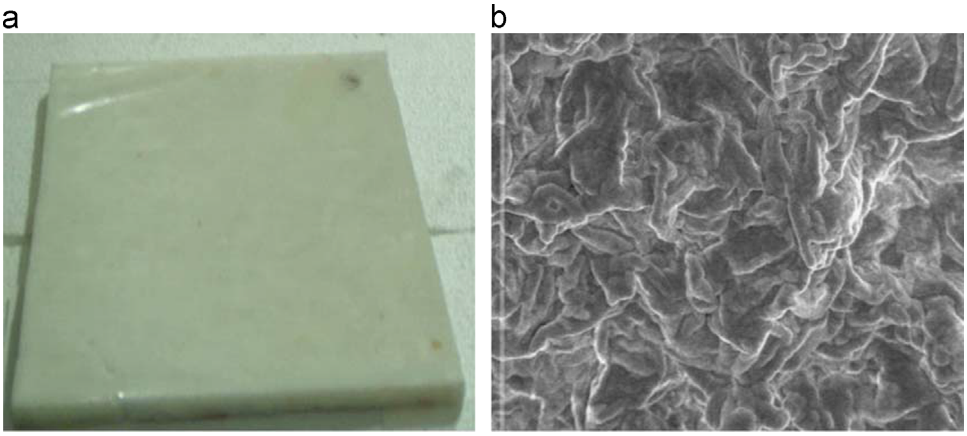

**Fig. 7.** Photos of a shape-stabilized PCM plate: (a) photo of the plate, (b) electronic microscopic picture by scanning electric microscope (SEM) (reproduced here with permission from [36]).

**Table 4**
Position of PCM layers on wall element and climate for which position was studied; positions indicated as optimum in the literature are highlighted in bold.

| PCM part position | PCM-gypsum board | Energain | SSPCM | Sandwich panels | Various panels | Filling |
|---|---|---|---|---|---|---|
| **Interior lining** | Dwa [135,137]<br>Csa [118],[138]<br>Cfb [69],[115],[65]<br>Dfb [77] | **Dfb** [121,160]<br>Dfa [161,160]<br>Csa, Csb, Dfc [160] | Cwa [82]<br>Dwa [60,96,162]<br>Cfa [162] | Csa [70] | – | N/A |
| **After outer brick leaf** | – | – | – | – | Af [123]<br>BSk [71]<br>Cfb [151] | N/A |
| **PCM in middle layer** | **Dfa, Cfa, Am** [84] | Cwa [85] | – | – | **Dfb** [107]<br>Cwa[114,87]<br>BSk[71]<br>Csb[155] | N/A |
| **As partition** | Csa [118] | – | – | – | Cfb [55] | N/A |
| **As external wall** | – | – | – | Cfb [102] | Dfa [144],[81]<br>BSk [71] | N/A |
| **In bricks** | N/A | N/A | N/A | N/A | N/A | Bwh [148]<br>Cfa [98]<br>Csa [149]<br>Csa [105] |

For consistency, climatic information is codified here following the Köppen climate classification [165]. Climate symbols (for the codes used) explained below:
Dwa: Cold/dry winter/hot summer.
Csa: Temperate/dry summer/hot summer.
Cfb: Temperate/without dry season/warm summer.
Dfb: Cold/without dry season/warm summer.
Dfa: Cold/without dry season/hot summer.
Csb: Temperate/dry summer/warm summer.
Dfc: Cold/without dry season/cold summer.
Cwa: Temperate/dry winter/hot summer.
Cfa: Temperate/without dry season/hot summer.
Af: Tropical/rainforest.
BSk: Arid/steppe/cold.
Am: Tropical/monsoon.

system was off. In [56] the incomplete solidification of the LHS-enhanced ceiling was credited to poor design factors, e.g. pipe spacing, inlet cooling water temperature and PCM thermal properties.

Paraffins, esters of fatty acids and hydrated salts have been examined to date. In some cases commercially available PCMs have also been studied [88,94,118,162]. Esters of fatty acids are usually impregnated in gypsum boards in a weight percentage ratio of 25–26 wt%. In [69] a total heat energy density of 430 kJ/m$^2$ for a gypsum board impregnated with 25 wt% liquid butyl stearate has been reported. Latent heat energy density was mentioned to be 85% of the total value, which gives 365.5 kJ/m$^2$. This value is similar to 312.9 kJ/m$^2$ reported in [80] for a 82 wt% capric acid + 18 wt% lauric acid mixture at 26 wt% in gypsum. It can be concluded that fatty acids impregnated in gypsum boards at a percentage of 25–26% are likely to result to a highly improved energy density of gypsum boards owing to latent storage.

