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Impact of Positioning Phase Change Materials on Thermal Performance of Buildings in Cold Climates

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Abstract. The building envelope, an essential component of any building, plays a critical role in meeting energy efficiency and thermal comfort requirements. Incorporating phase change materials (PCM) into the building envelope can offer an opportunity to minimize energy usage and enhance thermal comfort by offsetting daily temperature fluctuations. However, the optimal performance of PCM is contingent on the material's placement and thickness within the building envelope. Therefore, this study investigated the effects of positioning and thickness of PCM on thermal comfort and heating loads in a lightweight timber building in Trondheim, Norway. Four scenarios were considered based on the positioning of the PCM layer in the exterior wall and roof. Using IDA ICE, parametric simulations were conducted for various PCM wallboard positions and thicknesses in the exterior wall and roof. In Nordic climates, adding PCM reduces the risk of annual overheating. The findings of this study showed that installing 75mm of PCM wallboard in the exterior wall's inner layer reduced the annual heating load by 2.3%. Compared to the base case scenario, increasing PCM thickness reduced zonal maximum indoor air temperatures by up to 6.2°C. This study underscored the importance of carefully considering the placement and thickness of PCM in building envelopes for optimal performance.

1. Introduction

Climate change and energy availability are threatened by rising energy consumption. Population growth and the demand for indoor thermal comfort drive buildings to consume more than one-third of global energy [1]. Thus, materials and technologies that maintain comfortable indoor temperatures are crucial. Overheating in buildings has been a significant issue in recent decades. Several studies have demonstrated that overheating is a concern not only in warm climates but also in cold climates countries such as Finland [2], Norway [3], and Netherlands [4,5] particularly in well-insulated structures. With the present rate of climate change, the situation is anticipated to deteriorate. This highlights the importance of considering climate conditions and building design when designing and retrofitting buildings to reduce the risk of overheating. In Europe, heating contributes to the most significant part of final energy consumption in the residential sector, with over 62,8% [6,7]. Several new technologies are developing to contribute to the achievement of the objective of decreasing energy use in buildings [8–10]. The potential technology of phase change materials (PCM), which has attracted much attention over the last decade, is also part of the thermal building envelope.

PCM can be passively or actively incorporated into structures [11]. The passive approach involves integrating PCM into building materials such as plasterboard, gypsum, or concrete without the use of any extra equipment. A passive thermal storage system is commonly used to integrate PCM into building fabrics such as walls, floors, and roofs. Preventing daytime overheating and minimizing the need for heating at night are the goals of adopting PCM as a passive building system [12]. Installing PCM-enhanced wallboards on building envelopes is the most popular method of incorporating PCMs into buildings. PCMs may significantly boost the thermal storage capacity of lightweight constructions with low thermal inertia. Wallboards can collect and release heat throughout the room for significant portions of the day when facing the interior rooms of a building or when they are utilized in partition walls.

However, PCM has the ability to save energy, it is also crucial to note that PCM could improve interior thermal comfort. When PCM was added to the exterior wall, the impact of overheating was mitigated, air temperature variations were reduced, and it was shown that the PCM wall released energy when temperatures dropped. Kuznik and Virgone [13] conducted experimental research for a typical winter, summer, and mid-season day in a full-scale test room with PCM-augmented wallboards. It has been demonstrated that the PCMs decrease the impacts of overheating, lower the surface temperatures of the walls, and improve the air's natural convection mixing.

The phase transition temperature, amount of PCM, and layer position all affected whether PCMs completed a daily phase transition cycle. Jin et al. [14] recommend installing PCM layers adjacent to the inner face of the wallboard in the most interior location. In northeast Kansas, Lee et al. [15] examined how PCM layers affected heat flow reductions and maximum heat flux time delay. The PCM layer 2.54 cm from the south-facing wallboard and 1.27 cm from the west-facing wallboard was recommended to reduce peak heat flux. Han and Taylor [16] found that PCM layers adjacent to internal wallboards increased thermal storage capacity and energy savings in Washington, D.C. buildings. Sun et al. [17] found that PCM needed close to the innermost layer of exterior walls in south-central China to undergo a complete phase shift. In Changsha, China, the PCM layer in the middle of a 12 cm wall saved the most energy.

