Investigating the use of Phase Change Materials to Reduce Space Conditioning Loads in Cold Climates

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Abstract

Because buildings are responsible for nearly 40% of global energy consumption, it is critical that emissions-intensive conditioning loads be minimized to achieve global climate targets. One option to decrease conditioning loads is using phase change materials (PCMs) which can be integrated into buildings to store solar gains during peak periods to decrease space cooling loads, and during the heating season, the midday stored energy can be used to decrease overnight heating loads. Reductions in cold climate heating and cooling loads with PCMs has been limited both in research and in practice, despite that the heating loads account for two thirds of energy consumption in some locations. The objective of this modelling study was to assess the ability of PCMs in full building simulations with various properties to decrease heating and cooling loads in the capital cities within Canada and Germany. It was found that in Ottawa and Berlin, space heating loads could be reduced by 4.7% and 6.5%, respectively, and cooling loads by 60.1% and 54.1%, respectively. The underlying causes of this discrepancy between space heating and cooling reductions are described within the paper. In addition, integrating PCMs with two melting temperatures was found to have limited impact compared to a single PCM with a melting temperature of 23ºC, and the greatest reductions in heating load reductions were achieved with a two-story house.

Keywords: Phase change material, latent thermal storage, EnergyPlus, full building simulation, solar gains

1. Introduction

Buildings are responsible for a substantial portion of energy consumption worldwide, and in locations such as Canada, 64% of residential energy is used to meet space heating loads (NRCan, 2018). It is critical that strategies be developed, optimized, and implemented to decrease these numbers if national and international climate targets are to be met. As such, approaches to decrease conditioning loads such as more effective utilization of solar gains are necessary. Building integrated latent thermal storage with phase change materials (PCMs) relies on a solid-liquid phase change to store solar energy during peak periods to decrease the energy that directly enters the air in a space and thus simultaneously reduces peak room temperatures and energy required for cooling. Reducing the peak cooling energy has the added benefit of limiting the utilization of peak energy throughout the summer that are often met using natural gas, which can have a significant impact on emissions. In the heating season, the energy that is stored during peak solar periods helps reduce any midday overheating that may occur. The energy can then be released in the evening or overnight to maintain room temperatures throughout the day and decrease energy required for overnight heating.

It has been found in past studies that the melting temperature was outside of the room temperature range, minimal, if any, energy reductions have been shown which is the root of the cold climate challenges with PCM (Gassar and Yun, 2017). Furthermore, improper selection of PCM melting temperatures can lead to worse performance of a building (Kheradmand et al., 2016). As such, for PCMs to be most beneficial in the reduction of space conditioning loads, their melting temperature should be near that of the room temperature setpoint. However, in locations with two distinct conditioning seasons, room temperature setpoints often vary by several degrees throughout the year, which can limit the effectiveness of the PCM for either the heating or cooling loads, depending on the PCM melting temperature selection. As such, utilization of two PCMs – one that is better suited to each conditioning load – may be a viable solution to minimize space conditioning

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loads year-round.

The objective of this study was to evaluate the ability of PCMs to decrease heating and cooling loads in Ottawa, Canada and Berlin, Germany – locations with two distinct conditioning seasons, and the capital cities of both countries assessed. This expands on past research by delving further into the factors affecting PCM implementation, including utilization of two PCMs, PCM melting and solidifying temperatures, and house layout. Without full knowledge of how each of these factors impacts building energy consumption and temperatures, and how the performance of PCMs varies between geographic locations, PCM systems will not be able to be most effectively designed and implemented. This research increases the current knowledge on PCM integration and provides insight into factors that can lead to the greatest reduction in conditioning loads and therefore emissions in Canada and Germany. This paper includes a review of related literature, description of the simulation methodology used, and results that are described and discussed.

Although PCMs have been well demonstrated to decrease cooling loads, evaluation and successful utilization of them for heating is limited. Guarino et al (2017) found that despite a 47-75% decrease in space cooling, there was a negligible difference in heating with PCM gypsum with a phase change range of 18-24°C in a building in Canada. In contrast, however, an annual heating load reduction as high as 44% was found in a review by Al-Yasiri and Szabo (2021), while Heim and Clarke (2004) found a reduction in heating loads of up to 90% at times during the winter. Various studies have been done to increase the effectiveness of PCMs, and lower thicknesses of PCM with greater surface area, which would be the case with PCM-integrated drywall, have been shown to significantly reduce conditioning energy consumption (Alam et al., 2014). This is caused by the fact that the PCM response to thermal excitations and thus ability to quickly store and release energy is limited in thicker wall assemblies (Kosny et al., 2013) or with increased insulation (Entrop et al., 2011).

