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A review of the performance of buildings integrated with Phase change material: Opportunities for application in cold climate

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Abstract

Buildings generally need serious attention in order to reduce global energy consumption and greenhouse gas emissions. Phase Change Materials (PCMs) that change phase just above normal room temperature are a promising means of reducing cooling-energy demand, and improving thermal comfort in buildings. This paper reviews the literature from studies of the thermal performance of different types of PCM and different ways of integrating them into buildings. Based on this review, the paper closes with an investigation of the potential for application of PCMs in passive-house standard dwellings and office buildings in the Nordic climate.

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Keywords: Passive house; Phase Change Materials (PCMs); Cooling systems; Lifecycle assessment

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1. Introduction

Buildings account for approximately 40% of the total energy use in Europe [1, 2]. A significant amount of this goes to space heating and cooling. In a bid to reduce this energy use and its related environmental impacts, all EU/EEA member states have tightened their national building regulations in line with European directives (most recently EPBD-Recast). These changes promote higher levels of thermal insulation along with lightweight building structures in order to minimize energy demand. However, initial studies have revealed that these energy-efficient buildings can experience problems with thermal discomfort due to elevated indoor air temperatures in warm weather[3]. One interesting way of easing this problem is to incorporate Phase Change Materials (PCMs) into the building fabric, in order to increase the effective heat storage capacity of lightweight buildings. PCMs are also

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incorporated building components other than fabric in order to increase the energy effectiveness of the building.

Best practice use of PCMs involves exploiting diurnal swings in outdoor temperature, whereby absorbed heat during the daytime is released at night when the outdoor and indoor air is cooler. Thus, PCMs serve to dampen the amplitude of indoor temperature swings and thus reduce peak indoor temperatures. This ensures better thermal comfort for occupants, while at the same time reducing, or avoiding the need for mechanical space cooling.

Several authors have investigated, both theoretically and experimentally, the thermal performance of PCMs incorporated into standard buildings for the passive cooling of building spaces [4-7].

In this paper, reviews on thermal energy performance of PCMs incorporated at various elements of buildings are presented. A through discussion on the possible applications of PCMs on buildings designed according to passive house standards is also included.

2. Phase Change Materials (PCMs)

PCMs are materials that undergo a phase transition between liquid and solid when heated or cooled, much like H_2O changing between ice and water. At the temperature at which phase change occurs, PCMs store incoming thermal energy in the form of latent heat (charging, melting) and reject it when being cooled (discharging, solidifying). PCMs used in buildings must fulfil the following fundamental criteria [1, 8, 9]; PCMs should undergo phase change near to the operating temperature of the building space, at the range of 20 °C to 32 °C [9, 10], they should also have good thermal conductivity and high latent heat per unit volume of the building material; and they should not pose a risk to health or the environment.

2.1. Classification of PCMs

PCMs exist in different forms (Fig.1) and are manufactured so as to perform at the required temperature range. Paraffin and salt hydrides are the most commonly used PCMs for application in buildings. The pros and cons of PCMs are discussed elsewhere [9, 11].

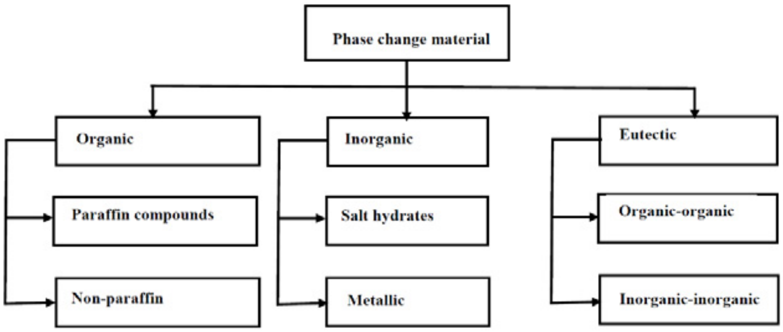

Fig. 1. Classification of PCMs [8, 9, 11-14].