This study aims to improve the thermal performance of Nordic climate residential buildings by implementing PCM. This research compares scenarios with implementing the PCM layers into the building envelope for overheating assessment of nearly zero energy timber construction in Trondheim, Norway. The impact of PCM layers on occupants' thermal comfort and building energy performance was studied, and different thicknesses of PCM layers were implemented in the case study building. The findings can benefit the EU in evaluating and reducing the risk of overheating in highly insulated residential buildings. This paper offers a crucial base for building thermal comfort and resilience to climate change employing PCM. This research could benefit PCM materials manufacturers, building owners, researchers, architects, and engineers seeking PCM.

2. Methodology

The simulation was carried out for a selected residential building. The Living Lab at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, has been considered for this study. Figure 1 shows the methodology's three primary stages. Each stage consists of a number of steps. The following list summarizes those steps:

Stage One: Model setup: This phase only identifies the project's boundary conditions. This study established a base case building, and several PCM placement scenarios in the outside walls and design parameters were put up for investigation.

Stage Two: Parametric simulations: The parametric analysis took place in this stage, during which several design factors were examined simultaneously. PCM has been assigned to the building roof and external walls with different thicknesses and placements (inner, middle, outer).

Stage Three: In this stage, decisions are made on the best locations and thicknesses of PCM to achieve higher thermal comfort. Finally, Python and MATLAB were complementary tools for storing and post-processing results.

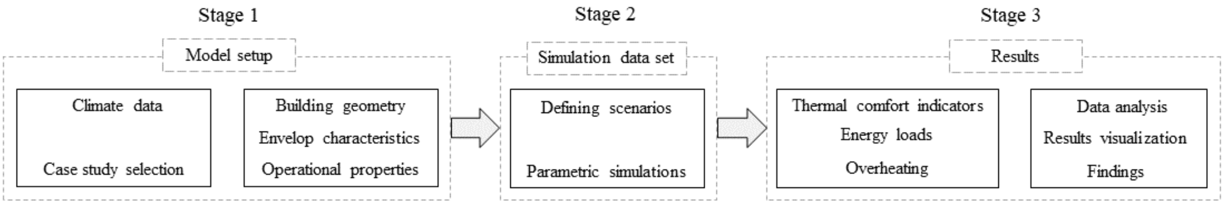

Figure 1. Methodology framework

2.1. *Case study building*

The Living Lab incorporates cutting-edge technology for energy efficiency and solar energy exploitation while representing the Norwegian residential building stock in terms of typology (detached, single-family dwelling) and surface. The Living Lab is a single-family house with a heated surface (floor area) of around 100 m^2 and a gross volume of about 500 m^3. The building's gross floor area is 132 m^{2,} with a net floor area of 97 m^2. Modern energy conservation measurements and renewable energy source exploitation technologies are used to realize it. The flexibility of the layout was focused on the potential for assigning various programs (young couples, elderly couples, or even student housing) inside the building surface. Figure 2 illustrates the case study building's perspective view and floor plan.

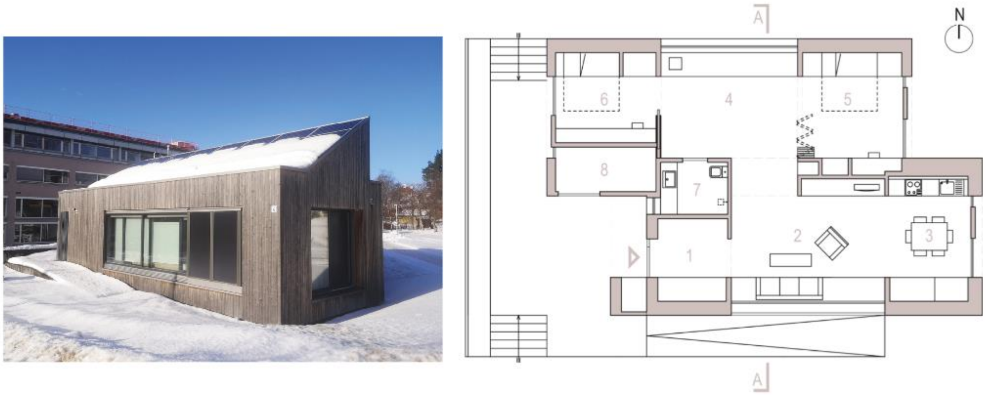

Figure 2. Case study building; left) View of Living Lab; right) Floor Plan [18]