PCMs have been shown to be most effective when their melting temperature is within 2ºC of the indoor temperature setpoint (Kosny et al., 2013). However, in locations with two distinct space conditioning seasons, the room temperature setpoints often vary by several degrees throughout the year, which can render a single PCM ineffective a significant portion of the time. As such, a method that has been shown to increase the effectiveness of PCMs is the utilization of two PCMs – one tailored to each the heating and cooling seasons. Memarian et al. (2018) analyzed the effects of one PCM versus two PCMs in a warm climate and found that PCMs nearly doubled the energy reduction compared to a single PCM from 8% to 15% energy load reductions. In this study, 21ºC and 29ºC melting temperature PCMs were implemented on the interior of the wallboard within a space. Other studies have shown that two PCMs increase the time during which thermal energy is stored by 57% compared to a single PCM, leading to a decrease in the peak space temperature by 2ºC (Lakhdari et al., 2020).

In an attempt to optimize PCMs for a cold Canadian climate, Beradi and Soudian (2019) studied a system with two PCM melting points in July through October. The best performance was found to be during the later months because large diurnal temperature swings occurred during the change of season from summer to fall, promoting nighttime solidification and therefore greater utilization of the latent storage capacity of the PCM. A study by Mathis et al. (2018) in Quebec, Canada also agreed that the greatest energy savings could be realized in shoulder seasons, finding 8.7%, 9%, and 41% reductions in March, April, and May, respectively. Nikoofard et al (2015) studied a single PCM system in Canada in a techno-economic analysis and concluded that a PCM with a melting temperature of 23ºC was capable of decreasing the national energy and emissions by 2.5%.

Mohseni and Tang (2020) conducted a simulation using EnergyPlus and found that regardless of the PCM location within the wall, the heating and cooling energy consumption could be decreased with a PCM melting temperature of 21ºC. Furthermore, it was concluded that the best melting temperature for cooling reductions in the summer were 25ºC and the best for heating reductions was 21ºC.

The limitations within the literature include that many studies have not been conducted on full houses – the experimental studies are limited to small test chambers and limited simulation-based research exists on full house models with two PCMs. Little to no research has been conducted on the variability of PCM performance between various housing archetypes or comparisons of PCMs in various geographic locations. In addition, limited optimization has been conducted for heating loads, and research is even more limited on increasing the effectiveness of PCMs for both conditioning seasons.

With proper design of PCMs and thorough understanding of their performance, PCM systems can be better equipped to significantly reduce both conditioning loads. However, due to the limited research in this area and mix of results on PCM effectiveness, additional evaluation of PCM properties and integration scenarios is critical to fully understand the scenarios in which PCMs are most suitable for integration into cold climate houses. In addition, it is necessary to understand which PCM properties and house layouts within the existing building stock may contribute to differing energy savings with PCMs.

2. Methodology

Three full house models with different common layouts were developed for this analysis using EnergyPlus – an open-source building simulation tool that provides detailed predictions of building physics elements such as infiltration, heat transfer, and solar gains (US Department of Energy, 2021). The three house layouts that were considered are open concept bungalow, partitioned bungalow, and two-story. All of these were assumed to have four occupants during weekday evenings and weekends and no occupancy during the day on weekdays. The bungalows had a 164 m^2 floor area (excluding the basement) and a 30% window to wall ratio on the south façade, and the same total window area was maintained for the two-story house case. The solar heat gain coefficient (SHGC) and U-factor of the windows were 1.4 and 0.4 $W/m^2{\cdot}K$, respectively. The air infiltration for the house was 2.5 ach (Placido and Pressnail, 2014), and there was a constant 600 W of electrical gains to represent lights and auxiliary electrical systems in total to the main floor and basement zones. The heating and cooling setpoints were 19ºC and 25ºC with setbacks to 16ºC overnight and during unoccupied weekdays in the winter, and 30ºC during unoccupied weekdays in the summer. The walls, floors, and roof were composed of typical residential construction components, as shown in Tab. 1, with the corresponding properties shown in Tab. 2.