Different compositions of fatty acid esters could result in different thermal capacities of a PCM-gypsum board even when same amount of PCM is impregnated in gypsum, as can be observed by comparing values reported by [79] and [135] (Table 5). The recorded data (Table 5) reveals that a mixture of capric acid (83 wt%) and steatic acid (17 wt%) impregnated in 25 wt% in gypsum has resulted to the highest thermal capacity value of PCM-gypsum board reported to date, at 48.97 kJ/kg [117].

A wide range of latent heat storage capacities of gypsum boards impregnated with paraffin, are reported in literature, as shown in Table 5. From the values reported in [49,73,136] it could be concluded that by increasing the paraffin weight percentage, a corresponding increase on the thermal capacity of gypsum board is expected. This is also confirmed by [52]. [66,98,138,154] have also indicated that by increasing the PCM filling or thickness the latent heat effect is increased.

The range of phase change temperatures that have been considered in the studies reviewed is shown in Fig. 10, in relation to the climates examined. For most PCM options and for each climate a range of melting and solidification temperatures have been studied in literature. The lowest recorded value is indicated as melting or solidification "low" and the highest recorded is indicated as melting or solidification "high" on this figure. When a single value was found, this is recorded as low (melting or solidification accordingly). In most cases the phase change temperature is determined by prevailing climatic conditions and falls within the human comfort range. High melting temperatures, up to 37 °C, have been considered for flat roofs, responding to the outdoor prevailing conditions. However the resulting inside surface and room temperatures of these constructions are within the thermal comfort levels as shown by [53,109,126]. Very high melting points have been mainly examined for active systems. A phase change temperature at 52 °C was considered for an underfloor electric heating system with SSPCM plates (between the plates and the final wood floor a 10 mm thick air layer interfered) [132,159].

The phase change temperature varies according to climate and in the same climate could vary from one season to another. Parametric studies have shown that optimum temperatures exist according to climatic context [59,68,74,84,160]. A study that examined optimum melting temperature and optimum latent heat levels for PCM for passive solar rooms in various climates concluded that LHS-enhanced fabric solutions may not be viable for some climates [59]. These are very cold climates, where the use of active heating systems is imperative for thermal comfort, or relatively mild climates, where passive heating techniques using traditional materials may be adequately effective. A number of studies [58,68,82,138] highlight the importance of selecting suitable melting temperatures as well as designing appropriate controls for optimising performance.

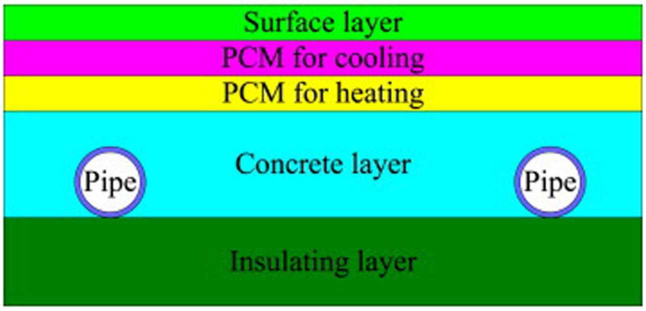

**Fig. 8.** The schematic of the double layer PCM floor (reproduced here with permission from [92]).

### 3.2.3. *Element performance*

Most studies report beneficial effects from PCM incorporation in building elements. A maximum 24.22% and 32.8% heat flux reduction (measured in W/m$^2$) on the inner surface has been reported from two different studies that tested bricks filled with PCM compared to ordinary bricks [148–149]. The cooling load reduction, resulting from monitoring the performance of outdoor experimental cabins has been found to be close to 7% for a sandwich panel cabin and 10.8% for a phase change frame wall (PCFW) cabin [70,144]. Agreement was found in the literature on the predicted heating load reduction of the sandwich panel cabin and of a PCM-gypsum board cabin. Predicted values were 17% and 15% respectively [69,70]. However due to inconsistencies in these data, no broad comparisons can be made. Furthermore, the results correspond to specific climatic conditions, internal gains and controls. For the purpose of this review an attempt is made to identify "optimised" effects that could be considered as indicative of cutting edge performance for these technologies.