2.2. *Simulation data set*

Building geometry and parametric variations have been modeled by IDA Indoor Climate and Energy (ICE) [19], which architects and building engineers widely use. A dynamic whole-building performance simulation program called IDA ICE was created at the Department of Building Sciences in Stockholm. Because it uses symbolic equations rather than variable assignments, adding new modeling features is very simple. The IDA ICE tool was validated for the simulation with the PCM in other studies [20,21]. It is worth mentioning that the survey by Mazzeo et al. [22], concluded that the IDA ICE led to the highest overall accuracy index when the test box with PCM was simulated. Therefore, IDA ICE was chosen to conduct the case study building simulation procedure. Figure 3 shows the multizone model of Living Lab, including the heating spaces and perspective of the building geometry.

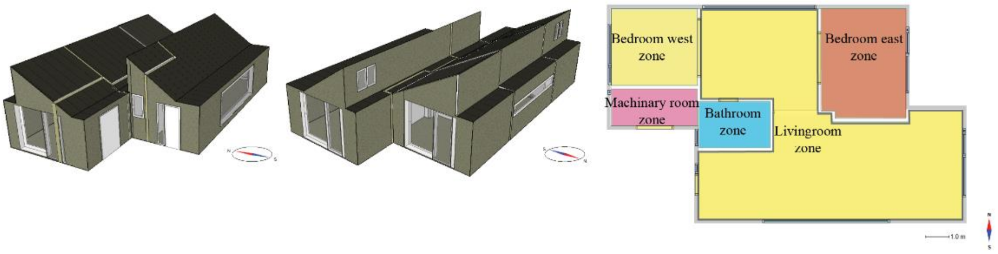

Figure 3. Building energy model in IDA ICE

For this study, four different scenarios have been considered. Scenarios are assigned based on the PCM layer's location in the external wall and roof. Each scenario has three different PCM layer thicknesses. As shown in Figure 4, the scenario definitions are as follows:

SC1 (Scenario 1): When the PCM layer was added to the inner part of the external wall;
SC2: When the PCM layer was added to between insulation layers of the external wall;
SC3: When the PCM layer was added to the outer part of the external wall;
SC4: When the PCM layer was added to the inner part of the roof;

Each scenario consisted of three thicknesses, 25 mm, 50mm, and 75 mm of the PCM layers. This determines whether it is more effective to install the PCM in the building's roof or walls.

It is worth mentioning that besides these scenarios, the base case scenario was considered as the actual condition of the external wall in the case study building without the PCM layer.

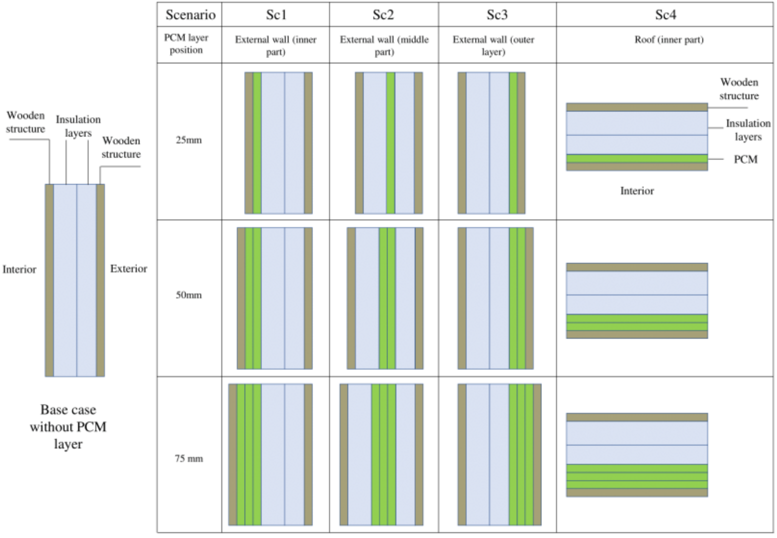

Figure 4. Details of considered scenarios with different positions and thicknesses of PCM

The building is a timber-framed structure with a raised timber floor construction. Table 1 summarizes the features of the building envelope. The exterior walls comprise lightweight timber frames with 0.479 m and a U-value of 0.11 W/m^2.K. The exterior walls are composed of 0.35 m of Rockwool insulation. Table 2 provides information on the exterior wall thickness of each material.

