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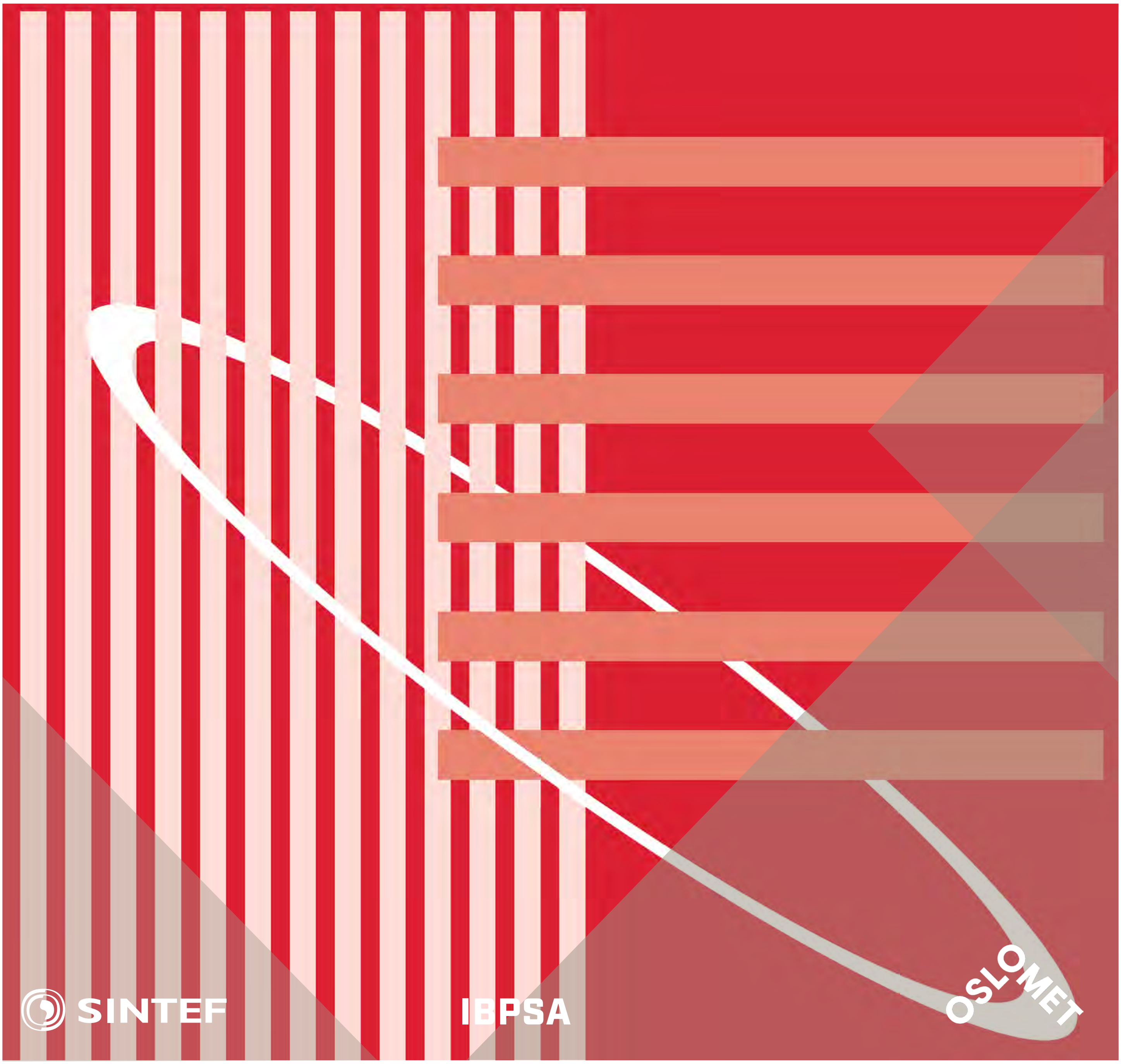

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Adapting to future climate change by integration of Phase Change Materials (PCMs) into the building envelope: a case study in Stockholm, Sweden

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Abstract

This paper presents a numerical investigation on the effectiveness of phase change materials (PCMs) wall implementation as building refurbishment solution, under both historical and future climate conditions. Specifically, the paper aims at proofing the PCM capability of being an effective refurbishment strategy. The study is based on dynamic building simulations carried out by IDA ICE on a typical residential single zone house in Stockholm city (Sweden). Specifically, two key performance indices have been considered: total energy demand and indoor thermal comfort. The results of the simulations highlight that in lightweight building envelope, PCM can contribute to a reduction of cooling demand and improve the indoor thermal comfort under both historical and future climate. PCM results slight effectiveness in reducing heating loads. However, the annual energy saving resulted between -1.5% and -2.4% for the historical period and between -1.9% and -5.7% for the future one.

