

Article

Investigating the Effects of PCM-Integrated Walls on Thermal Performance for UK Residential Buildings of Different Typologies

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Abstract: Phase change materials (PCMs) can improve the thermal performance of building facades. The integration position of a PCM in the facades is influenced by multiple factors including the material properties of the PCM, building types, and the internal and external conditions of a building. However, this has not been a focus within the UK dwelling stock, where many dwellings are not thermally protected. This paper, therefore, presents a numerical study with the aid of building simulation that comparatively analysed the thermal performance between four typical UK dwelling types (semi-detached house, terraced house, detached house, and apartment) situated in North East England. The PCM was implemented into the external wall of the dwellings with the positions altered to determine the most effective position. It was determined that the PCM positioned internally was the most effective for all the dwelling types. These results demonstrated that the PCM being implemented in the apartment, semi-detached, and terraced houses had only marginal heat loss reductions (by 8%, 14%, and 8%, respectively) in comparison with that of the detached house (by 30%). It was also found that the large external wall area of the detached house acted as significant thermal energy storage, which was capable of offsetting heat transmission and stabilising indoor thermal conditions. In summary, this paper contributes to the matters concerning the effect of PCMs on indoor thermal performance in dwellings of different typologies in the UK.

Keywords: building envelopes; phase change materials; dwelling types; building performance assessment; thermal modelling



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1. Introduction

Building energy consumption has become one of the pressing issues facing sustainable development in many countries around the world [1,2]. The UK Green Building Council reports that buildings in the UK account for 60% of total electricity consumption and 25% of total carbon emissions, primarily due to heating and cooling to provide thermal comfort [3,4], in which, UK residential buildings contribute 26% and 17%, respectively, to energy consumption and carbon emissions [5]. Given the current climate crisis, reducing greenhouse gas emissions and building energy consumption is crucial for the planet's future [6,7]. In recent years, it was clarified by the UK Government that the UK's interim aim is to cut carbon emissions by 78% compared with 1990 levels by 2035 [8].

The building envelope plays an important role in reducing building energy consumption and many researchers have explored different solutions to maximise the thermal performance of building envelopes [9–14]. Converting the thermal envelope of buildings into a thermal energy storage device is a promising avenue [15–17]. Phase change materials (PCMs) can be used as the thermal energy storage (TES) device to improve energy efficiency,

reduce heat gains and losses, and enhance thermal comfort in buildings [18], through the processes of melting and freezing [19]. PCMs have the potential to improve the thermal properties of building materials such as thermal mass, capacity, and inertia, by transitioning phases within specific temperature ranges to absorb and release large quantities of heat energy [20,21]. The implementation of PCMs have essentially enhanced the capabilities of thermal energy storage within building structures. Consequently, the ability to reduce high-temperature gains and losses within internal spaces has been improved, ultimately lowering energy costs and emissions by reducing heating, ventilation, and air conditioning (HVAC) requirements [22]. Recently, numerous studies have focused on incorporating PCMs into building fabrics. Lei et al. [23] found that PCMs can effectively reduce heat gains through building envelopes throughout the year, indicating the significant advantage of using a PCM in buildings located in hot circumstances. Shi et al. [24], who used a PCM board as the floor make-up within an office, shows a reduced energy consumption of 18–19% within the summer and winter as well as a good level of thermal comfort being maintained. Regarding PCM applications in residential buildings, the results of Hou et al. [25], which were based on a parametric study for dwellings in China, display that the optimum PCM integration into the test wall reduced energy consumption by over 21%, however, these experiments were performed only in old-fashioned Chinese bungalows.

Fundamentally, the effectiveness of PCMs in building envelopes is influenced by various factors, including the thermal properties of the PCM, indoor and outdoor boundary conditions, climatic conditions, application position, and building type [26,27]. External walls, due to their large surface area compared to other envelope structures, provide a greater capacity for PCM integration [28]. The position of the PCM within the external building walls is a critical parameter, which significantly influences the wall performance under transient thermal fluxes [29]. Many studies have been conducted to determine the optimal position for a PCM. Khan et al. [30] found that placing a PCM closer to the heat source provides the most benefit by limiting heat gains. In contrast, Arici et al. [28] found that the optimal PCM position is dependent on a building's location and the local climate; for example, a PCM located between the interior plaster and the concrete performs better, while PCM placement between the insulation and the exterior wall is the optimal position in an opposing climate. Li et al. [31] developed a mathematical model using an energy equation modified by latent and sensible enthalpy, which demonstrates that placing a PCM close to the exterior wall can better reduce heat transfer because higher exterior temperatures promote phase change, and this theory can be applied to residential buildings [32].