Table 1. a) Building envelope's characteristics of the Living Lab; b) External walls construction details

a)

Building Physics	U-Value (W/m^2.K)	Thickness (m)
Wall	0.11	0.479
Roof	0.10	0.569
Floor	0.10	0.469
Window (U_w) (south façade)	0.65	0.054
Window (U_w) (north façade)	0.97	0.054
Window (U_w) (east/west façade)	0.80	0.054

b)

Material	Thickness (m)
Cladding	0.022
Airgap	0.044
UV proof barrier	-
Rockwool	0.2
Vapour barrier	-
Rockwool	0.15
Vapour barrier airguard	-
Airgap	0.048
Plywood panels	0.048

The roof section also consists of thin timer frames but is insulated with 0.36 m of Rockwool with a U-value of 0.10 W/m^2.K. Living lab is equipped with a double skin façade in the south façade with a U-value of 0.65 W/m^2.K when ventilated. The north façade window has a U-value of 0.97 W/m^2.K while the east and west facade windows were 0.80 W/m^2.K. The simulations were performed assuming the air tightness of 0.7 ach, an air-to-water heat pump with a (constant) COP factor of 2.8, and a ventilation air-handling unit with a heat recovery efficiency of 85%. The balanced mechanical ventilation plant has a nominal airflow of 130 m^3/h with the supply air temperature of 18°C. It should be noted that the simulated case study building does not have a cooling system, and this analysis aims to find a balance between reducing overheating hours in summer and heating loads in winter.

The PCM layer utilized for this study was the SP21E provided by RUBITHERM Technologies GmbH. The melting and freezing temperature of the selected PCM was 23 °C and 19 °C, respectively. The thermal conductivity of the PCM was 0.6 W/m.K with 170 kJ/kg total enthalpy change.

3. Results

The simulation was conducted with IDA ICE and PCM was implemented on external walls and roofs with three different thicknesses and locations. Based on the study by Wang et al. [23], the PCM layer has been considered in the inner, middle (between insulation layers), and outer parts of the external wall and roof. The thickness of 25 mm, 50 mm, and 75 mm of PCM wallboard was considered for each scenario. After comparing the thermal performance and evaluating the risk of overheating each scenario at the zone level, the heating load of the whole building was compared and presented.

The living room, the largest zone in the case study building, was chosen to compare overheating and thermal comfort. Figure 5 depicts the zone indoor air temperature, outdoor air temperature, and zone heating load in the base case model without PCM. The outdoor air temperature varied between -14 °C in winter to 29.4 °C in summer.

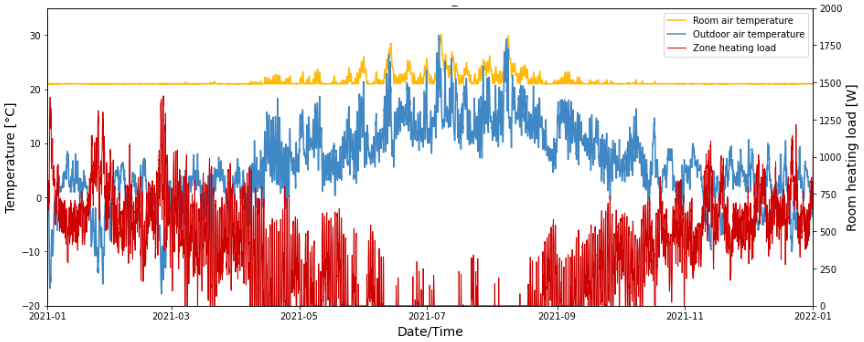

Figure 5. Comparison of indoor air temperature, heating load, and outdoor air temperature for the base case scenario

The maximum indoor operative temperature fixed thresholds of 25.5 °C of Category I (residential buildings) are illustrated based on the static comfort model of ISO 17772–1 [24]. The dashed line states this limit in the graph. The numbers on the top of each bar in Figure 6 indicated the number of hours that each scenario exceeded the upper limit of the ISO 17772-1 for thermal comfort.