2.2 PCM integration methods

Incorporating PCMs into lightweight indoor surfaces (walls, ceilings or floors) is an effective way of increasing their effective thermal capacity. Another means of application is incorporating a PCM in the building's thermal envelope (external walls/roof, windows/shutters, ventilation system), such that the PCM can more easily discharge heat at night to the environment. In all cases, the integration method should be carefully assessed. The three most widely used techniques of integrating PCMs into building elements are immersion, direct incorporation and encapsulation [1, 5, 15-19].

- Immersion involves immersing the building material into melted PCM; the material absorbs the PCM by capillary action.
- In the case of direct incorporation, the PCM is added directly into the construction material during the production

process, such as mixing PCM powder with gypsum powder during the manufacturing of the gypsum board.

- Encapsulation comes in two forms, microencapsulation and macroencapsulation; in microencapsulation, particles or droplets of PCM are surrounded or coated with a continuous film of polymeric material to produce capsules, while in macroencapsulation, the PCM is contained in larger containers (bags, tubes) before integration into the building.

3. Literature review

Table 1 lists the recent literature on PCMs integrated into different building elements and summarizes the findings. Of the many studies of the performance of buildings containing PCMs, nearly all conclude that integrating PCM into buildings reduces peak indoor temperature and improves thermal comfort.

Table 1a: Studies focused on PCMs integrated into different components of buildings

Building element	PCM type	PCM integration techniques	Important findings	Reference
Window/ or shutter	Paraffin	Not mentioned	This experimental study showed that in the summer season the PCM window lowers solar energy gain by more than 50% as compared to the traditional fenestration. In winter, a suitable reduction in the heat loss via the fenestration during the day was observed, but the direct solar gain is also drastically reduced. The PCM was able to provide good thermal conditions for the indoor environment.	[20, 21]
	n-Octadecane, n-Eicosane, and paraffin	Not mentioned	This numerical study revealed that the PCM on the window shutter has the capacity to reduce the heat gain via window by about 23%. It was also concluded that the melting point of the PCM should be as close as possible to the upper temperature limit of the window.	[22]
	Not mentioned	Immersion	This study showed that glass sheet filled with liquid PCM shows better thermal performance than air-filled glass. The study also revealed that the PCM reduces infrared and UV radiation while good visibility is maintained	[23]
Wall	Paraffin	Microencapsulated	This study showed that the PCM, compared to tests without PCM, is able to reduce the peak temperature of the testing chamber by about 3 °C.	[5]
	Paraffin	Microencapsulated	This experimental study revealed that the PCM reduces peak room temperature by about 3 °C and the interior surface temperature by about 2 °C.	[24]
	Eutectic mixture of capric acid and lauric acid	Not mentioned	This study showed that the temperature of the south wall of the cubicle without PCM at midday is 2 °C higher than that of the cubicle with PCM indicating that the PCM has an insulation effect. Further investigation on the effect of the PCM on the south wall showed that the cubicle without PCM has a maximum temperature of 1 °C higher and a minimum temperature 2 °C lower.	[25]
	Organic PCM	Not mentioned	Honeycomb PCM wallboards on the inner surface of the partition walls yields a reduction in the peak operative temperature of about 1 °C and a reduced daily temperature swing of approaching 3 °C, down from 5.7 °C to 2.9 °C.	[26]