Introduction

In Sweden, a large part of the housing stock is more than 50 years (Mangold et al., 2016), which means that it is presumably energy inefficient and with a limited capability to adapt to the future climate conditions. In this regard, it is noteworthy that the envelope optimization represents a straightforward strategy for a building to adapt to climate change (Shen et al., 2020). In fact, optimizing the building envelope allow less energy dependence on heating and cooling, while still maintaining the desired indoor thermal comfort conditions (Shen et al. 2020). Latent Thermal Energy Storage (LTES) is considered an effective way to temporary store energy in terms of latent heat, which is beneficial to enhance the building energy efficiency by increasing the lightweight envelope heat capacity. Accordingly, Phase Change Materials (PCMs) offer a great solution in energy storage due to their high latent heat capacity, which allow them to store and release a huge amount of energy in a small temperature interval (de Gracia and Cabeza, 2015). Specifically, when PCM is applied as a passive component, it is able to produce a sort of extra thermal capacity to the building envelope. Owning to this, the indoor temperature swings are smoothed as well as the heating and cooling demand reduced. PCMs and their passive applications in building envelope have been under study by many researchers around the world for over 30 years, showing remarkable results in terms of reduced heating and cooling energy consumption, peak load shaving and indoor thermal comfort improvement. Among them, PCM melting temperature, thickness, position and their interaction with the climatic conditions of a specific geographic location has been deeply addressed. It has been found that PCM as a passive component should be designed for each building type and climatic conditions. Moreover, considering that the lifetime of a building (50-100 years) (Constantinos et al. 2007) and PCM (30-80 years) (Panayiotou et al. 2016) corresponds to a period over which substantial changes in climate conditions are expected, it becomes important to have a valuable information on the PCM building refurbishment strategy viability not only in the present period but also into the future. To the best of the Authors knowledge, only Gassar and Yun (2017) assessed the effect of future climate on the performance of PCM applied in a new office building in humid and warm temperate climate (East Asia). They found that adding a PCM layer on the building envelope can increase the building energy performance during both heating and cooling seasons, also under future climate conditions. The **study motivation** lies on deepening findings from a previous paper published by the Authors Shen et al. (2020), where climate adaptive designs of multi-family building in a typical Scandinavian city were explored. The study highlighted that high thermal mass building envelope represents a good building adaptation strategy to climate change. This is especially true in Scandinavian Countries where the use of lightweight wood-based building envelopes is the most prevalent. In fact, a low thermal inertia envelope, even if characterised by high thermal resistance, could lead to overheating risks when irradiated by the sun with a consequent increase in the indoor temperature, energy consumption and occupants' thermal discomfort. Based on this, the **aim of the study** is to assess the building performance of a residential single zone house (in Stockholm city, Sweden), which lightweight envelope has been fully refurbished with PCM. The single zone house performance will be studied under both historical and future climate conditions, with the purpose of evaluating the effectiveness of this refurbishment solution also in the future. Hence, **the objectives of the study** are to: 1) define the climate change impacts on thermal comfort and heating/cooling demand of a residential single zone house in Sweden; 2) investigate the passive potential of PCM addition into conventional construction material and specify the optimal PCM thickness and melting temperature for both historical and future climate conditions. Even though there is a limited number (in Scandinavian regions) of residential buildings equipped with a unit cooler, overheating in summer can lead the occupants to adopt air-conditioning increasing the energy consumption of the building. Therefore, it seems wise to investigate the PCM cooling load reduction potential also in Scandinavian Countries.

Methods

Energy simulation

In this study, the IDA ICE (Indoor Climate and Energy) software has been used in order to perform the dynamic energy simulations of a single zone-house. The PCM layer is an IDA ICE module that calculates the amount of latent heat absorbed and released by the PCM. It uses the enthalpy method to define the relation between temperature and enthalpy (h-T curves) during PCM melting and solidification phase.

Building model description

A residential single zone house (day zone, including living room, kitchen and dining area) has been defined as reference model for Stockholm city. The reference model is a rectangular single-zone house (2.44 wide × 6.09 length × 2.6 height) with no internal portions (Figure 1).

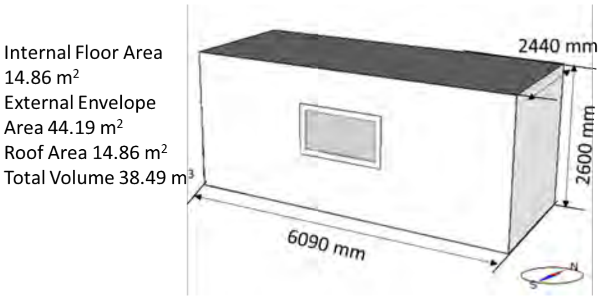


Figure 1: Residential single zone model

The main glazed façade is oriented to the south with a window to floor ratio of 10%, which can be considered typical among the single zone house with similar purposes (BREEAM-Health and Wellbeing). Window properties are shown in Table 1. No internal and external sun screening have been considered at this stage.