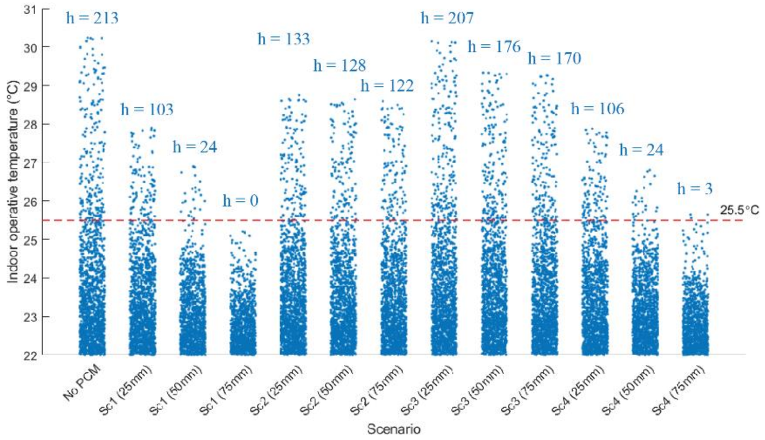

Figure 6. The indoor operative temperature of different scenarios during a year

The indoor operative temperature in all scenarios except the scenario with the Int 75mm of PCM exceeded the limit. In the scenario SC1_75mm the indoor environment was comfortable throughout the year. The most uncomfortable hours were related to the No PCM scenario, with 213 exceeded hours. It is followed by scenarios SC3_25, SC3_55, and SC2_75 mm with the number of exceeded hours of 207, 176, and 170, respectively. However, in the scenario SC4_75mm, only in a few hours (3 hours) the indoor operative temperature exceeded the higher limit of ISO 17772-2. The worse scenario in terms of overheating hours was related to SC3_25mm.

Figure 7 shows the Predicted Percentage Dissatisfied (PPD) and indoor air temperature of different scenarios with the same thicknesses (75 mm) during summertime.

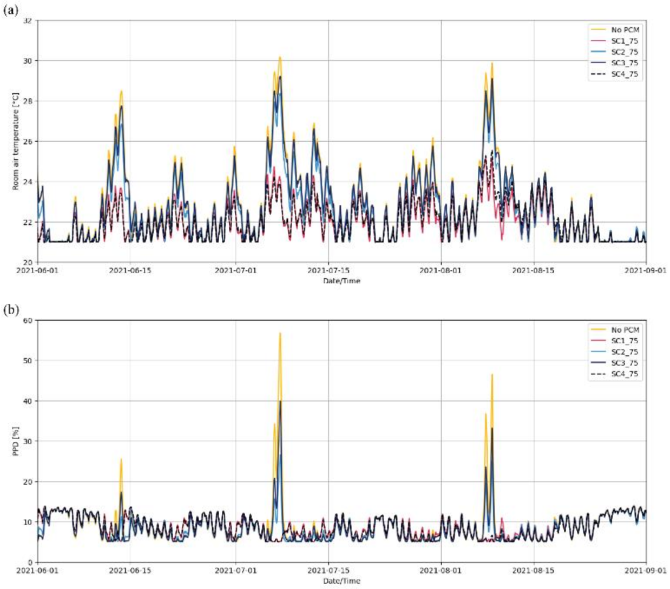

Figure 7. a) Indoor air temperature; b) PPD of each scenario with the thickness of 75mm of PCM layer during summer.

On the one hand, on July 7, around 18:00, the PPD value for No PCM scenario was 56.8%, the highest among all scenarios. PPD for scenario SC3_75 was the second highest, with 39.9% and for SC2_75 was 26.6 %. However, PPD at the same time for scenarios int 75mm and roof 75mm was the lowest, with values of 5.1% and 5.06%, respectively. PPD for the SC1_75 and SC4_75 were sustained without fluctuation during the summer and behaved similarly. The comparison of various scenarios reveals that the PPD for int 75mm and roof was reduced by approximately 51% compared to the base case scenario. It demonstrates that implementing the PCM layer in the wall's interior could effectively reduce the risk of overheating. Moreover, adding the PCM is also an efficient way to increase thermal comfort and occupant satisfaction.

On the other hand, the results of indoor air temperature showed that extreme overheating occurred on June 13, July 7, and August 8 for the base case scenario with a value of 28.4 °C, 30.2 °C, and 29.9 °C, respectively. The highest indoor air temperature was related to the No PCM scenario by a value of 30.2 °C on July 07. While in the same date, the indoor air temperature for scenarios SC1, SC2, SC3, and SC4 reached 24 °C, 28.3 °C, 29.2 °C, and 23.8 °C, respectively. The difference in temperature between the base case scenario and the SC1 was about 6.2 °C on July 07. The indoor temperature was reduced by 4.8 °C on July 13 and 4.9 °C on August 08 compared to the base case scenario.