That being said, the best positions for PCM application in building walls are where a complete daily melting and freezing cycle can be achieved, which results from the interaction of multiple intertwined parameters, leading to significant discrepancies in current research [33]. Al-Yasiri and Szabó [34] highlight the discrepancies in PCM positioning, noting that some studies suggest the PCM layer should be closer to the heat source, while others find that an interior position performs better. Thus, the optimal PCM positions have never been truly determined. However, the consensus is that the effectiveness of PCM placement is predominantly dependent on the building's climate. For instance, when PCMs are used for heating purposes, an interior placement is often more effective, whereas for cooling purposes, an exterior placement is preferable [34]. This assumes that the correct type of PCM is used, with melting temperatures compatible with the internal and external conditions for heating and cooling, respectively. Conversely, Lagou et al. [35] conducted a study in six different geographic locations in Europe, each featuring an identical building with an appropriately selected PCM based on their melting temperatures. The building was non-conditioned with no form of heating, cooling, or mechanical ventilation, representing historic and vernacular structures. The study was found that, in all cases, the PCM was most effectively implemented on the internal surface of the wall, regardless of the external conditions. Although the results are intriguing for non-conditioned spaces, they are not conclusive due to only one wall type being tested. To validate these findings, further

tests on various wall types are necessary to determine if the results are consistent or if discrepancies exist between different construction types. Al-Absi et al. [33], in an extensive literature review, concluded that the higher the wall's thermal resistance, the closer the PCM must be to the external environment. This is due to the PCM having a reduced amount of heat transfer being received, therefore, it is less likely to transition if located internally. Al-Absi et al. [33] further pointed out that in cold climates, PCM placement is most effective internally, whereas in hot and summer climates, the PCM is preferred externally. Furthermore, increasing the quantity and thickness of the PCM enhances thermal heat storage, and thus makes external placement near the wall most suitable in warm climates where phase transition is more likely to occur. In a subsequent study, the high efficiency of external PCM applications was further demonstrated [36]. However, limited research has been conducted to identify PCM positions for different UK dwellings, where the country has a very diverse dwelling market. Auzeby et al. [37] conducted a numerical study on PCM integration for residential applications in the UK, in which they reported that internally positioned PCMs could effectively reduce the risk of overheating, but this study investigated only a terraced house.

Common techniques for implementing PCMs into building materials include impregnation, macro or microencapsulation, direct incorporation, and immersion [38]. Leakage of PCMs may occur when impregnating PCMs into certain construction materials such as lightweight aggregates during the phase change of the PCM from solid to liquid [39]. The incorporation of PCMs into building envelopes can control thermal load for energy saving purposes [34], however, the leakage will still occur when incorporating PCMs into concrete through immersion [40]. In comparison, macro or microencapsulation methods have been proven to be able to solve PCM leakage effectively [41]. Microencapsulation, in particular, includes having the PCM particles enclosed in a solid shell, which can be produced from numerous natural and synthetic materials [42], thus achieving a form-stable PCM for reducing leakage rates [43].

In addition, the type of building, to a certain degree, can also influence building thermal performance [44,45] as well as the PCM performance in buildings, which, however, has not been well explored. Due to the building fabric being a variable parameter, it is difficult to determine the exact influences that the external facades have on the thermal comfort or energy consumption of individual building types [46], especially for residential buildings of various types. For instance, there are more than ten different types of dwelling in the UK, which fall mainly into four types, namely semi-detached, terraced, detached, and apartment [47]. It is fair to assume that the larger external wall area of the detached dwelling type in comparison to the multi-story apartment would result in higher heat losses and therefore a poorer thermal performance, but little research has been performed to verify the underlying issues. Poel et al. [48] assessed the building energy performance of different types of buildings including independent houses and apartment blocks, and concluded that the use of new building materials, along with improved insulation standards, is one of the key factors to improving building energy efficiency. However, their study only concentrated particularly on a wide range of building types, from commercial buildings to private dwellings, in which PCMs were not considered. A recent document by Unilin Insulation [49] reported the carbon emissions for the four UK dwelling types; it was found that the total carbon emissions per unit area, in order from most to least, is detached, semi-detached, terraced, and apartment block. However, it is worthwhile to explore the performance gap when a PCM is being applied.