In [48], a TROMBE wall with a Triple Glass Unit (TGU) was studied for Dfb. For this construction, a PCM plaster board was

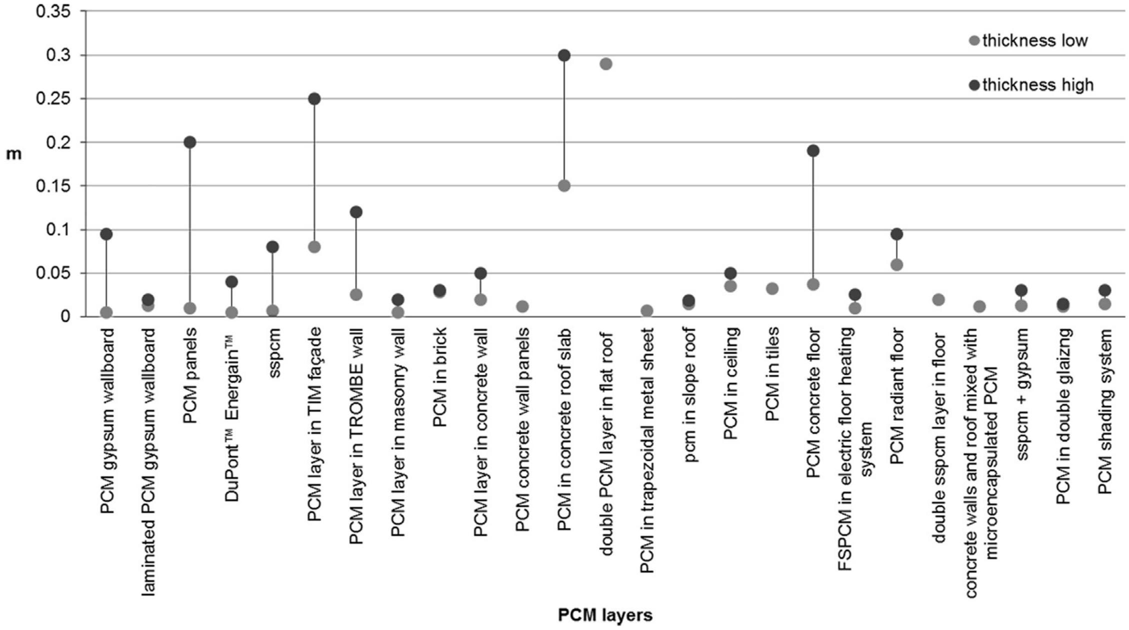

**Fig. 9.** Thickness of PCM boards/panels and PCM layers in various building elements that have been studied in literature. As low has been indicated the lowest value found in literature. As high has been indicated the highest value found in literature. Where only one value was recorded, this was indicated as low.

**Table 5**
Observations on the relation between PCM type, amount and thermal capacity. Superscripts explained; a: total thermal capacity of board and b: latent only thermal capacity of board. Only studies that could provide all three parameters have been cited.