The results of simulations referring to thermal comfort indicate that adding a PCM layer to the case study building could mitigate overheating. In order to evaluate the impact of the PCM layer on building energy performance, the case study building was simulated with and without the PCM, and the results are presented in Figure 8.

Figure 8 demonstrates that the annual heating load of the building in the case study without the PCM layer was the greatest at 7389 kWh. Upon addition of the PCM layer, the energy consumption decreased in all scenarios relative to the No PCM condition. The PCM utilized the least heating load when it was positioned between insulation layers with a thickness of 75 mm (SC2_75).

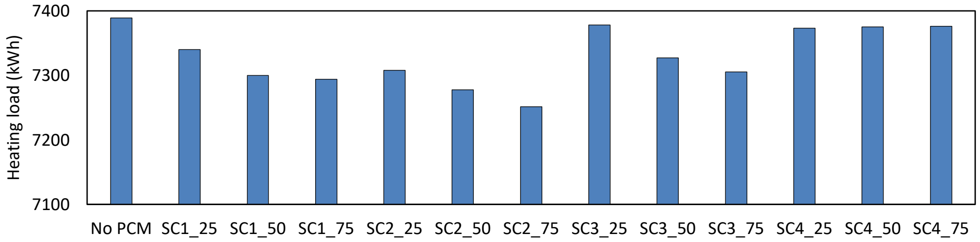

Figure 8. The whole building annual heating load for each scenario.

In this scenario, the heating load was about 7251 kWh which shows a reduction of 3.02 % compared to the base case scenario. When the PCM layer was implemented on the roof, the heating load was 7373 kWh, 7375 kWh, and 7376 kWh in case of a PCM thickness of 25 mm, 50mm, and 75 mm, respectively. Compared to the base case scenario, the results showed negligible heating energy use reduction when PCM was implemented on the roof (lower than 0.7 %). These insignificant changes in heating load when the PCM in the outer part of the external wall or the roof can be explained by the slightly decrease in U-value of the wall and roof, which increasing the thermal resistance of the wall and roof caused by the PCM, which traps heat inside during the warm months. With 75mm PCM in the middle part of the wall (SC2_75), the U-value of wall decreases from 0.1641 W/m2K to 0.1608 W/m2K, while the decrease in U-value of roof was quite negligible when adding a 75mm layer of PCM, which changed from 0.1155 W/m2K (No PCM) to 0.1134 W/m2K (SC4_75). As the PCM layer's thickness increased, the energy consumption altered similarly across all scenarios. Specifically, as PCM thickness increased, the building's heating load decreased. However, the differences between locations within the PCM layer varied. For instance, the heating load was reduced from 7340 kWh to 7293 kWh with 25 mm and 75 mm thicknesses, respectively, when the PCM layer was placed on the inner part of the exterior walls. Similarly, PCM in the outer layer of the wall affected the heating load, which decreased from 7378 kWh with 25mm of PCM to 7305 kWh with 75mm of PCM.

4. Discussion

Building overheating is a problem that is receiving more attention worldwide due to the immediate impact of climate change [3]. PCM materials are a new solution to overcome the problem of overheating, especially for lightweight buildings. In this study, the authors compared the effect of PCM locations and thicknesses on thermal comfort and energy use of nearly zero-energy residential buildings in Norway.

The results indicated that the placement of PCM layer in inner part and middle of the external wall yielded the highest performance in terms of heating load reduction. As the evaluated case study building complies with the Norwegian building rule, the building is well insulated with a very low overall thermal transmittance of the constructions. This is one of the reasons why it was determined that installing the PCM layer on the exterior of the building does not result in heating energy savings. This research results align with the study of [17], which concluded by placing the PCM layer next to the internal layer of the external wall to enhance thermal comfort. Findings showed that PCM layers in the exterior wall's inner part give the best thermal comfort results. The lowest uncomfortable hours were related to the Sc1_75mm with no overheating hours. With 75mm PCM layers in the inner part of the external wall, the risk of overheating was avoided, and occupants did not experience any uncomfortable hours. The other scenarios have different results that seem uncomfortable enough to be considered in Norway's climate condition. Therefore, we recommend using the PCM layers with higher thicknesses in the inner part of the external wall.