In summary, PCMs are a proven advanced building material to improve building energy efficiency. The position of a PCM and its implementation in building fabrics have a great influence on buildings' thermal performance and the effectiveness of the PCM itself, which, however, remains to be an open-ended question. On the other hand, the thermal performance of a building is also dependent on the type of the building. Given the diverse dwelling types in the UK, thermal performance may vary greatly from type to type, which has not been well researched; PCM application in different UK dwellings receives even

less attention. Therefore, this paper presents a numerical study on assessing the thermal performance of four typical UK residential buildings when using PCMs, which aims to identify the possible benefits of integrating PCMs into the buildings' facades.

2. Materials and Methods

This study investigates the application of PCMs in building envelopes in the UK housing context. Four different UK dwelling types were chosen for the study, including the semi-detached house, terraced house, detached house, and apartment. First, the type of dwelling was used as an initial parameter to understand its effect on dwellings' thermal performance, for instance, heat loss during periods of cold weather. The results were then analysed to identify the suitability of PCM implementation in terms of the dwelling types. The chosen dwellings, derived from real building cases, were modelled using the EDSL Tas (version 9.5.6) building simulation software to assess the thermal performance of the dwelling with PCM under a UK climate condition, while the simulation results were validated accordingly. EDSL Tas is a comprehensive building simulation software for assessing the environmental performance and energy consumption of buildings [50]. This software can perform hourly dynamic thermal simulations for complex building models. In this way, the thermal state of a building is tracked via a more advanced and reliable calculation method [51]. As a matter of fact, EDSL Tas-based PCM modelling has been validated through various studies [52–54], which, therefore, was applied to this study.

2.1. Design Conditions

The proposed four dwellings, according to the actual buildings' locations, are situated in North East England. As such, a weather file of Newcastle upon Tyne (the nearest weather pattern) was utilised. This climate condition experiences an average annual temperature of around 10 °C [55]. During winter, temperatures typically range between 4 °C and 6 °C, needing substantial heating to keep warm indoors. In contrast, summer temperatures are milder, ranging from 11 °C to 20 °C, and thus result in a lower demand for cooling. The weather file used within this study is a CIBSE (Chartered Institution of Building Services Engineers) licensed DSY1 file (that is, Design Summer Year—moderately warm summer): 2050s—Medium—50th percentile. This weather file predicts conditions for the years between 2041 and 2070 based on the UK Climate Projections 2009 [56] and TM49 methodology [57], taking in account the influence of climate change.

2.2. Building Description

Figure 1 displays the 3D models of the four dwellings created in EDSL Tas. None of the dwellings' layouts (Figure 2) were modified or adjusted for this study, and were modelled in adherence to the floor layouts and dimensions given by the architects who originally designed them. The only parameters changed were the building material's U-values (that is, thermal transmittance), which were kept consistent among all building/dwelling types, as well as the building's orientation (facing north). These were intentionally changed to ensure that the parameters between the building types were consistent so that realistic and valid results were obtained.

All of the U-values used within this study were set to the limiting conditions stipulated in the latest of England's Building Regulations (Part L Volume 1) [58]. The construction properties of the case study buildings, such as thermal conductivity and the solar heat gain coefficient, were modelled to reflect real world conditions. Basically, the proposed study kept the building simulation parameters as accurate as possible to construction of a common UK dwelling, while the simulation precisely replicated the existing dwellings with a retrofit PCM. Given that 80% of UK dwellings in the 2050s scenario already are being currently built [3], the performance of the PCM as a retrofit is crucial. The geometrical information of the four dwellings is given in Table 1. The physical and thermal properties of the used building materials, including both opaque and transparent elements, are shown in Table 2.