Table 1: Window properties of the single zone model

Two-layer panel window	Values
Solar heat gain coefficient (g)	0.60
Solar transmittance (t)	0.7
U (W/m^{2}K)	2.9
Internal emissivity	0.837
External emissivity	0.837
Visible transmittance	0.81

The construction materials are defined based on a survey about the existing building stock in Sweden (TABULA project, https://episcope.eu/welcome/) Table 2– 4. In Table 6 the U-transmittance values are set based on the existing requirements (https://www.eurima.org/). This will allow to focus only on the building envelope refurbishment in terms of increasing thermal mass.

Table 2: Wall construction of the single zone model

Material	Thickness (m)	K (W/mK)	Density (kg/m^3)	Cp (J/kg K)
Gypsum	0.026	0.22	970	1090
Frames cc 600+ insulation	0.25	0.130	56	1720
Air in 20 mm vertical air gap	0.02	0.160	1.2	1006
Wood cladding	0.025	0.14	500	2300

Table 3: Roof construction of the single zone model

Material	Thickness (m)	K (W/mK)	Density (kg/m^3)	Cp (J/kg K)
Roof material	0.02	0.58	1500	840
Frames cc 600 + insulation	0.25	0.130	56	1720
Gypsum	0.013	0.22	970	1090

Table 4: Floor construction of the single zone model

Material	Thickness (m)	K (W/mK)	Density (kg/m^3)	Cp (J/kg K)
Wood flooring	0.025	0.14	500	2300
Mineral Wool 0.037	0.25	0.037	20	750
Concrete medium density	0.2	1.42	2000	1000

RUBITHERM® RT organic PCMs (RT 21, RT 21 HC, RT 24 and RT 26) with three different thickness (1 cm, 2 cm and 3 cm) and three different melting temperature (21 °C, 24 °C and 26 °C) are investigated on the vertical walls of the reference single zone house. The RT 21 HC has been also included in order to test its higher heat storage capacity (20-30% higher than classic RT) and ability to melt in a narrower temperature range. Specifically, a melting temperature range between 21 °C and 26 °C will be explored, as belonging to the maximum and minimum thermal comfort temperature range during winter and summer period in Stockholm city (Climate Consultant v6.0) (Saffari et al. 2016). The thickness will vary between 1 cm and 3 cm as any further increase means that not all the thickness can be involved in the phase change process (Copertaro et al. 2016). The PCM added wall construction specification is given in Table 5.

Table 5: Refurbished wall construction with PCM

Material	Thickness (m)	K (W/mK)	Density (kg/m^3)	Cp (J/kg K)
Gypsum	0.026	0.22	970	1090
Rubitherm PCM	0.03 0.02 0.01	0.20	880	2000
Frames cc 600 + insulation	0.25	0.130	56	1720
Air in 20 mm vertical air gap	0.02	0.160	1.2	1006
Wood cladding	0.025	0.14	500	2300

A mechanical ventilation system providing a constant and fixed rate of 0.4 air change per hour (ACH) is used. The latter is based on comfort and health criteria and defined according with the required ventilation for pollution from occupants and building components under EN 15251. Moreover, it is expected to increase the amount of heat discharged by PCMs, which improves their efficiency. During the occupancy period (not at home from 8:00 to 17:00 during the weekdays), internal gains are due to people (one, which has been assumed reading 108 W), lighting (2 W/m^2) and other electrical equipment (2.4 W/m^2) based on ASHRAE Fundamentals. The summary of the main simulation parameters is given in Table 6.

Table 6: Simulation parameters

Vertical walls U-value	0.18 (W/m^{2}K)
Vertical PCM added walls U-values	0.18 (W/m^{2}K), PCM 3 cm 0.18 (W/m^{2}K) PCM 2 cm 0.18 (W/m^{2}K) PCM 1cm
Roof U-value	0.17 (W/m^{2}K)
Floor U-value	0.14 (W/m^{2}K)
Window g-value	0.60
Ventilation rate always on	0.4 ACH
Occupancy time	From 17:00 to 8:00 from Monday to Friday. Always at home from Saturday to Sunday.
Number of people	1
People sensible heat load	108 (W)
Artificial light load	2 (W/m^2)
Electric equipment load	2.4 (W/m^2)
RT21 and RT21HC melting temperature peak	21 °C
RT24 melting temperature peak	24 °C
RT26 melting temperature peak	26 °C

Future climate data

Stockholm city, in Sweden (Lat: 59.350N, Long: 18.067E) is considered as reference site in the present study. According to Köppen-Geiger climate classification Stockholm is classified as Dfb (temperate continental climate/humid continental climate) as representative of typical maritime northern European cities climate. In order to assess the single zone house performance under future climate scenarios, an hourly dependent climate dataset is necessary for a dynamic simulation. In this regard, the future climate data 2080s (2071-2100) have been generated by using a morphing approach based on the UK Met Office Hadley Centre general circulation model (GCM) predictions for a 'medium-high' emissions scenario (A2). The historical year is derived by the average period of 1971-2000 (Jentsch et al. 2008).