The main limitation of this research remained to be the difficulties in comparing the PCM layers' impact on building heating loads. The case study building was a highly insulated building in Norway's cold climate. As a result, the influence of the PCM layers was negligible on heating demand in this specific case study. Moreover, based on the findings of Sun et al. [17], the PCM had a more significant impact on cooling demand than heating demand. Also, it is recommended to use the PCM layer for the climate with higher diurnal temperature differences.

It is recommended that future research perform the same study and compare the results of PCM implementation in different climate zones. In addition, it is recommended for future research to analyze the impact of PCM on energy demand and thermal comfort with the variable set point instead of the fixed set point. Furthermore, future research is encouraged to evaluate the impact of the PCM layer thicknesses on space efficiency and useable space in buildings. It is worth mentioning that this study showed that the thicker PCM layer could be an option for avoiding overheating and enhancing the energy performance of the buildings. However, it should be noted that adding a PCM layer to the inner part of external walls would occupy the useable indoor spaces and decrease the square meters of the area. In this regard, comprehensive research is encouraged as a future study to compare the cost-effectiveness of PCM with the consideration of space saving.

5. Conclusions

The different positions and thicknesses of the PCM wallboard in the external wall, considering the maximum thermal comfort of occupants, useable of space, and reduced energy consumption, were parametrically simulated. The case study building that has been studied in this article is located at latitude 63°4'N and longitude 10°4E, Trondheim, Norway. Four different scenarios have been taken into account based on the placement of the PCM layer in the external wall and roof. Each scenario has three different PCM layer thicknesses: 25mm, 50mm, and 75mm. Scenarios were simulated using IDA ICE. The results demonstrate that adding a PCM in a lightweight timber construction can potentially reduce the risk of annual overheating in the Nordic climate. With 75mm of PCM wallboard in the inner layer of the external wall, the heating load was decreased by 2.3% compared to the base case scenario. Moreover, the overheating hours were reduced from 213 hours in the base case scenario (no PCM) to zero uncomfortable hours in SC1_75. Finally, increasing PCM thickness to 75mm proved to be an appropriate measure by reducing zonal peak indoor air temperatures by up to 6.2°C compared to the base case scenario.

References

[1] IEA, Global Energy Review. https://www.iea.org/topics/global-energy-review, Glob. Energy Rev. 2020. (2021).

[2] M. Hamdy, A. Hasan, K. Siren, Impact of adaptive thermal comfort criteria on building energy use and cooling equipment size using a multi-objective optimization scheme, Energy Build. 43 (2011) 2055–2067. https://doi.org/10.1016/j.enbuild.2011.04.006.

[3] Z. Tian, S. Zhang, J. Deng, B.D. Hrynyszyn, Evaluation on overheating risk of a typical Norwegian residential building under future extreme weather conditions, Energies. 13 (2020). https://doi.org/10.3390/en13030658.

[4] M. Hamdy, L.M. Jan Hensen, Ranking of dwelling types in terms of overheating risk and sensitivity to climate change, in: 14th Int. Conf. IBPSA - Build. Simul. 2015, BS 2015, Conf. Proc., 2015: pp. 2142–2149. https://doi.org/10.26868/25222708.2015.2120.

[5] M. Hamdy, S. Carlucci, P.J. Hoes, J.L.M. Hensen, The impact of climate change on the overheating risk in dwellings—A Dutch case study, Build. Environ. 122 (2017) 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031.

[6] European Commission, Eurostat Statistics Explained, Freight Transp. Stat. (2015). http://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics.

[7] R. Rahif, A. Norouziasas, E. Elnagar, S. Doutreloup, S.M. Pourkiaei, D. Amaripadath, A.C. Romain, X. Fettweis, S. Attia, Impact of climate change on nearly zero-energy dwelling in temperate climate: Time-integrated discomfort, HVAC energy performance, and GHG emissions, Build. Environ. 223 (2022) 109397. https://doi.org/10.1016/j.buildenv.2022.109397.

[8] B.P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities, Energy Build. 43 (2011) 2549–2563. https://doi.org/10.1016/j.enbuild.2011.05.015.