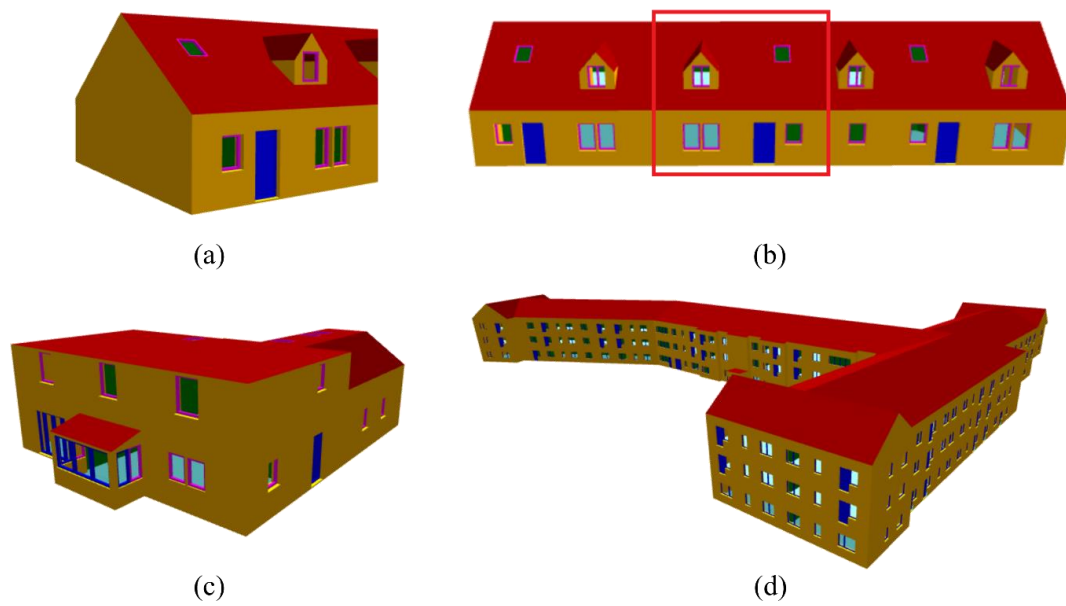


Figure 1. Four case study dwelling models: (a) semi-detached house, (b) terraced house (highlighted in red), (c) detached house, (d) apartment.