| System | PCM | PCM amount (%) | Thickness (m) | Thermal capacity (kJ/kg) | Ref. |
|---|---|---|---|---|---|
| Laminated gypsum board | Paraffin based encapsulated PCM (hexadecane) | **11.8 wt** | 0.0125 | **20.1**$^a$ | [49] |
| Gypsum board attached to wood structural panel | RT27 | **13.5 wt** | 0.012 | **56**$^a$ | [136] |
| Gypsum wallboard | Ester of fatty acids: 93 – 95 wt% MeP and 7 – 5 wt% MeS | 23 wt | – | 38.2$^a$ | [93] |
| Gypsum wallboard | Liquid butil stearate (BS) | 25 wt | 0.013 | 30.7$^b$ | [69] |
| Gypsum wallboard for wall/ceiling | Paraffin | 25 wt | 0.013 | 33.5$^b$ | [84] |
| Form-stable gypsum wallboard | Eutectic mixture of capric acid (83 wt%CA) and steatic acid (17 wt%SA) | 25 wt | 0.01 | 48.97$^b$ | [117] |
| FSPCM in electric floor heating system | FSPCM: micro-encapsulated paraffin blended with HDPE/wood flour composite | 25 wt | 0.01 – 0.025 | 27.6$^b$ (melting) 28.2$^b$ (freezing) | [58] |
| Gypsum wallboard | Eutectic mixture of capric acid (CA65%) and lauric acid (LA35%) | 26 wt | 0.095 | 35.1$^b$ | [79] |
| PCM-gyppsum board as interior lining | **Eutectic mixture of capric acid (CA82%) and lauric acid (LA18%)** | **26 wt** | **0.095** | **36.9**$^b$ | [135] |
| Gypsum wallboard | n-octadecane, 5 – 15μm | **50 wt** | – | **65.5**$^b$ (melting) **64.2**$^b$ (cooling) | [73] |
| DuPont™ Energain™ | **Microencapsulated paraffin within a comopolymer** | **60** | **0.0052** | **34.8**$^b$ **(average)** | [94] |
| DuPont™ Energain™ | **Microencapsulated paraffin within a comopolymer** | **60** | **0.015** | **70**$^b$ | [121] |
| SSPCM | Paraffin dispersed PCM | 70 wt | 0.02 | 120$^b$ | [91] |
| Water pipe floor heating with sspcm | Paraffin as dispersed PCM in polyethylene as supporting material and expanded graphite | 75 wt | 0.016 | 139$^b$ | [133] |
| Under-floor electric heating system | SSPCM: paraffin as dispersed PCM in polyethylene as supporting material | 75 wt | 0.015 | 150$^b$ | [159] |
| Hollow concrete floor panel | SSPCM: paraffin (RT 27 from Rubitherm) | 85 wt | 0.19 | 110 ± 11$^b$ | [112] |
| Panels containing micro-encapsulated PCM | Paraffin wax in powder form | 85.71 | 0.01 | 45$^b$ | [145] |

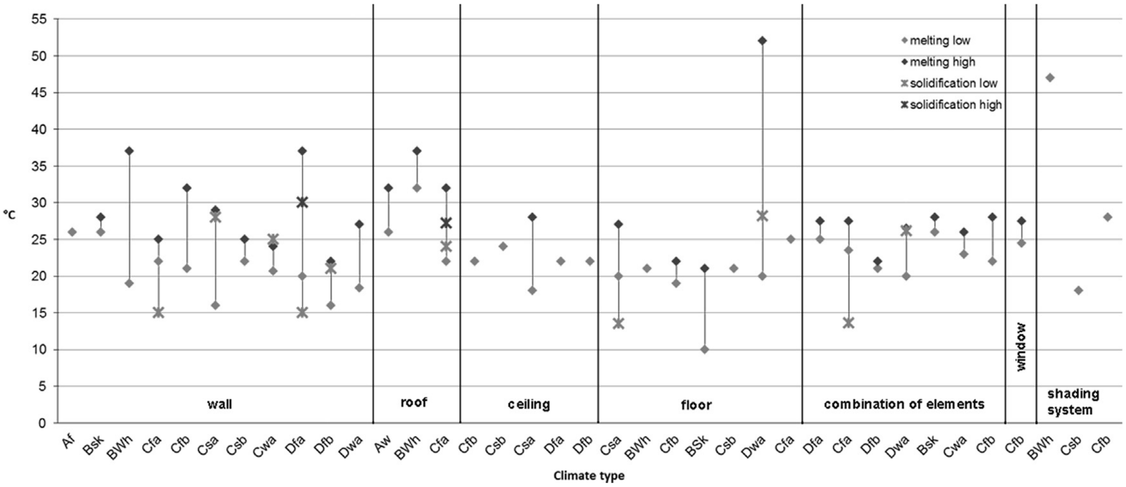

**Fig. 10.** Phase change temperature and its relation to climate. As low has been indicated the lowest value found in literature. As high has been indicated the highest value found in literature. Where only one value was recorded, this was indicated as low.

placed on the outer side of the masonry wall and a TGU was placed in front of the wall, instead of ordinary glass. A Prismasolar® glass in the middle of the TGU was designed to reflect direct solar radiation to reach the PCM during summer months, thus preventing overheating. The efficiency of the system was found to vary from 37% in October to 21% in February and no benefits could be obtained for the rest of the heating season, that was reported to last until April in the considered location. It was concluded that a TGU was not an appropriate choice for that climate. The selection of an appropriate glazing system, or shading strategy, would help utilise higher amount of the stored heat by reducing radiative heat losses, as discussed by [71,119]. A 30% efficiency for a TROMBE wall with PCM was also predicted by [119], who discussed the option of reducing radiative heat losses by using a low emissivity glass.