Heating and cooling system

The sensible cooling and heating needs are evaluated by using built-in IDA ICE function "ideal heater and cooler" with an infinite capacity to satisfy heating and cooling loads. This choice will help to keep the results independent from a specific mechanical system performance. The indoor comfort set point temperatures are 26 °C during summertime and 21 °C during wintertime.

Thermal comfort assessment

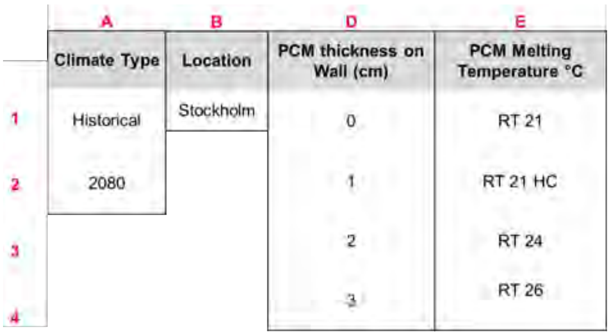
The ANSI/ASHRAE Standard 55-2013 defines the thermal comfort as a condition in which the human mind express satisfaction with the thermal environment. The latter is strongly dependent on indoor air temperature and to mean radiant temperature, which can be combined through the definition of the operative temperature (Eq.1).

$$t_0 = \frac{h_r t_{mr} + h_c t_a}{h_r + h_c} \tag{1}$$

Where h_r is the radiative heat transfer coefficient, h_c is the convective heat transfer coefficient, t_a is the air temperature and t_{mr} is the mean radiant temperature. Specifically, in cases where the air temperature and the mean radiant temperature are similar to each other and the air speed is less than 0.1 m/s the air temperature itself can be a reasonable indicator of thermal comfort. However, in cases in which the surfaces have a significant thermal mass due to e.g. PCM addition, it is strongly recommended to take into account the operative temperature in assessing thermal comfort. In fact, PCM thank to their capability of melting at a constant temperature range, can keep the surface temperatures more stable, and allow for better thermal comfort.

Analytical approach of the parametric study

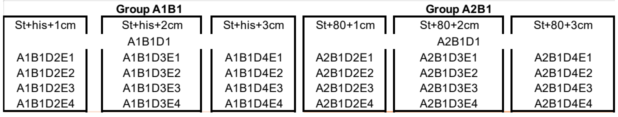
The total 26 simulated scenarios are categorized based on the climate typology (i.e. historical and future) and location (Stockholm). For each of them, a parametric analysis with different PCM melting temperature and thickness is performed. A summary of the analytical approach for the simulated scenarios is provided in Figure 2.



	A Climate Type	B Location	D PCM thickness on Wall (cm)	E PCM Melting Temperature °C
1	Historical	Stockholm	0	RT 21
2	2080		1	RT 21 HC
3			2	RT 24
4			3	RT 26

Figure 2: Analytical approach of simulated scenarios

For sake of simplicity, the simulations are classified and discussed in the Results and Discussion Section as reported in Figure 3.



Group A1B1			Group A2B1		
St+his+1cm	St+his+2cm	St+his+3cm	St+80+1cm	St+80+2cm	St+80+3cm
	A1B1D1			A2B1D1	
A1B1D2E1	A1B1D3E1	A1B1D4E1	A2B1D2E1	A2B1D3E1	A2B1D4E1
A1B1D2E2	A1B1D3E2	A1B1D4E2	A2B1D2E2	A2B1D3E2	A2B1D4E2
A1B1D2E3	A1B1D3E3	A1B1D4E3	A2B1D2E3	A2B1D3E3	A2B1D4E3
A1B1D2E4	A1B1D3E4	A1B1D4E4	A2B1D2E4	A2B1D3E4	A2B1D4E4

Figure 3: Parametric study analysis

Results and Discussion

Climate change impact on the reference single zone house without PCM

This section assesses the climate change impact on the indoor thermal comfort of the reference single zone house. Figure 4 shows the historical and future trends in a year, of the monthly average operative temperatures and operative temperatures in the reference single zone house (without PCM). Moreover, the monthly average outdoor temperature for the historical and future period is presented. As it can be observed the highest difference (between historical and future) can be found in the intermediate (spring and autumn) and summer seasons. Specifically, during winter months (January, February, November and December), there is an outdoor temperature increase between 2.7 °C and 4.6 °C, which becomes more significant during the summer months (June, July, August and September) with an increase until 5.7 °C in August. This outdoor temperature increase clearly affects the indoor operative temperatures. Specifically, the indoor operative temperature is showing a limited variation in winter, while the climate change influence is more visible in summer, determining an increase of 2-3 °C in the future climate. Accordingly with the Swedish Guidelines for the Specification of Indoor Climate Requirements released by SWEDVAC, the operative temperature target value of a residential building are equal to 20.0-24.0 ºC and 23.0-26.0 ºC during winter and summer season respectively. While in winter, the operative temperature values fall into the required target also in the future, in months like July and August it exceeds the maximum value, increasing thermal discomfort risks. The following section further evaluated the climate change impact on the heating and cooling demands of the reference single zone house. Table 7 shows a clear influence of climate change over the heating and cooling demand. Specifically, in 2080s it is expected a decrease of the heating demand by about -25 kWh/m^2, while the cooling one is likely to increase of +24.2 kWh/m^2. These results are in accordance with the main findings highlighted by the Authors (Shen et al. 2020). In fact, the 21st century climate trends will be characterized by a significant increase of winter-season temperature over the Scandinavian region, driven also by the positive feedback deriving from loss of snow-cover and related decrease of albedo. On the other hand, in summer season, higher environmental temperature and extreme events (like heat waves) are also expected in the next decade climate.