Roof/ceiling	Bio-based PCM	Macroencapsulated	This study focused on PCM integrated in an attic, with photovoltaic panels mounted on the roof. The results showed that the PV-PCM attic reduces winter heating demand by 30 % and the summer cooling load by 55 % as compared to a conventional shingle attic.	[27]
	Eutectic mixture of lauric-stearic acid	Immersion	This numerical study of the application of PCM in gypsum board as a ceiling component showed the boards reduced the peak indoor temperature by about 2 ºC. The study concludes that the PCM improves thermal performance and energy savings especially in single story buildings.	[6]
	Eutectic mixture of $CaCl_2$ +NaCl + KCl + H_2O	Macroencapsulated	This study showed that introduction of PCM panels in the roof effects the maintenance of a constant temperature at the ceiling unlike in the case of a room without PCM.	[28]
Floor	Paraffin	Macroencapsulated	The study looked at the effect of a radiant floor heating system integrated with PCM for cooling purposes without affecting the winter warming capacity. The PCM ensured savings of approximately 25 % of the water used for cooling, while the PCM-based floor surface temperature was 4 °C lower than that of the standard radiant floor.	[29]
	Paraffin	Micro encapsulated	This study showed PCM integration improved thermal comfort due to the PCM capability of increasing the time lag and reducing surface temperature by about 2 ºC.	[30]
	Paraffin|	Direct incorporation	Investigation of shape-stabilized PCM plates for an under floor electric heating system showed that the temperature of the PCM top cover surface can be kept at near the phase transition temperature. The indoor air temperature increased with better thermal comfort conditions.	[31]
Heat exchanger in ventilation and heating system	Inorganic and organic PCM	Macroencapsulation	Experiments were conducted on two types of PCM. It was concluded that, for free-cooling applications, more emphasis should be put into designing the heat exchanger than enhancing the PCM's thermal conductivity.	[32]
	Fatty acid	Macroencapsulation	This experimental and numerical study revealed that thermal comfort during daytime can be improved when night ventilation is used in combination with PCM.	[7]
	Paraffin	Macroencapsulation	This study showed that the thickness of PCM slabs plays a vital role in the effectiveness of the cooling process at night.	[33]
	Salt hydrate	Not mentioned	This was a theoretical and experimental study conducted on heat transfer between air and PCM in a heat pipe. The model overestimated heat transfer rate but predicted heat pipe surface temperature within 28 °C.	[34]
	Paraffin	Microencapsulated	This experimental and theoretical investigation found that a PCM-based free-cooling technique enables a reduction of ventilation system size, and it also provides better thermal comfort.	[9]

Paraffin (RUBITHERM)	Microencapsulated	Granules containing PCM stabilized the ventilation supply air temperature within the phase change temperature range and showed the potential of reducing the ventilation load during summer.	[30]
Not mentioned (but thermo-physical data given)	Not mentioned	This study indicated that a PCM-based active- cooling system with certain trade-offs, is an economically viable and environmentally sound solution for passive building.	[35]

Table 1b: Review articles.

Summary of review articles	**Reference**
Literature survey covering 28 PCMs with different melting points and heat of fusion. Discusses PCM encapsulation, including PCM-based ventilation, and absorption and adsorption cooling systems. Emphasis on experimental and numerical evaluations of PCM-based free cooling.	[34]
Review of theoretical and experimental studies of a number of PCMs for free cooling of buildings. Covers parametric studies and economical and environmental considerations of different PCMs.	[14]
Review of 29 papers (period 1983-2012) on PCM based heat storage applications in buildings, dynamic simulation tools for energy analysis, Life Cycle Assessment and economic evaluation of PCM integrated buildings.	[1]
Study of thermal energy storage technologies in buildings using PCMs in different construction materials, different building elements (windows, shutters, HVAC units), and different heat transfer enhancement techniques for PCM.	[36]
Survey of a number of materials that could be used as PCM in thermal energy storage in buildings, focusing on thermo-physical properties and stability.	[37]
Numerical techniques for modeling PCMs. Review of energy simulation tools to study the performance of PCM-embodied building enclosures.	[38]
Review of techniques for incorporating PCM into construction materials, test methods to decide the chemical compatibility, thermo physical properties, and thermal stability.	[17]

4. Integrating PCMs into passive houses

4.1 Norwegian passive houses

The passive house concept originated in Germany in the 1990s and has since gained popularity in Europe and North America. According to Norwegian Standard NS 3700 [39] , a residential passive-house is defined as a building with an annual heating demand of less than 15 kWh/m² (Table 2). For buildings in a local climate with annual average temperatures of less than 6.3 °C, this requirement is more lenient. In order to satisfy these requirements, Norwegian passive houses are built with conventional building materials but with higher levels of insulation (walls, roof, floor, windows). The low thermal bridges and high efficiency for heat recovery of the ventilation system are also the main characteristics of passive houses. The standard also requires a high level of airtightness, which both minimizes infiltration and reduces the risk of condensation damage in the thermal envelope.

Table 2. Basic criteria for Norwegians passive house standard for residential buildings [39].