The predicted heat flux reduction from roof slabs incorporating PCM was reported to be 39% by [126] for Bwh and 56% by [53] for Aw in comparison to conventional roof structures. Furthermore [72] has predicted a 55% reduction in average cooling loads (W/m$^2$) for the space under the attic with the PCM layer placed below the insulation layer of a sloped roof in Cfa (Fig. 11). These values, although not directly comparable, indicate the beneficial effects of PCM incorporation into various roof constructions. In the roof presented by [53] a satisfactory heat flow control was noticed even when the PCM did not completely melt and/or solidify during a day cycle. During half of the year the solid fraction would increase, while during the other half the liquid portion would increase throughout the day cycles. A similar finding for a ceiling was presented by [56] who proved that comfortable surface temperatures and smoothed-out electricity peak loads were achievable even when the PCM does not completely melt during daytime. Both [124] and [125] reported that Thermally Activated Building Systems (TABS) do not substantially benefit from the PCM addition

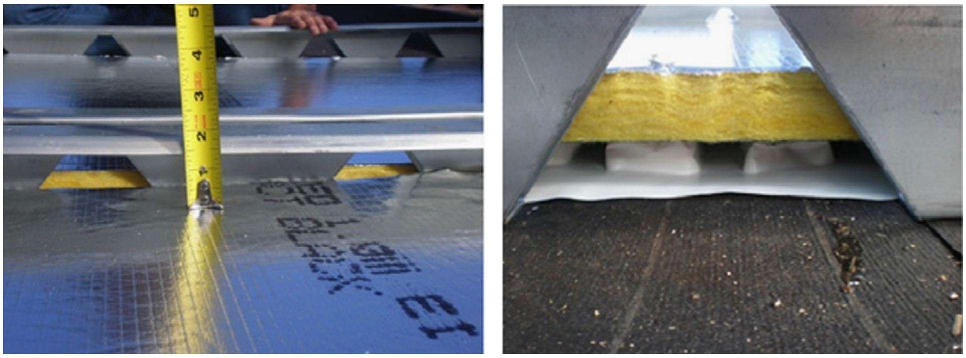

**Fig. 11.** Location of the PCM heat sink directly on top of the roofing deck material with air channels above and below the fibreglass insulation (reproduced here with permission from [72]).

neither in the concrete deck nor as ceiling PCM-mortar tiles. Researchers suggested that further options could be investigated with other material mixtures, such as PCM-gypsum.

In most cases the resulting indoor temperature swing was reported to be short and dependent on the applied control. Predicted swings from laboratory results were in the range of 5–6 °C and from simulations around 6–7 °C. Monitoring of outdoor rooms has given swings that range from 2 °C to 10 °C. In the outdoor cabin where the 10 °C swing was monitored, a heating system was in operation during night times, with a set point temperature at 16 °C and during the day, when the passive solar strategy was applied, temperature in the room would reach 26 °C [69].

### 3.2.4. Implementation aspects

Unaffected lifetime ranging from 60 to 5000 cycles was recorded for PCM-gypsum boards [51,73,79,99,117]. For other types of wall constructions there is no information about lifetime. Results of actual lifetime performance were obtained from [114,162,163]. Unchanged performance of the PCM layer 'PEG1000+PEG600' during the two years that the monitoring of the outdoor cabin lasted was reported by [114]. Likewise, [162] reported unchanged performance of concrete walls mixed with micro-encapsulated PCM after 6 months of monitoring. Considering that the following research [163] on the same cubicles was dated 5 years later, a minimum lifetime of 5 years can be assumed.

The LHS integration is reported to result to an overall improved efficiency of HVAC operation by regulating heat transmitted to the interior environment. Low cost of HVAC operation was discussed in [69,80–82,137]. Reduced cost of electricity consumption can be expected due to night-time operation of the ceiling systems, which eliminates the need for additional use of air conditioning during the day. Reduced operation cost was also reported with relation to PCM floors, owing to the reduction of peak loads and overall energy demand for space conditioning and extended lifetime of auxiliary system due to efficient operation [58,83,89,92,127]. Floor systems that are subject to controlled charging and discharging are charged preferably during off-peak electricity pricing hours, providing benefits due to demand shifting [90,92,113,132].