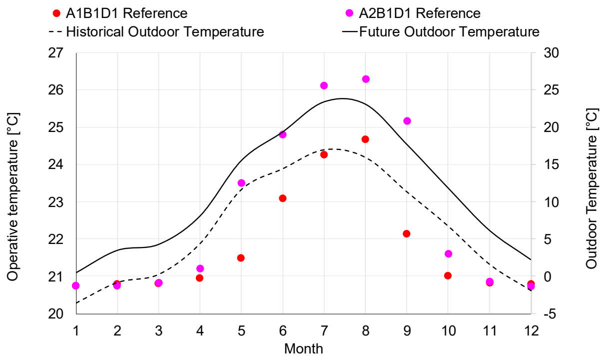


Figure 4: Monthly outdoor and resulted operative temperature variations under historical and future cases without PCM

Table 7: Annual heating and cooling demand for the historical and future climate cases without PCM

	A1B1D1 Reference (kWh/m^2)	A2B1D1 Reference (kWh/m^2)
Heating	105	80
Cooling	1.8	26

Figure 5 shows the total wall conduction heat transfer across the reference single zone house walls during heating, cooling and the rest of time. In IDA ICE, the average conduction heat transfer across the external walls results from the average of the inside face heat conduction and outside face heat conduction. Therefore, positive values indicate resultant heat flowing to the internal space, while the negative one defines the resultant heat released to the external environment. As it can be appreciated, in 2080s, due to the outdoor temperature increase during the winter season, less energy is released to external environment and then delivered to the space. During the summer season the relation is the reversed. In this case, the high thermal resistance value offered by the insulation layer coupled with higher future outdoor temperature presumably increased the indoor temperature, determining a slight increase of the heat flowing to the external environment.

Effect of PCM on the indoor environment for the historical period

The PCM influence on the indoor thermal environment of the single zone house is studied in the historical period. Figure 6 shows the comparison of the average operative temperature throughout the year in the A1B1 group. As it can be appreciated the highest variations between the A1B1D1 reference case and the PCM variants occur in summer (i.e. June, July and August) and middle season months (i.e. May and September). Overall, it can be stated that the building refurbishment with PCM application successfully yields a reduction in the average indoor operative temperature during the summer months, due to the latent heat storage of PCM.

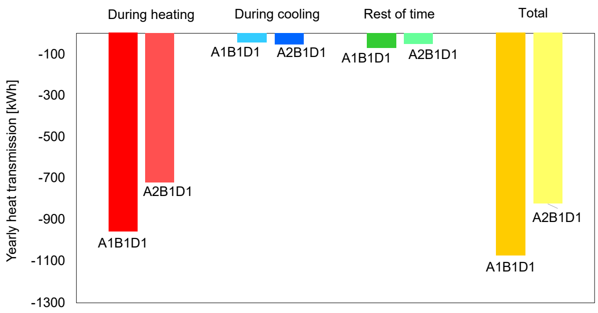


Figure 5: Annual wall conduction for the historical and future climate cases without PCM

Specifically, among all studied variants, the maximum mean operative temperature deviation (– 0.43 °C) from the A1B1D1 reference case has been found for A1B1D4 group which refers to the thickest PCM layer (PCM 3 cm). Then it follows A1B1D3 group (PCM 2 cm), with a maximum operative temperature deviation of – 0.26 °C from the A1B1D1 reference case. Finally, A1B1D2 group (PCM 1 cm) with a maximum operative temperature deviation of – 0.13 °C from the reference case. The reason can be related to the fact that a large amount of incoming heat can be stored in the PCM layer, keeping the indoor surface temperature lower for a longer period. However, during the August month, the walls with the highest PCM melting temperature (D4, 26 °C) showed a slight increase of the average operative temperature (+ 0.26 °C A1B1D2, + 0.37 °C A1B1D3, + 0.34 °C A1B1D4), compared with the reference case. The reason of this reduced PCM potential is owing to the reduced cool storage capacity of PCM during warm nights. In fact, high night temperature could cause the PCM surface to be around or beyond the solidification, remaining liquid during the night and just exploiting the sensible heat capacity the following day. High variations between the all studied variants and the A1B1D1 reference case can be found in September, where the PCM helped to maintain a higher operative temperature, providing a better thermal environment in a month characterized by low external temperature.