Criterion	**Value**
Heating demand	≤ 15 kWh/year per m² floor area
Cooling demand	0 kWh/year per m² floor area
Heat loss factor (normalized)	≤ 0.5 W/K per m² floor area
Thermal bridges (normalized)	≤ 0.03 W/K per m² floor area
Average ventilation requirements	1.39 m³/h per m² floor area
Ventilation heat recovery	≥ 82 % (rotary heat exchanger)
Specific fan power (SFP)	≤ 1,5 kW/(m³/s)
Airtightness @ 50 Pa	≤ 0,60 h^{-1}
Total window area	≥ 20 % of the floor area ((25% E, 25% S, 40% W, 10%N)

The cooling demand requirement for non-residential passive buildings is allowed to maximum amount of 10 kWh/year per m^2 of floor area. There is ongoing research into the evaluation of the indoor temperature of passive houses. Unpublished documents and the latest research output [3] reveal that passive houses experience elevated indoor temperature during summer.

4.2 Possibilities to apply PCM in passive houses

As it is observed from the review (above), the most common ways of utilizing PCMs in buildings is by integrating them (macro or micro encapsulated) in the building envelope or building components other than envelope. Latent Heat Thermal Energy Storage (LHTES) units utilizing PCM as a separate unit are also employed for buildings' energy savings. In this section, the most applicable solutions for utilizing PCMs for passive houses are discussed.

Paraffin is the most widely used PCM for conventional building applications, because of its thermal stability, cheapness and its flexibly to adjust the phase change temperature. It has been proven to have the ability to reduce excess indoor temperature beyond the thermal comfort limit, as well as to reduce heating and cooling energy demand of buildings. The effectiveness of paraffin, however, depends on a number of factors, including building location, type of building materials, and the heating, cooling and ventilation systems.

An active cooling system, with good control strategies, may be an attractive solution for the cooling of PCM-based non-residential buildings (office buildings, commercial buildings, etc.) constructed with passive house standard at a given climatic zone with maximum annual cooling-energy demand of about 10 kWh/m^2 [42]. The stored thermal energy in different PCM-integrated building elements (e.g. floor) can be actively recovered using simple electric driven fans. This can reduce the overall energy consumption required for cooling compared to a conventional mechanical cooling-plant. The PCM melting temperature, heat transfer area between the PCM-containing surface and circulating air and the thickness of the PCM, are critical parameters that govern cooling capacity and efficiently.

Free-cooling systems have shown their ability to reduce peak indoor temperatures in conventional buildings [7, 33]. The same method could also be applied to passive houses incorporating PCM. As shown in fig. 2, incorporation of PCM into the ventilation supply is particularly interesting for non-residential passive houses that are heated by ventilation air.

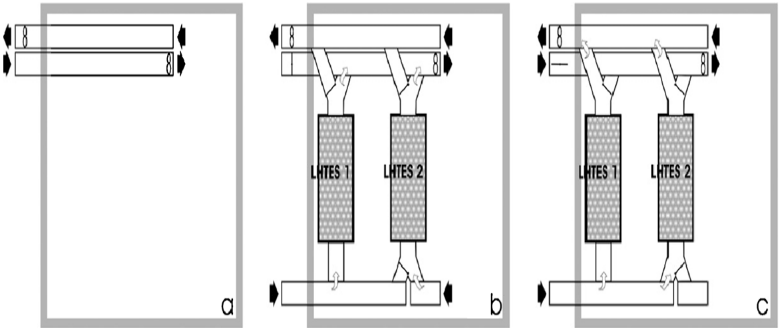

Fig.2. Fig. 2. Different mechanical ventilation modes: (a) mechanical ventilation or night cooling, (b) free cooling during the daytime operation, (c) free cooling during the night-time operation [34].

When the outdoor temperature is rises above the a cooling coil set-point, the outside air could bypass the heat recovery unit and exchange heat with the PCM. The excess heat from the outside air is then removed by the PCM. Later during the night, when the outdoor temperature drops below room temperature, the air draws heat from the PCM. The PCM is then recrystallized and will be ready for the next day's excess heat absorption. This method increases the convective heat transfer coefficient between the PCM and the supply air, and it may avoid the need to activate the cooling coil in the ventilation unit. However, this may require a redesign of the ventilation supply duct system to incorporate an additional duct that accommodates the PCM and operates during the summer season. Moreover, it is important to consider the air flow resistance over the PCM so that the time-averaged specific fan power (SFP) will not increase beyond the required value of 1.5 kW/(m³/s) [39]. However, it should be noted that it could be possible to compensate for any increase in Specific Fan Power (SFP) by compensatory measures (e.g. better thermal insulation), so that building's total annual energy demand does not increase. There is also the fundamental condition that the PCM-system must provide more free-cooling than the increase in heat gain from the fan system.