Tab. 1: Building envelope construction

Exterior Wall	Interior Floor	Exterior Roof	Foundation Wall
Siding	OSB	Shingles	Concrete
Air gap	Air gap	Air gap	Insulation
OSB	OSB	OSB	Gypsum
Insulation	-	-	-
XPS	-	-	-
Gypsum	-	-	-

Tab. 2: Building material properties

	Siding	OSB	Insulation	XPS	Gypsum	Shingles	Concrete
Thickness (mm)	12.7	12.7	150	25.4	12.7	5.0	2.032
Density (kg/m^3)	2240	1000	28	55	800	800	2240
Conductivity (W/m·K)	0.094	0.17	0.038	0.027	0.17	0.1	1.95
Specific Heat (J/kg·K)	1170	1300	750	1210	1090	1200	900

Each house layout was simulated in Ottawa, Canada and Belin, Germany with and without PCM. The simulations were conducted using Canadian Weather for Energy Calculations (CWEC) data for Ottawa, Canada and Typical Meteorological Year (TMY) data for Berlin, Germany. PCM was implemented on the inside surface of the gypsum on all walls on the main floor, to represent PCM-integrated drywall or a simple PCM retrofit. In the case of the partitioned bungalow, the east and west walls and the partition wall in the south zone had PCM, and for the two-story case, the east and west walls of both the main and second floors had PCM in addition to the north wall of the main floor. These PCM locations were chosen to maintain the quantity of PCM between all layouts. The PCM properties are shown in Tab. 3, which were obtained using differential scanning calorimetry (DSC) and guarded hot plate (GHP) experiments.

Tab. 3: PCM properties simulated

Property	Value
Latent Heat (kJ/kg)	160.0
Thermal Conductivity (W/m·K)	0.22
Density (kg/m^3)	900
Subcooling (ºC)	6.0
Liquid Specific Heat (kJ/kg·K)	0.98
Solid Specific Heat (kJ/kg·K)	3.96

Annual simulations were conducted while varying PCM properties such as the degree of subcooling (the temperature difference between the melting and solidifying temperatures) and PCM melting temperatures, to indicate trends and desirable properties to seek during PCM sourcing. In addition, building parameters such as layout and window locations were varied, and simulations were conducted to determine the impact of including two PCMs of different melting temperatures compared to a single PCM scenario. In terms of the PCM properties, three different degrees of subcooling were assessed: 1ºC, 3ºC, and 6ºC, which indicates the temperature difference between the melting and solidifying temperatures. For these cases, the melting temperature was held constant, and the solidifying temperature was adjusted to be the corresponding temperature below the melting temperature. Three melting temperatures were also assessed: 21ºC, 23ºC, 25ºC, which were selected to be between the heating and cooling setpoints.

In the base open concept house, three thermal zones were used – one for each the attic, main floor, and basement. The partition wall layout included four thermal zones because the main floor was split into a front and back zone, and the two-story layout included four thermal zones which included a thermal zone for the second floor. The front and back thermal zones and the second-floor zone operated identically to the single main floor zone in terms of heating and cooling setpoints and infiltration, while electrical loads and occupancy were split between the main and additional zone. The open concept house had PCM integrated into all walls on the main floor, and to maintain the same quantity of PCM, the partition wall layout did not contain PCM in the back wall. In situations where only one melting temperature PCM was used, the same total mass of PCM was used as cases with two different PCMs to further maintain similarity between the cases studied.

The limitations of the model used include utilization of the ideal heating and cooling objects for space conditioning loads. These objects do not model a central conditioning unit, but rather an independent variable air flow unit for each thermal zone that modulates the air flow rate and temperature to meet the conditioning loads. As such, there is no thermal lag that would occur with a radiant heating system, and the spaces are treated as though they have their own conditioning units. This is a limitation of the models because in a typical house, the setpoints for each space would be met using one conditioning unit that was modulated by the main zone air conditions. Independent control was chosen in this study in an attempt to maximize the usefulness of the PCM within each zone.

3. Results and Discussion

The results of the simulations conducted within this study predict the cases of PCM properties, integration methods, and house layouts that lead to reduced space conditioning loads in Ottawa, Canada and Berlin, Germany. Within a base case open concept house with no PCM, the heating and cooling loads were found to be 527.96 MJ/m^2 and 14.50 MJ/m^2, respectively in Ottawa, Canada and 329.66 MJ/m^2 and 10.23 MJ/m^2 in

Berlin, Germany. These values were compared to houses with PCM throughout the study. Tab. 4 illustrates the base conditioning loads without PCM for the three house layouts in both cities. For the partitioned wall layout, the main floor zone that was 12 m in depth in the open concept case was split into two 6 m deep zones.