Table 8 is showing the annual number of hours with the operative temperature above 26 °C. Generally, the implementation of PCM demonstrated a successful reduction in overheating risks from 215 hours (A1B1D2 base case) to 31 hours (A1B1D3E4) in one year. More in detail, the number of hours when the operative temperature goes over 26 °C is lower when the thickest PCM layer is applied, whichever the phase transition temperature. For example, the number of hours with the operative temperature higher than 26 °C were reduced from 144 h to 79 h when the thickness of PCM increased from 1 cm to 3 cm for PCMs with a melting temperature of 21 °C and 24 °C. However, as the melting temperature increased to 26 °C, there is a significant reduction (31 h) of the number of hours with operative temperature higher than 26 °C. This result has been obtained for the PCM layer with 3 cm thickness.

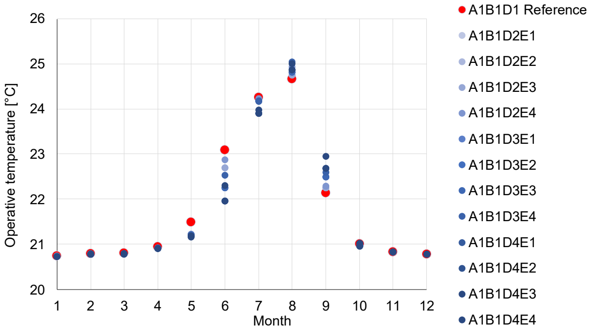


Figure 6: Annual average operative temperature comparison in A1B1 group.

Table 8: Annual number of hours with operative temperature above 26 °C

A1B1 group	Number of hour
A1B1D1 Reference	215
A1B1D2E1/2/3	≈144
A1B1D2E4	91
A1B1D3E1/2/3	≈96
A2B1D3E4	60
A1B1D4E1/2/3	≈79
A2B1D4E4	31

Effect of PCM on the heating and cooling demand for the historical period

In addition, the PCM influence on the heating and cooling demands of the single zone house is investigated in the historical period (Table 9). Overall, the heating demand resulted the predominant one and nearly no influences on all the PCM studied variants, with respect to the A1B1D1 reference case. The reasons for this reduced PCM potential can be related to the fact that an insufficient amount of solar heat gains passed through the limited window area or that a limited amount of sensible heat has been generated by internal load sources. In this regard, is assumed that during the wintertime the PCM could not undergo as many melting and solidification cycles as possible. By this way the PCM remained solid for most of the time, and so utilizing its sensible heat capacity. Conversely, a cooling demand reduction can be observed when PCM is applied. Specifically, the cooling demand is lower when the thickest PCM is applied, whichever the phase transition temperature. As an example, the cooling demand is reduced from -33% to -60% when the PCM thickness is increased from 1 cm to 3 cm for PCMs with a melting temperature of 21 °C and 24 °C. However, as RT26 (3 cm thick) is applied, a significant reduction of the cooling demand (i.e. -57% A1B1D2E4; -77%

A1B1D3E4 and -88% A1B1D4E4) has been obtained. Therefore, it can be stated that a PCM with a melting temperature of 26 °C and 3 cm thick is appropriate for reducing the cooling load and thus providing significant benefit in cooling season. Overall, the total energy demand savings varied from -1.5% to -2.4%, at the increase of PCM melting temperature and thickness, compared with the reference case.

Table 9: Annual heating and cooling demands comparison in A1B1 group (Unit: kWh/m^2)

	A1B1D1 Reference	**A1B1D2E1/2/3**	**A1B1D2E4**
Heating	105	104	104
Cooling	1.8	1.2	0.78
	A1B1D1 Reference	**A1B1D3E1/2/3**	**A1B1D3E4**
Heating	105	104	104
Cooling	1.8	0.83	0.42
	A1B1D1 Reference	**A1B1D4E1/2/3**	**A1B1D4E4**
Heating	105	103	104
Cooling	1.8	0.72	0.22

Table 10 shows the total wall conduction across the PCM added walls of single zone house during heating, cooling and the rest of time. As it can be appreciated during the heating season, the variants A1B1D4E1/2/3 had the best performance in retaining more useful heat gain inside. Firstly because the A1B1D4 variants belong to the largest PCM thickness in this study, which determines a highest thermal mass value. Secondly because E1, E2, E3 belong to the PCMs with melting temperature between 21 °C (E1 and E2) and 24 °C (E3), which determines a reduced temperature difference between the internal and external surfaces. In this regard, most of the heat which has been stored during the daytime is re-radiate back to the indoor environment throughout the night, reducing the heat transfer to the outside. Obviously, when the PCM RT 26 °C is applied, less useful heat gains can be retained. Anyway, the heat transmission value decreased at the increase of the PCM RT26 thickness, due to the increased wall´s thermal mass. During the cooling season, A1B1D3E4 and A1B1D4E4 helped in dissipating more undesirable heat gain outside, compared with the other PCM variants. This result is because of fact that during the summer a significant temperature variation between night-time and daytime can occur. In fact, during the daytime the PCM absorbs the heat at a constant temperature equal to 26 °C and re-radiate it at night due to the reduced outdoor temperature. Obviously, the higher is the indoor surface temperature, the higher is the heat dissipated through the wall.