A ventilated façade could also a possibility, in which the ventilation air flows over PCM incorporated either as an additional layer of the building wall or as a filler in the air cavity between building's interior and exterior walls. These types of façades have proven their potential to reduce the thermal load and shift peak temperatures by several hours.

The other possibility to reduce peak temperature in passive houses is through the application of PCM on window glazing. Due to the requirement for daylight in building spaces (daylight factor > 2%), passive houses need a window area of approximately 20% of the floor area. This requirement, combined with the high level of thermal insulation, causes elevated indoor temperatures during summer. This problem is observed especially in passive houses with a highly glazed façade, inferior solar shading and limited means for window airing. The integration of paraffin in the large window area could lower the indoor temperature [20, 21]. However, the current commercially available PCMs have low solar transmittance during their melting phase, and their integration between the panes in double-glazed windows could reduce the daylight factor (see fig.3). Hence, advanced materials, such as nano-treated PCMs should be considered in order to improve the transparency of the PCM-based window glass. Furthermore, the long-term durability of the PCM-based glass or window to external exposure, including solar radiation, needs to be considered. Presently, much research is being directed towards PCM-based smart-glass materials for windows with low solar and high visible transmittance that have strong potentials to produce low cooling loads for buildings.

Fig. 3. DGU_PMC (bottom) and DGU_CG (top) assembled on the outdoor test facility [20]

PCM-based polyethylene window shutters for large glazed windows could be another way of preventing overheating. An appropriate type of PCM (by melting point and amount-per-unit-shutter surface area) could be selected so that the PCM melts and freezes based on the specified outdoor temperature range. Placement of the shading (internal or external to the window) is another interesting point that needs further investigation.

Floor-based heating systems are becoming increasingly popular in modern buildings, owning to their potential to improve thermal comfort for occupants while utilizing low-temperature energy sources. Underfloor heating systems integrated with PCM have the potential to store heat at night and release it during the day [29,30]. Heating the PCM at night shifts the consumption of electrical energy from peak to off-peak periods and secures the economic advantage of cheap electricity at off-peak periods if there is a non-flat electricity tariff (e.g. wind power).

Integration of PCM (with melting temperature of 22-25 ^{o}C) in the floors of non-residential passive houses with large glazing areas in the southern and western-facing directions would have significant potential to reduce peak indoor temperatures due to solar gain. However, it is important to note that the stack effect may cause overheating on the top floors of multi-story buildings, and the amount of the PCM applied on each floor may then need to be varied accordingly to maintain uniform thermal comfort in the whole building.

The addition of PCM to building envelopes and internal partition walls increases the building's thermal mass. The highly insulated envelopes of passive houses could, to a certain extent, increase the thermal mass of the building. However, owning to the high air tightness of passive houses and the nature of sensible heat thermal energy storage of the envelopes, this would not support the remove of excess indoor temperature of passive dwellings. Therefore, incorporation of a PCM with good latent-heat capacity offers a better alternative in order to improve indoor temperatures (reducing either the indoor temperature or the duration of periods above the maximum set-point). The PCM could be placed in the interior (fig.4) or exterior of the envelope. However, it is important to understand the effect of the PCM thickness, as well as the integration technique. For better performance, free night ventilation systems through openings working with simple automatic control are recommended for efficient recovery of the absorbed heat and solidifying the PCM. The automatic control criteria for night ventilation could look at the average outdoor temperature, indoor temperature and indoor-outdoor temperature difference. Even though conventional night ventilation is believed to remove more heat from the internal surfaces (walls, floors, callings and blinds), there are reports that use of the PCM in the outside surfaces improves indoor temperature more. This suggests that the ventilation rate needed to extract the heat may be different when the PCM is placed in internal or external surfaces. Hence, these issues need to be investigated further. For non-residential passive buildings, it may be necessary to incorporate an additional mechanical cooling system to achieve thermal comfort. The range of the cooling set-point for the ventilation cooling coil should be investigated well for the melting point of the PCM selected so that the chiller is utilized as little as possible.