Tab. 4: Base case conditioning loads without PCM

		Heating (MJ/m^2)	**Cooling (MJ/m^2)**
Ottawa	**Open Concept**	527.96	14.50
	Partitioned	528.18	14.47
	Two Story	533.22	30.9
Berlin	**Open Concept**	329.66	10.23
	Partitioned	328.58	10.19
	Two Story	329.01	23.58

The two-story cases had greater cooling loads due to the additional perimeter area which increased heat transfer between the outdoors and the conditioned space, as compared to the bungalow cases. Within this study, PCM properties including the difference between melting and solidifying temperatures were assessed with a single-PCM open concept house, followed by different combinations of PCM melting temperatures and different housing layouts in both cities considered.

3.1. Single PCM Open Concept House

Fig. 1 illustrates the variations that occur in annual heating and cooling loads due to single PCMs with different melting temperatures and degrees of subcooling. In these simulations, one PCM was implemented into an open concept house within Ottawa. The melting temperatures selected were 21ºC, 23ºC, and 25ºC, such that they were all within the range of space conditioning setpoints throughout the year.

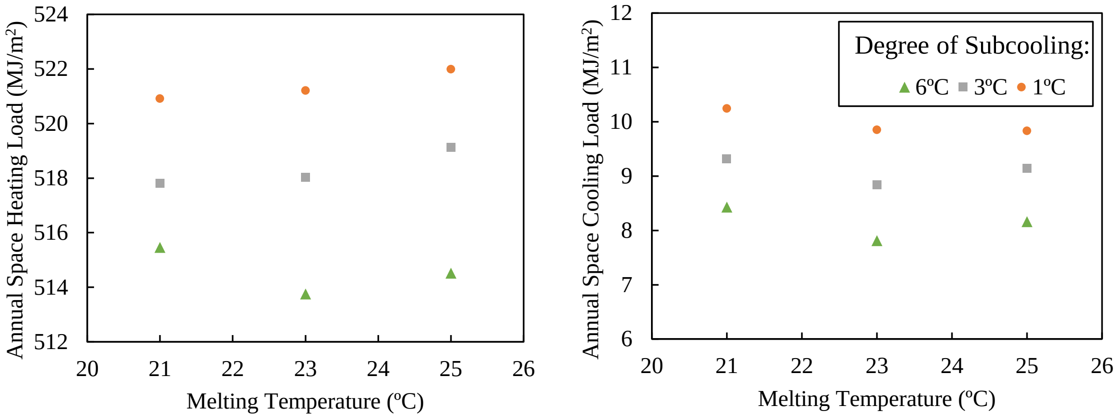

Fig. 1: Heating (left) and cooling (right) loads with a single PCM in Ottawa

It can be seen that a single PCM with a 6ºC lower solidifying temperature than the melting temperature caused the lowest annual heating and cooling loads, regardless of the melting temperatures examined. This analysis was limited to melting temperatures within the 21-25ºC range to be between the heating and cooling setpoints and thus be as effective as possible for both throughout the year. With lower subcooling, PCM melting temperatures that were closer to the space conditioning setpoint were found to minimize conditioning loads, as predicted based on past research. However, as the degree of subcooling increased to 6ºC, both the heating and cooling loads were found to be minimized with melting temperatures of 23ºC. This is caused by the PCM with this melting temperature more readily solidifying to better use the latent storage capacity, whereas with the 21ºC PCM, it would have to cool to 15ºC to fully solidify when there is a large degree of subcooling.

Based on these results, it could be recommended that PCMs be selected to have melting temperatures closer to that of the cooling setpoint with greater subcooling, particularly if the exact heating and cooling setpoints are unknown. Greater subcooling allows a PCM to be more effective over a wider range of room temperature setpoints and thus mitigates concerns of limited PCM effectiveness that have been indicated in past studies. Overall, however, the relative difference between any of the studied options is relatively low, with heating and cooling reductions from the base house without PCM varying between 1.1-2.7% and 27.5-47.7%, respectively.

3.2. Two PCM Open Concept House

Based on the results for PCM melting temperatures, the main cases studied were a single PCM with melting temperature of either 21ºC or 23ºC, two PCMs with melting temperatures of 21ºC and 23ºC, and a base case without PCMs. The space air temperature, north wall temperature, and solar gains transmitted through the window for a summer (July 2) and winter (January 24) day are shown in Fig. 2 with 21ºC and 23ºC PCM in the main zone walls of the open concept house in Ottawa.