Table 10: Annual heat transmission summary through external walls in A1B1 group (Unit: kWh)

	A1B1D1 Reference	**A1B1D2E1/2/3**	**A1B1D2E4**
Heating	-959.2	-938.6	-938.6
Cooling	-44	-35.6	-35.6
Rest of time	-71.4	-92.9	-92.9
Total	-1074.6	-1067.1	-1067.1
	A1B1D1 Reference	**A1B1D3E1/2/3**	**A1B1D3E4**
Heating	-959.2	-925.6	-935.8
Cooling	-44	-35	-50
Rest of time	-71.4	-102.3	-78.2
Total	-1074.6	-1062.9	-1064
	A1B1D1 Reference	**A1B1D4E1/2/3**	**A1B1D4E4**
Heating	-959.2	-913.1	-923.1
Cooling	-44	-36.2	-53.1
Rest of time	-71.4	-108.7	-83.9
Total	-1074.6	-1058	-1060.1

Effect of PCM on the indoor environment for the future period (2080s)

The PCM influence in the indoor thermal environment of the single zone house under is simulated under future climate conditions. Figure 7 shows the average operative temperature comparison in the A2B1 group. It is observed that the highest variation between A2B1 reference case and all the PCM variants occurs during middle season, while during summer season it is greatly reduced. Overall, the building refurbishment with PCM application perform worse under future climate, compared with the historical one. In fact, during the summer season is not possible to appreciate any considerable mean operative temperature reduction compared with the reference case. The maximum mean operative temperature deviation of –0.08 °C has been found for the A1B1D4 group which belong to the thickest PCM layer (3 cm). As for the historical period, this result is related to the fact that more heat can be stored in the PCM layer at constant temperature. Generally, the climate change negatively affected the PCM effectiveness of reducing the mean operative temperature during the summer period, increasing thermal discomfort risks. This result might be related to the fact that the increased environmental temperature, expected in 2080s, cannot match the different melting temperatures selected (21 °C, 24 °C and 26 °C) determining only a partial exploitation of the PCM latent heat storage capacity. In this regard when the transition temperature is lower than the expected operating temperature the PCM remains mainly in the liquid state, providing nearly no or reduced influence on the operative temperature reduction. The obtained results can be confirmed by the annual number of hours with indoor air temperature above 26 °C, which are shown in Table 11. In short, the number of hours with the operative air temperature above 26 °C is significantly increased compared with the historical period. PCM implementation showed a reduction of overheating risks from 1420 hours (A2B1D1 reference case) to a maximum of 1220 hours (A2B1D4E4) in one year.

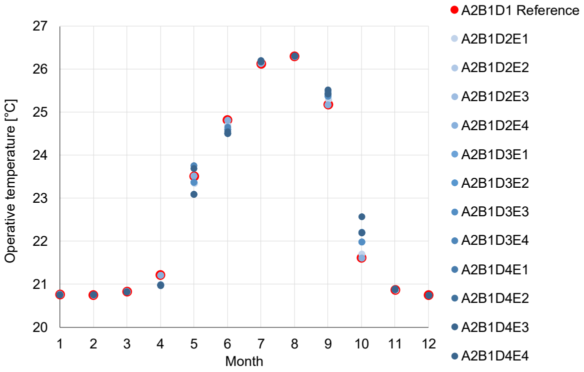


Figure 7: Annual average operative temperature comparison in A2B1 group.

The number of hours for the operative temperature over 26 °C is still lower when the thickest PCM layer is applied, whichever the phase transition temperature. For instance, the number of hours with indoor air temperature above 26 °C where reduced from 1370 h to 1298 h when the PCM thickness increased from 1 cm to 3 cm. This result is related to PCMs with a melting temperature of 21 °C and 24 °C. Specifically, the best performance has been shown by the A2B1D4 group which belongs to the thickest PCM with a successful reduction ratio between 8.6% and 14.1%. PCM RT 26 °C, resulting in the best performance also under future climate conditions.

Table 11: Annual number of hours with operative temperature above 26 °C.