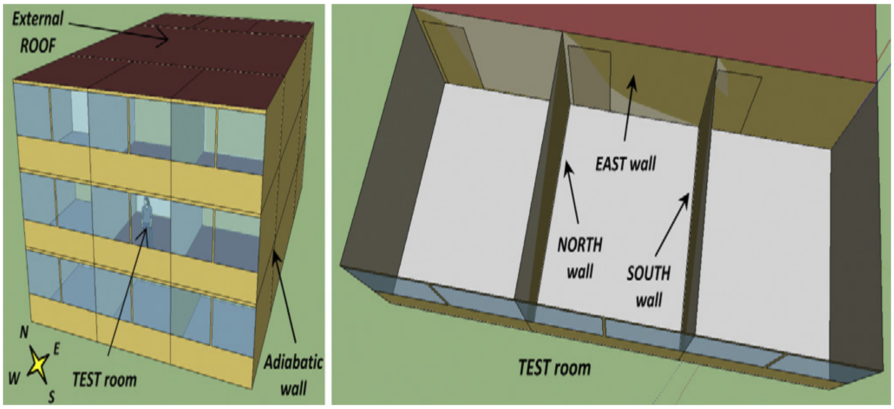

Fig. 4. Left: model of the simulated building. Right: Partition walls covered with PCM wallboards [26].

Along with all these possibilities, PCMs, particularly paraffin, do have some drawbacks including poor thermal conductivity. As a continuation of this work, the author will perform a numerical simulation of Norwegian passive houses incorporating PCMs that will look at different parameters, including type and amount of PCM, phase change transition temperature, building components for the integration of PCM, local climate and size of house.

4.3 Environmental impacts

The environmental impact of using PCM in buildings should be well addressed before marketing PCM-integrated passive houses. Presently, only the reduction in energy use, and resulting CO_2 emissions, have been well documented. There have so far been few Life Cycle Assessment (LCA) studies of PCM integrated buildings. The LCA studies performed by [40] for PCM integrated in Mediterranean buildings showed that the energy-saving in the operation phase was not enough to offset the environmental impact from the manufacturing phase, which is derived from the high embodied energy of PCM. Although paraffin has been widely used as a PCM, comparative analysis results identified a lower environmental impact from the use of inorganic salt hydrates than from paraffin [40]. The LCA study for seven experimentally masonry cubicles built in Spain showed similar results [41].

However, the inclusion of PCM in passive houses may have differing impacts depending on the type of energy supplied to the passive house, along with the raw materials and production site for the manufacture of the PCM. In this regard, a Norwegian passive house integrated with PCM manufactured locally using predominantly hydroelectric- power is more promising. Thus, assessment of the overall environmental performance and the relative contribution of the different life-cycle stages of PCM-integrated passive house throughout the building life is crucial.

5. Conclusions

There is a large body of research that shows the potential use of PCMs in buildings. Several studies have covered topics ranging from the production and characterization of PCMs to their incorporation in buildings, as well as the potential energy savings and environmental impact of PCM-incorporated buildings. The articles reviewed revealed that PCMs have the capacity to reduce indoor peak temperature, shift the time of peak temperature (reducing excess temperature hours beyond the thermal comfort range), enhance the overall energy performance of the building, utilize off-peak electric energy and increase thermal resistance like an insulation layer.

This work has clearly showed that PCMs have a large potential, which can be replicated for both residential and non-residential buildings designed according to passive house standards, for which mechanical cooling is not allowed or only used at low levels. Particularly, PCM-based building envelope or internal partition walls coupled with free cooling appear promising. PCM-integrated glass windows or windows shading also represent a promising area that needs further investigation. The LCA study revealed that PCM-integrated buildings reduce the energy footprint of buildings, though some PCMs have high embodied energy. Importantly, in this respect, manufacture of the PCM in a renewable-energy dominated location such as Norway would reduce the overall environmental impacts of the PCM based buildings.