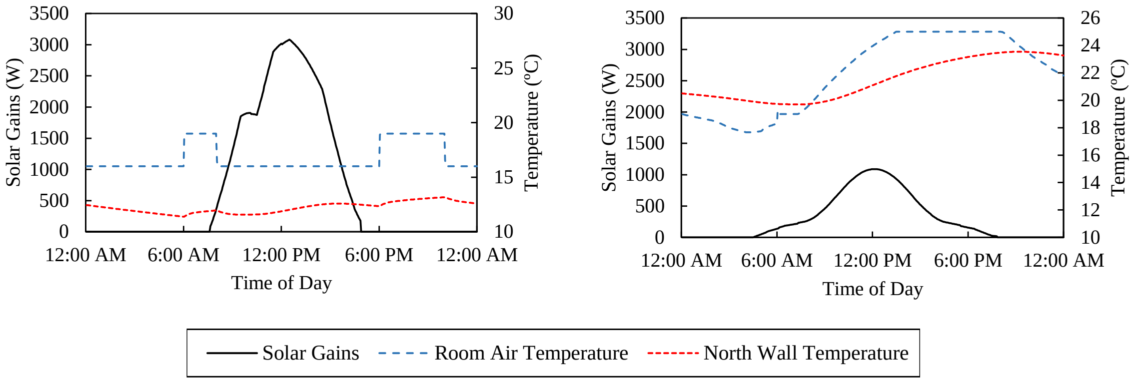

Fig. 2: Solar gains and main floor temperatures on January 24 (left) and July 2 (right)

Fig. 2 illustrates the cause for limited PCM effectiveness in winter and the ease of achieving benefits with PCMs in summer. Throughout the summer, PCM within the walls is used to store peak solar energy entering the space as the room temperature heats up. This effectively delays and reduces the operation of space cooling systems. However, in winter, the room air temperature setpoints and therefore space heating loads are greatest in the morning and evening during the occupancy hours. As such, the midday solar gains stored within the PCM can aid with the space heating energy required for the evening conditioning but have negligible effectiveness during morning heating. It is this discrepancy for heating and agreement for cooling seasons between the time conditioning systems are typically operational and the time of peak solar gains that leads to the overall effects on annual conditioning loads.

Fig. 3 shows a comparison of room air temperatures with and without 21ºC and 23ºC PCM in July in Ottawa, Canada, which further illustrates the benefits of PCM in decreasing the time during which the space cooling system operates. Fig. 3 illustrates the impact of PCM on a summer day compared to a house without PCM. The room air temperatures are more uniform with PCM included and due to the storage capacity of the PCMs, it took longer for the house with PCMs to reach the cooling setpoint temperature of 25ºC, thus leading the cooling equipment to operate for a shorter duration with PCM. The room air temperatures are not shown for a winter date such as January 24th, because there was insufficient solar energy added to the air to lead to a peak temperature above the setpoint of 16ºC or 19ºC. The constant room temperature regardless of PCM integration is an additional factor in leading the space heating loads to be less affected by PCM than space cooling loads.

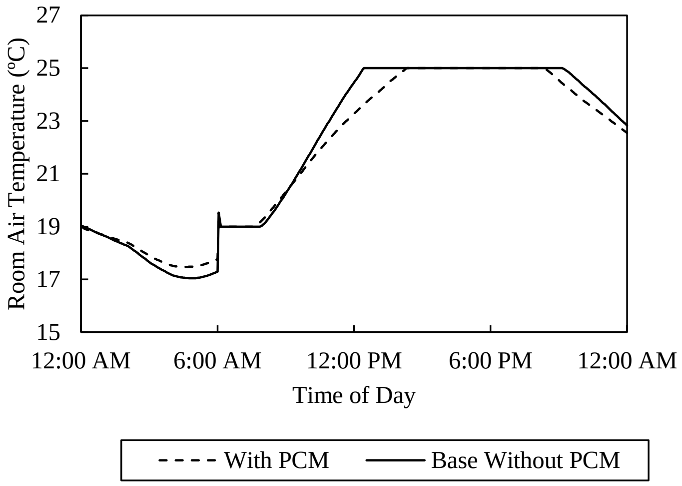

Fig. 3: Comparison of room air temperatures on July 2 in Ottawa with and without PCM

3.3. Partitioned House in Ottawa

The results shown in Fig. 1 through Fig. 3 are for an open concept house in Ottawa, Canada, while Fig. 4 illustrates the effects on annual conditioning loads of an east-west partition wall through the main floor, at various distances from the south wall. The base conditioning loads refer to those without PCM, while the 21ºC and 23ºC conditioning loads have both PCMs within the walls.