Additional economic factors have been considered by some authors. Low cost of PCM has been reported by [79,93,101] for fatty acids and type "PEG600". Furthermore [117] and [102] stated that the manufacturing cost is low for gypsum impregnation with PCM and for sandwich panels, respectively. However high capital cost was mentioned by a study using a commercial product [85]. Considering the same product as interior lining of a lightweight wall for cold climates, [121] commented that it was a costly alternative to traditional brick walls with insulation. In [58] the payback cost was estimated to vary from 9.9 to 99.3 years according to the applied control mode, in the case of a form stable PCM (FSPCM) radiant floor. A payback of 11 years was estimated by [87] for PCM layer added in concrete wall. The importance of selecting appropriate thickness and controls in order to achieve the best possible cost benefits was also discussed in this research. Another important issue raised by the same study is cost comparison with common materials. The results showed that improving wall insulation was a more economically attractive option than installing a FSPCM floor.

Despite the high payback time predicted for a commercial product, its energy payback period was estimated by [85] at 23.4 years. This number is less than half the building's lifespan (60 years according to researchers); consequently energy saved by the application of the element could make up for its embodied energy. Optimistic results from the environmental impact point of view were given by two more studies that applied LCA [50,88]. These two studies also found that salt hydrates have a lower environmental impact than paraffin, considering 50 year building lifetime; the first used the 'Recipe indicator' and calculated percentage of emissions reduction, whilst the second used the 'EcoIndicator 99' method and calculated impact reduction in impact points. [50] performed a LCA of PCM tiles. Three PCM types (paraffin MicronalDS5008X-Basf, salt hydrates ClimSel C24, ClimSel C21-Climator) and five different climate types were studied. Salt hydrates were found to offer higher environmental impact reduction than paraffin and this was true for all climate types considered. Also, PCM tiles were found to have greater environmental impact reduction potential in two of the climates (Bwh, BSk) compared to the other three (Csa, Csb, Cfb). In all climates the three PCM types were considered with unaltered thermal properties. It was therefore noted that by choosing PCM type according to climate, better performance and limited environmental impact during operation could be expected.

Finally, finishing options have been mostly discussed in studies on PCM floors. These include wood floor [92,132], tiles [83,90,133], marble [58] and carpet [134]. Clay stoneware was the finishing of PCM-tiles proposed by [89] and thin concrete-PCM layer was suggested by [127]. Also both studies mention that the floor areas that were more efficient, were those near the windows and at unobstructed parts of the space that can receive direct solar irradiation.

## 3.3. Windows and shading systems

Windows and shading systems have been studied for their potential to reduce incoming solar gains [95,116,166,167,168]. As they represent a small part of the related research, drawing from them general conclusions on system performance implementation aspects is not possible. However, useful information could be extracted from publications discussing monitoring results.

An outdoor installation with double glazing façade was studied by [116]. The system could effectively shift peak loads and reduce solar gains approximately by 50% with either paraffin RT25 or with salt hydrate S27. The two PCM options presented differences in appearance during solidification, forming flakes and crystal needles, respectively. These issues were seen as easy to overcome by adding screen-print on the façade.

A PCM-slats shading system has been experimentally installed in two offices in a Cfb climate. The monitoring study revealed satisfactory outcomes under the experimental conditions, reducing the summer operative temperature by 2 °C. However, operating restrictions imposed by researchers during the experimental period resulted to occupants rejecting and dismantling the system before the completion of monitoringcs neutral or slightly positive in terms of resulting optical environment in the offices [167].

## 4. Discussion

The data collected and reviewed here reveal that there is a potential for energy savings through the use of a range of PCM-enhanced elements. The data suggests that the longer the PCM is active within a year cycle, the lower its environmental impact will be. This would be true for regions that demonstrate stable climatic conditions throughout the year as also mentioned in [88]. However, as this is rarely the case, the PCM selection appears as a key design parameter to consider when optimising performance considering seasonality [50,64,88,152,162]. On that matter, the option of using double PCM layers seems to offer a potential for year-round performance in climates that demonstrate both heating and cooling needs. However this choice may also increase manufacturing impact as well as investment costs. Since analysis on double layers from a combined – economic and environmental impact – perspective was not found in the available literature, no safe conclusion on their feasibility can be currently drawn.