Overall, I believe that the incorporation of PCM that melts at room temperature alone or in a combination with free cooling has the capacity to reduce overheating due to peak indoor temperatures (above 26 ^{o}C) and create acceptable thermal comfort for passive houses with less or no mechanical cooling systems. Hence, the energy-savings potential of all the various options and combinations needs to be critically investigated and evaluated. Furthermore, economic analysis of the integration PCMs into buildings for cooling application and comparison with the conventional mechanical cooling should be also performed as future work.

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References

[1] Soares, N., Costa, J. J., Gaspar, A. R., and Santos, P., 'Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency,' *Energy Build.* **59** (2013) 82-103.

[2] European Union, 'Directives 2012/27/EU of the European parliament and of the council of 25 October 2012 on the energy efficiency, L315,' *Official journal of the European Union* **55** (2012) 1-57.

[3] Persson, J. and Westermark, M., 'Phase change material cool storage for a Swedish Passive House,' *Energy Build.* **54** (2012) 490-495.

[4] Hadjieva, M., Stoykov, R., and Filipova, T., 'Composite salt-hydrate concrete system for building energy storage,' *Renewable Energy* **19** (2000) 111-115.

[5] Voelker, C., Kornadt, O., and Ostry, M., 'Temperature reduction due to the application of phase change materials,' *Energy Build.* **40** (2008) 937-944.

[6] Yahay, N. A. and Ahmad, H., 'Numerical Investigation of Indoor Air Temperature with the Application of PCM Gypsum Board as Ceiling Panels in Buildings,' *Procedia Engineering* **20** (2011) 238-248.

[7] Yanbing, K., Yi, J., and Yinping, Z., 'Modeling and experimental study on an innovative passive cooling system—NVP system,' *Energy Build.* **35** (2003) 417-425.

[8] Sharma, A., Tyagi, V. V., Chen, C. R., and Buddhi, D., 'Review on thermal energy storage with phase change materials and applications,' *Renewable and Sustainable Energy Reviews* **13** (2009) 318-345.

[9] Tyagi, V. V. and Buddhi, D., 'PCM thermal storage in buildings: A state of art,' *Renewable and Sustainable Energy Reviews* **11** (2007) 1146-1166.

[10] Agyenim, F., Hewitt, N., Eames, P., and Smyth, M., 'A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS),' *Renewable and Sustainable Energy Reviews* **14** (2010) 615-628.

[11] Zalba, B., Marín, J. M., Cabeza, L. F., and Mehling, H., 'Review on thermal energy storage with phase change: materials, heat transfer analysis and applications,' *Applied Thermal Engineering* **23** (2003) 251-283.

[12] Kenisarin, M. and Mahkamov, K., 'Solar energy storage using phase change materials,' *Renewable and Sustainable Energy Reviews* **11** (2007) 1913-1965.

[13] Abhat, A., 'Low temperature latent heat thermal energy storage: Heat storage materials,' *Solar Energy* **30** (1983) 313-332.

[14] Waqas, A. and Ud Din, Z., 'Phase change material (PCM) storage for free cooling of buildings—A review,' *Renewable and Sustainable Energy Reviews* **18** (2013) 607-625.

[15] Hawes, D. W., Banu, D., and Feldman, D., 'Latent heat storage in concrete,' *Solar Energy Materials* **19** (1989) 335-348.

[16] Feldman, D., Banu, D., Hawes, D., and Ghanbari, E., 'Obtaining an energy storing building material by direct incorporation of an organic phase change material in gypsum wallboard,' *Solar Energy Materials* **22** (1991) 231-242.

[17] Memon, S. A., 'Phase change materials integrated in building walls: A state of the art review,' *Renewable and Sustainable Energy Reviews* **31** (2014) 870-906.

[18] Hawes, D. W., Feldman, D., and Banu, D., 'Latent heat storage in building materials,' *Energy Build.* **20** (1993) 77-86.

[19] Tyagi, V. V., Kaushik, S. C., Tyagi, S. K., and Akiyama, T., 'Development of phase change materials based microencapsulated technology for buildings: A review,' *Renewable and Sustainable Energy Reviews* **15** (2011) 1373-1391.

[20] Goia, F., Perino, M., and Serra, V., 'Experimental analysis of the energy performance of a full-scale PCM glazing prototype,' *Solar Energy* **100** (2014) 217-233.