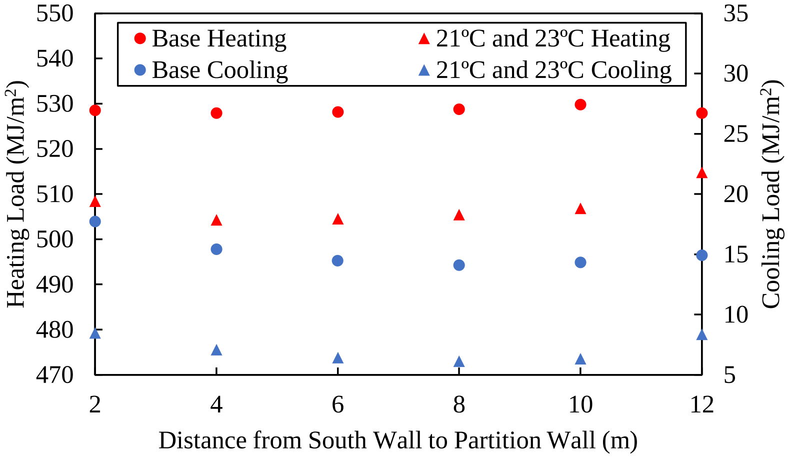

Fig. 4: Impact of dividing wall on annual conditioning loads in Ottawa

The house layout was found to have a small effect on the annual PCM performance, as shown in Fig. 4. When considering the energy savings between the base and PCM scenarios, it was found that implementing 21ºC and 23ºC PCM into all walls caused up to a 4.5% decrease in heating loads and a 56.5% decrease in cooling loads. Proportionally greater reductions were observed in cooling loads due to the relatively small base cooling values and due to the better alignment between solar gain storage and release for peak cooling than for times requiring heating.

It was found that partition wall layouts that split the main floor into areas that were close to equal in floor area (such as the 6 m partition distance) had slightly lower conditioning loads, particularly for cooling, in the base and PCM cases. This is caused because with a smaller front room (2 m), the front room is heated up and exposed to significantly more solar gains than the back room, so the PCM along the back walls is underutilized. In contrast, with larger front rooms (10 m), it takes a greater period of time to heat up the surfaces which reduces the time during which the PCM is within the temperature range for thermal storage. As such, the 6 m partition distance was found to balance the solar gains within the front room such that there was a sufficient portion of PCM available and able to reach temperatures that facilitated thermal storage of the PCMs throughout the greatest portion of the year. Due to this trend, a 6 m partition wall distance was selected for the comparisons between Ottawa and Berlin.

3.4. Two Story House in Ottawa

A two-story house in Ottawa with the same floor area as the open concept and partitioned layouts was found to have a similar trend to that of the single-story options. The room air temperature for the main and second floors of a two-story house with and without PCM are shown in Fig. 5 for July 2.

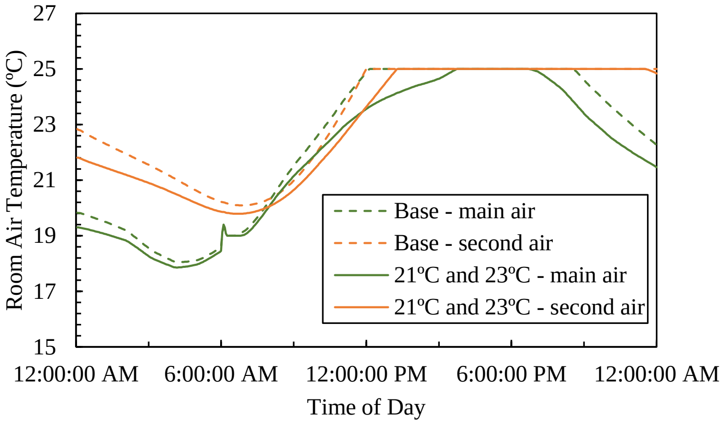

Fig. 5: Temperature profile of air with and without PCM in a two-story house

It can be seen from Fig. 5 that the PCM cases for both floors caused a more uniform temperature distribution throughout the space. The second-floor zone had less of an impact due to PCM than the first-floor zone due to there being no solar gains and less PCM into the second story. In the base cases without PCM, the living spaces were at the maximum temperature of 25ºC for up to 12 hours of the day on a hot summer day, while with PCM, the thermal storage capabilities prevented the air conditioning system from operating for as long of a duration. On a hot, sunny day in Ottawa like July 2, the thermal load within the air without PCM was so great that it led to the base case having higher temperatures than the PCM case even overnight while the PCM was slowly releasing the thermal load. This was an unusual instance, as PCM often causes greater overnight temperatures than cases without PCM due to this thermal load release.