A2B1D1 group	Number of hour
A2B1D1 Reference	1420
A2B1D2E1/2/3	≈1370
A2B1D2E4	1317
A2B1D3E1/2/3	≈1317
A2B1D3E4	1248
A2B1D4E1/2/3	≈1298
A2B1D4E4	1220

Effect of PCM on the heating and cooling demand for the future period (2080s)

Moreover, the PCM impact on the heating and cooling demands of the single zone house is depicted as following (Table 12). Both heating and cooling demand are varying slightly among the all PCM variants with respect to the reference case. As in the historical period, the heating demand is the most prominent and nearly constant for all the PCM studied variants, with respect to the A1B1D1 reference case. Conversely, a slight decrease in cooling demand can be observed when PCM RT26 is applied. Specifically, whichever the thickness, a cooling demand reduction of 15% is observed. The total heating and cooling demand savings varied between 1.9% and 5.7%, increasing along the PCM thickness and melting temperature. In this regard PCM RT26 is still able to reduce the cooling loads and thus providing significant benefits in cooling seasons also under future climate. As for the historical period, no significant variations in the heating demand have been found. The total energy demand savings vary from -1.9% to -5.7% with the increase of PCM melting temperature and thickness, compared with the reference case.

Table 12: Heating and cooling demands comparison in A2B1 group (Unit: kWh/m²)

	A2B1D1 Reference	**A2B1D2E1/2/3**	**A2B1D2E4**
Heating	80	79	78
Cooling	26	25	22
	A2B1D1 Reference	**A2B1D3E1/2/3**	**A2B1D3E4**
Heating	80	78	78
Cooling	26	24	22
	A2B1D1 Reference	**A2B1D4E1/2/3**	**A2B1D4E4**
Heating	80	78	78
Cooling	26	23	22

Table 13 illustrates the total wall conduction across the PCM added walls of single zone house walls during heating, cooling and the rest of time. During the heating season in the future, the variants A1B1D4E1/2/3 are still showing the best performance in retaining the highest useful gains inside. The main reason relies on the increased thermal mass value and to reduced temperature difference between internal and external surface, which can be achieved by using the thickest PCM layer with melting temperature ranging between 21°C and 24 °C. During the cooling season, all the PCM variants enhances the dissipating undesirable heat gain outside, if compared with the historical period. However, RT26 with 3 cm thickness, still showed the best performance.

Table 13: Heat transmission summary through external walls in A2B1 group (Unit: kWh)

	A2B1D1 Reference	**A2B1D2E1/2/3**	**A2B1D2E4**
Heating	-719.7	-691.4	-698.3
Cooling	-53.9	-57.2	-76.3
Rest of time	-50.2	-71.8	-47.5
Total	-823.8	-820.4	-822.1
	A2B1D1 Reference	**A2B1D3E1/2/3**	**A2B1D3E4**
Cooling	-53.9	-65.4	-87.4
Rest of time	-50.2	-83.2	-58
Total	-823.8	-820	-822.9
	A2B1D1 Reference	**A2B1D4E1/2/3**	**A2B1D4E4**
Heating	-719.7	-659.4	-669.4
Cooling	-53.9	-64.4	-91.6
Rest of time	-50.2	-94.6	-62
Total	-823.8	-818.4	-823

Study limitations

In the present study, the performance of a residential single zone house (in Stockholm city, Sweden) fully refurbished with PCM has been assessed by IDA-ICE modelling. However, it presents some study limitations which should be pointed out:

1) The numerical simulations are not taking into account the macroencapsulation of the PCM, which might be considered when coming to a real application for numerical model validation purposes. This can be done only by applying the PCM as separate component as sheet of macro-encapsulated PCM pouches that are generally installed in walls behind the gypsum boards (ENERG Blanket https://phasechange.com/)
2) More methodological advancement (such as optimization and advanced controls) in the study of PCM effects must be considered in future studies.

Conclusions

The results of this study indicated that the incorporation of a PCM layer in the building envelope, with a correctly selected melting temperature and thickness, could reduce heating and cooling demand, while still maintaining the indoor thermal comfort. Specifically, the PCM RT26 (3 cm thick, with a melting temperature of 26 °C) has the highest annual energy saving for historical (-2.4%) and future climate (-5.7%) conditions, when assuming an all-day around HVAC operation. Most of the energy saving derives from the cooling season (-88% for historical and -15% for future climate), as the RT26 melting temperature is equal to the cooling-set point. The limited energy saving in the heating season, for future and historical climate, could be attributable to the reduced amount of solar heat gains passed through the window. In this regard, it can be assumed that whichever the melting temperature, PCM failed in undergoing as many melting and solidification cycles as possible. This can be improved from either a large window to wall ratio or additional heat gains from internal loads. Finally, PCMs with the largest thickness (3 cm), whichever the melting temperature, has the highest reduction in terms of average operative temperature during summer months for historical (-0.43 °C) and future climate (-0.08 °C). This result is related to the fact that a large amount of heat can be stored in PCM layer, keeping the indoor surface temperature low for a longer period. Specifically, PCM RT26 (3 cm thick) has the best performance in terms of reduced number of hours with an operative temperature higher than 26 °C for both historical (-184h up to 215h of reference case) and future climate conditions (-200h up to 1420h of reference case). In general, the future climate negatively affected the PCM capability in reducing the mean operative temperature during the summer period.

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