[21] Goia, F., Perino, M., and Serra, V., 'Improving thermal comfort conditions by means of PCM glazing systems,' *Energy Build.* **60** (2013) 442-452.

[22] Alawadhi, E. M., 'Using phase change materials in window shutter to reduce the solar heat gain,' *Energy Build.* **47** (2012) 421-429.

[23] Ismail, K. A. R. and Henríquez, J. R., 'Thermally effective windows with moving phase change material curtains,' *Applied Thermal Engineering* **21** (2001) 1909-1923.

[24] Kuznik, F. and Virgone, J., 'Experimental assessment of a phase change material for wall building use,' *Applied Energy* **86** (2009) 2038-2046.

[25] Shilei, L., Neng, Z., and Guohui, F., 'Impact of phase change wall room on indoor thermal environment in winter,' *Energy Build.* **38** (2006) 18-24.

[26] Evola, G., Marletta, L., and Sicurella, F., 'A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings,' *Building and Environment* **59** (2013) 517-527.

[27] Kośny, J., Biswas, K., Miller, W., and Kriner, S., 'Field thermal performance of naturally ventilated solar roof with PCM heat sink,' *Solar Energy* **86** (2012) 2504-2514.

[28] Pasupathy, A., Athanasius, L., Velraj, R., and Seeniraj, R. V., 'Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management,' *Applied Thermal Engineering* **28** (2008) 556-565.

[29] Ansuini, R., Larghetti, R., Giretti, A., and Lemma, M., 'Radiant floors integrated with PCM for indoor temperature control,' *Energy Build.* **43** (2011) 3019-3026.

[30] Royon, L., Karim, L., and Bontemps, A., 'Thermal energy storage and release of a new component with PCM for integration in floors for thermal management of buildings,' *Energy Build.* **63** (2013) 29-35.

[31] Lin, K., Zhang, Y., Xu, X., Di, H., Yang, R., and Qin, P., 'Experimental study of under-floor electric heating system with shape-stabilized PCM plates,' *Energy Build.* **37** (2005) 215-220.

[32] Lazaro, A., Dolado, P., Marín, J. M., and Zalba, B., 'PCM–air heat exchangers for free-cooling applications in buildings: Experimental results of two real-scale prototypes,' *Energy Conversion and Management* **50** (2009) 439-443.

[33] Zalba, B., Marín, J. M., Cabeza, L. F., and Mehling, H., 'Free-cooling of buildings with phase change materials,' *International Journal of Refrigeration* **27** (2004) 839-849.

[34] Osterman, E., Tyagi, V. V., Butala, V., Rahim, N. A., and Stritih, U., 'Review of PCM based cooling technologies for buildings,' *Energy Build.* **49** (2012) 37-49.

[35] Chiu, J. N. W., Gravoille, P., and Martin, V., 'Active free cooling optimization with thermal energy storage in Stockholm,' *Applied Energy* **109** (2013) 523-529.

[36] Pomianowski, M., Heiselberg, P., and Zhang, Y., 'Review of thermal energy storage technologies based on PCM application in buildings,' *Energy Build.* **67** (2013) 56-69.

[37] Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., and Fernández, A. I., 'Materials used as PCM in thermal energy storage in buildings: A review,' *Renewable and Sustainable Energy Reviews* **15** (2011) 1675-1695.

[38] Al-Saadi, S. N. and Zhai, Z., 'Modeling phase change materials embedded in building enclosure: A review,' *Renewable and Sustainable Energy Reviews* **21** (2013) 659-673.

[39] NS 3700, 'Criteria for passive houses and low energy buildings - Residential buildings (in Norwegian),' Standards Norway, (2010).

[40] de Gracia, A., Rincón, L., Castell, A., Jiménez, M., Boer, D., Medrano, M., and Cabeza, L. F., 'Life Cycle Assessment of the inclusion of phase change materials (PCM) in experimental buildings,' *Energy Build.* **42** (2010) 1517-1523.
[41] Menoufi, K., Castell, A., Navarro, L., Pérez, G., Boer, D., and Cabeza, L. F., 'Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase,' *Applied Energy* **92** (2012) 534-544.
[42] NS 3701, 'Criteria for passive houses and low energy buildings - Non residential buildings (in Norwegian),' Standards Norway, (2010).