As the selection of appropriate PCM and resulting element performance appears to be highly climate dependent, more attention on climate change effects may need to be drawn in LHS research in the future. Climate change considerations can be related to both element lifetime and cost, as it is likely to affect the required melting temperature range. The environmental payback estimates discussed above, though hopeful, are based on the assumption that the element will “live” that long. However, data reviewed on the lifetime parameter cannot confirm – neither can refute – such a long life expectancy. This issue is relevant to cost payback too. Even if investment cost is decreased, a promising lifetime should be guaranteed so that a second investment will be delayed as much as possible to avoid frequent disruptions in space use as well as additional labour costs. One more parameter to be considered is the selection of suitable controls that will allow efficient use of the PCM element [58,82]. This might mean selecting the most appropriate working mode for the auxiliary system, where one exists, as described in [58, 68,82], or controlingthe night ventilation strategy, either natural or mechanical (free cooling concept) [55,85,120,128,162,167]. It is also noted that all published cost analyses are based on electricity prices that were current at the moment of writing and material costs specific to the region where the research was done. Hence, the only general conclusion that can be drawn is that the use of PCM elements can be a cost beneficial option if appropriate controls are applied and current manufacturing cost is decreased to compete well with conventional materials. It is further noted here that future research will also have to examine material availability in the short and long term future, as this is missing from the current literature.

SSPCM elements appear to be a promising LHS option. However the use of microencapsulated paraffin and the reported high commercial cost of these systems suggest that further research needs to be performed having a focus on cost and environmental impact considerations. It is also becoming evident through this review that LHS in radiant floors and ceilings might be at the moment the two most promising applications for residential applications. These appear viable in achieving considerable energy savings with the addition of a PCM layer, subject to a suitable system control and a high capital cost. However research on this particular subject area is still limited, in contrast to research on wall elements.

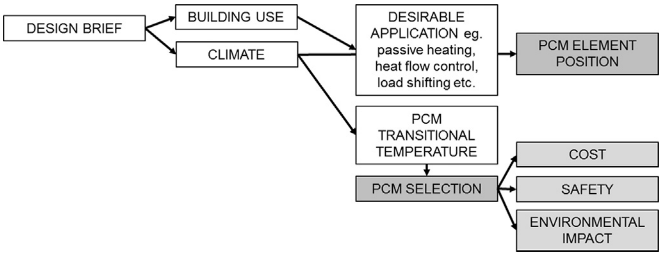

**Fig. 12.** Flowchart of critical parameters to be considered when deciding to integrate a PCM element in the building envelope.

Fig. 12 presents a decision-making diagram for integrating LHS in building elements, based on the analysis of the results in Section 3.

## 5. Conclusion

A systematic review has been conducted to examine LHS-enhanced building fabric systems. A total of 120 paper was identified as suitable for review and a list of investigated parameters, organised in six groups, guided the data extraction. The review of published research revealed that a range of parameters that are key to the performance of these systems can be identified. However published information on those aspects appeared to be diverse and in many cases insufficient, in contrast to respective information on other energy storage systems for which a more comprehensive knowledge base exists [169].

The review has shown that with appropriate design, PCM elements can contribute to reducing loads and achieving energy savings in buildings, while securing a comfortable indoor environment. More specifically:

- Phase change temperature should be chosen according to climate and (target) season;
- If year-round performance is required double layers might be a suitable option;
- Optimum position should be selected according to climate and intended application;
- LHS benefits cannot be utilised effectively without the appropriate control.
- The auxiliary system's working mode affects the PCM element's performance.

The diversity of test conditions and variety of reported values indicate that physical properties and performance data concerning materials and complete elements that are found in the literature are not directly comparable. The analysis of published data also reveals that even with desirable performance assured, parameters such as investment cost, investment payback and environmental payback may inhibit the use of a PCM-element and favour the use of conventional materials. The systematic review has further revealed that information on the above mentioned aspects is deficient. The results highlight areas where future research would be beneficial in broadening our understanding of the actual potential held by these technologies in energy and carbon reductions from heating and cooling. At the moment of writing matching technologies and applications for specific climates and building typologies is not possible solely through published information. Further research is needed to enrich the knowledge base and enable a broader mapping of performance aspects that could guide design.

## Acknowledgement

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