[9] A. Norouziasas, A. Tabadkani, R. Rahif, M. Amer, D. van Dijk, H. Lamy, S. Attia,

Implementation of ISO/DIS 52016-3 for adaptive façades: A case study of an office building, Build. Environ. (2023) 110195. https://doi.org/10.1016/j.buildenv.2023.110195.
[10] A. Norouziasas, P. Pilehchi Ha, M. Ahmadi, H.B. Rijal, Evaluation of urban form influence on pedestrians' wind comfort, Build. Environ. 224 (2022) 109522. https://doi.org/10.1016/j.buildenv.2022.109522.
[11] Y. Guan, T. Wang, R. Tang, W. Hu, J. Guo, H. Yang, Y. Zhang, S. Duan, Numerical study on the heat release capacity of the active-passive phase change wall affected by ventilation velocity, Renew. Energy. 150 (2020) 1047–1056. https://doi.org/10.1016/j.renene.2019.11.026.
[12] S.E. Kalnæs, B.P. Jelle, Phase change materials and products for building applications: A state-of-the-art review and future research opportunities, Energy Build. 94 (2015) 150–176. https://doi.org/10.1016/j.enbuild.2015.02.023.
[13] F. Kuznik, J. Virgone, Experimental investigation of wallboard containing phase change material: Data for validation of numerical modeling, Energy Build. 41 (2009) 561–570. https://doi.org/10.1016/j.enbuild.2008.11.022.
[14] X. Jin, M.A. Medina, X. Zhang, On the placement of a phase change material thermal shield within the cavity of buildings walls for heat transfer rate reduction, Energy. 73 (2014) 780–786. https://doi.org/10.1016/j.energy.2014.06.079.
[15] K.O. Lee, M.A. Medina, E. Raith, X. Sun, Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management, Appl. Energy. 137 (2015) 699–706. https://doi.org/10.1016/j.apenergy.2014.09.003.
[16] Y. Han, J.E. Taylor, Simulating the Inter-Building Effect on energy consumption from embedding phase change materials in building envelopes, Sustain. Cities Soc. 27 (2016) 287–295. https://doi.org/10.1016/j.scs.2016.03.001.
[17] X. Sun, J. Jovanovic, Y. Zhang, S. Fan, Y. Chu, Y. Mo, S. Liao, Use of encapsulated phase change materials in lightweight building walls for annual thermal regulation, Energy. 180 (2019) 858–872. https://doi.org/10.1016/j.energy.2019.05.112.
[18] F. Goia, L. Finocchiaro, A. Gustavsen, 7 . Passivhus Norden | Sustainable Cities and Buildings The ZEB Living Laboratory at the Norwegian University of Science and Technology : a zero emission house for engineering and social science experiments, (2015) 20–21.
[19] EQUA, Building Performance - Simulation Software, (2021). https://www.equa.se/en/.
[20] C. Cornaro, F. Bucci, M. Pierro, M.E. Bonadonna, G. Siniscalco, A new method for the thermal characterization of transparent and semi-transparent materials using outdoor measurements and dynamic simulation, Energy Build. 104 (2015) 57–64. https://doi.org/10.1016/j.enbuild.2015.06.081.
[21] C. Cornaro, M. Pierro, V.A. Puggioni, D. Roncarati, Outdoor characterization of phase change materials and Assessment of their energy saving potential to reach NZEB, Buildings. 7 (2017). https://doi.org/10.3390/buildings7030055.
[22] D. Mazzeo, N. Matera, C. Cornaro, G. Oliveti, P. Romagnoni, L. De Santoli, EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module, Energy Build. 212 (2020). https://doi.org/10.1016/j.enbuild.2020.109812.
[23] Z. Wang, Y. Qiao, Y. Liu, J. Bao, Q. Gao, J. Chen, H. Yao, L. Yang, Thermal storage performance of building envelopes for nearly-zero energy buildings during cooling season in Western China: An experimental study, Build. Environ. 194 (2021). https://doi.org/10.1016/j.buildenv.2021.107709.
[24] ISO/TC 163, DRAFT INTERNATIONAL STANDARD ISO / DIS 17772-1 Energy performance of buildings — Indoor environmental Quality — Part 1 : Indoor environmental input parameters for the design and assessment of energy performance of buildings, 2015 (2016). https://www.iso.org/obp/ui/#iso:std:iso:17772:-1:dis:ed-1:v1:en.