In the two-story house of the same floor area, the heating and cooling loads were found to follow the same trends as the single-story alternatives, but with greater reductions of up to 4.7% and 48.6%, respectively. It was found that the 23ºC PCM minimized the space heating loads for the two-story case, due to the greater temperatures of the second story, compared to the bungalow layouts, which led to the 23ºC PCM storing more thermal energy than the other PCM cases.

3.5. Ottawa and Berlin Comparison

Fig. 6 and Fig. 7 show the heating and cooling load reductions, respectively, with one or two PCMs, in both Ottawa and Berlin. It can be seen that when a second PCM was added, there was a more significant benefit to space cooling than heating. This stems from the factors described from Fig. 2 and Fig. 3 in regards to the larger base cooling loads that lead to a proportionally greater offset and due to the ability of PCMs to reduce the duration of time the space is at peak cooling temperatures and limited ability of the PCMs to alter the space temperature during the heating season.

It was found that Berlin experienced reductions in heating loads of up to 6.5%, while Ottawa was limited to 4.7%; this is caused by the more northern latitude of Berlin, which has solar gains that are more directed towards the walls in the heating season to better facilitate thermal storage. In addition, the results illustrate that there are additional benefits of the PCM when there is a partition wall within the space, as opposed to an open concept layout, particularly in Ottawa. This is caused by the solar gains being more concentrated within the zone with a partition wall, thus leading to higher surface temperatures and increased latent thermal storage within the front zone of the main floor for any PCM melting temperature combination.

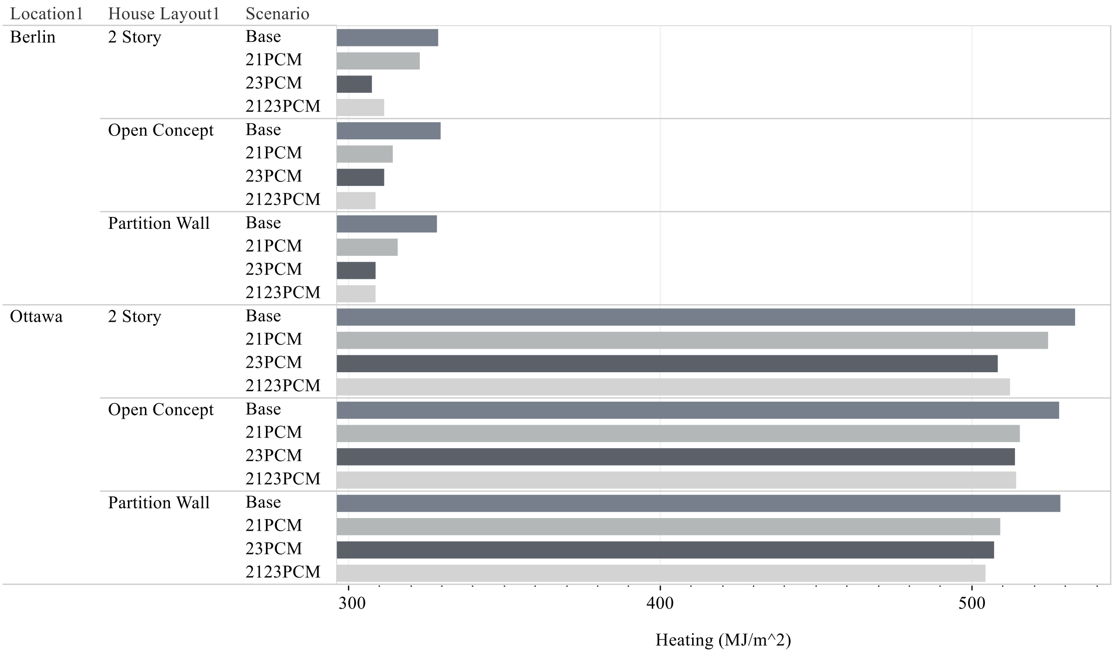

Fig. 6: Heating reductions with one or two PCMs

For both Berlin and Ottawa, the space heating load in the bungalow layouts was reduced most with two PCMs, while in the two-story layout the space heating load was reduced most with the 23ºC PCM. In addition, in all cases the 21ºC PCM alone was found to lead to the greatest heating loads because it requires cooling to 15ºC to fully solidify and utilize its full latent capacity, which does not occur frequently throughout the year. The results for cooling loads are shown in Fig. 7.

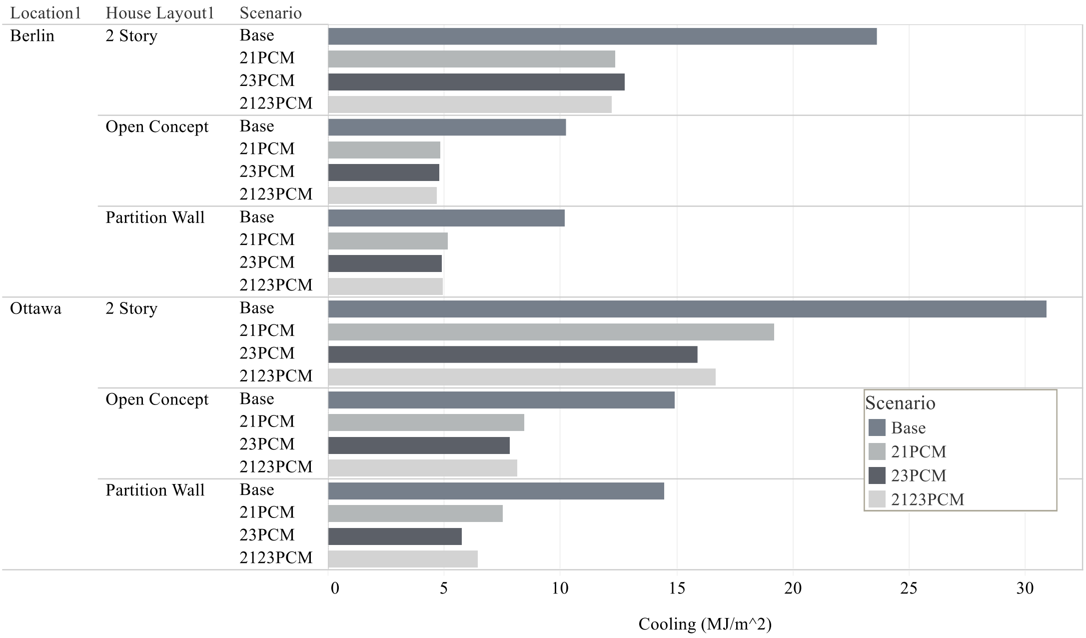

Fig. 7: Cooling reductions with one or two PCMs

Fig. 6 and Fig. 7 show that although there was found to be little difference between integrating one PCM or two for heating, the cooling load benefitted more significantly when only the PCM with melting temperature of 23ºC was included, particularly in Ottawa. However, in all cases, the cooling load was found to have little difference between the 23ºC melting temperature PCM and the use of two PCMs. It was found that although heating loads could be reduced most drastically with the two-story house layout, cooling loads were often reduced most significantly with the partitioned bungalow layout due to the additional heat transfer area of the two-story house which resulted in greater space cooling loads that can be attributed to the second-floor zone.

4. Conclusions

In this study, three layouts of house were assessed in two locations (Canada and Germany) with PCM to determine the impacts of various assumptions associated with PCM system design. The objective of this was to determine the factors that lead to PCMs most reducing heating and cooling loads in locations with two distinct conditioning seasons. It was found that regardless of location, house layout, or PCM properties, the cooling loads could be reduced by over 60% in some cases, whereas the heating load could only be reduced by about 5%. Furthermore, utilizing two PCMs at melting temperatures of 21ºC and 23ºC was found to lead to comparable conditioning loads than the 23ºC melting temperature PCM alone, due to the large thermal storage temperature range of 17-23ºC that was utilized throughout both conditioning seasons with the 23ºC PCM. Heating loads were found to be reduced more substantially in Berlin than Ottawa due to its more northern location and thus more horizontal solar profile within the winter months that lead to increased thermal storage by the PCM. In terms of house layout, it was found that a two-story layout could decrease heating loads most significantly – up to 6.5% in Berlin and 4.7% in Ottawa, while the partitioned wall layout decreased cooling loads by 60.1% in Ottawa and 52.0% in Berlin.

4.1. Future Work

The future work of this study should include additional simulations to predict the performance of one or two PCMs in a wider range of climates to assess whether any locations would benefit more significantly from two PCMs compared to one. In addition, these future simulations can provide trends regarding the impacts of climate zones in general on PCM performance and implementation. A complete analysis of the emissions and embodied carbon, as well as the economic impacts of PCMs in various locations should be conducted to provide stakeholders with full knowledge of PCM effects prior to their widespread integration.

5. Acknowledgements

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