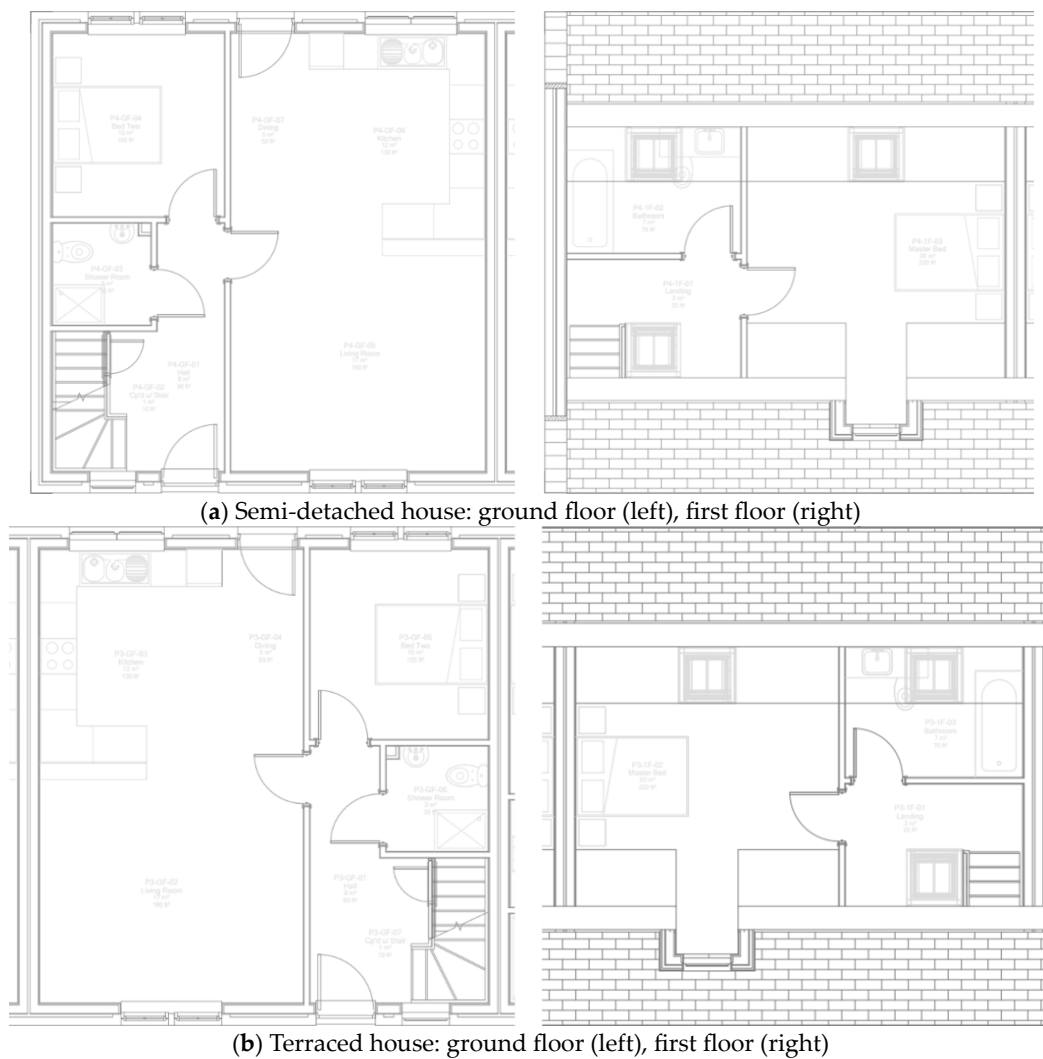


Figure 2. Cont.



Figure 2. Model layout plans for the four case study dwellings.

Table 3 presents the thermal profile applied to the simulations for all dwelling types. The design temperature schedule was set from 06:00 to 10:00 and from 16:00 to 22:00 based on the typical UK residential circumstances, while setback temperatures were applied to the periods outside of these times. There were assumptions made due to the inaccessibility of the actual operations in the dwellings. Specifically, infiltration rates were assumed based on the CIBSE Guide B [59], reflecting the airtightness of dwellings. Internal gains were assumed as per the CIBSE Guide A [60], while occupancy gains were considered only for rooms occupied for long periods. It should be noted that the bedroom occupancy gain profile was set from 22:00 to 06:00, while the lounge occupancy gain profile was set from 17:00 to 22:00.

Table 1. Geometrical information of case study dwellings.

	Semi-Detached House	Terraced House	Detached House	Apartment
External wall area (m ²)	83.75	49.59	202.05	17.96
Window area (m ²)	9.54	9.54	33.29	5.38
Window-to-wall ratio	11%	19%	17%	30%
Total floor area (m ²)	118	117.27	253	62.46
L × W × H (m)	7.7 × 7.7 × 5.95	7.65 × 7.65 × 5.95	13 × 14.5 × 5	9 × 6.9 × 3.1

Table 2. Physical and thermal properties of case study dwellings.

Envelope	Layer	Width (mm)	Thermal Conductivity (W/m·K)	Weighted U-Value (W/m ² ·K)
External wall	Brick	105	0.77	0.26
	Insulation	80	0.026	
	Air layer	50	0.01	
	Engineering block	100	1.13	
	Plasterboard	12	0.57	
Internal wall	Plasterboard	12	0.57	0.2
	Timber frame with rockwool insulation	100	0.026	
	Plasterboard	12	0.57	
Floor	Hardcore	300	0.1	0.18
	Insulation	200	0.04	
	Concrete slab	200	2.3	
	Screed	40	0.15	
Roof	Plasterboard	12	0.57	0.16
	Insulation	240	0.04	
	Felt	10	1	
	Roof tiles	10	1.5	
Door	-	-	-	1.6
Glazing Type	Layer	Width (mm)	Weighted Solar Heat Gain Coefficient	Weighted U-value (W/m ² ·K)
Triple-glazed window	Glazing (×3)	10	0.305	1.6
	Air (×2)	12		

Table 3. Design thermal parameters.

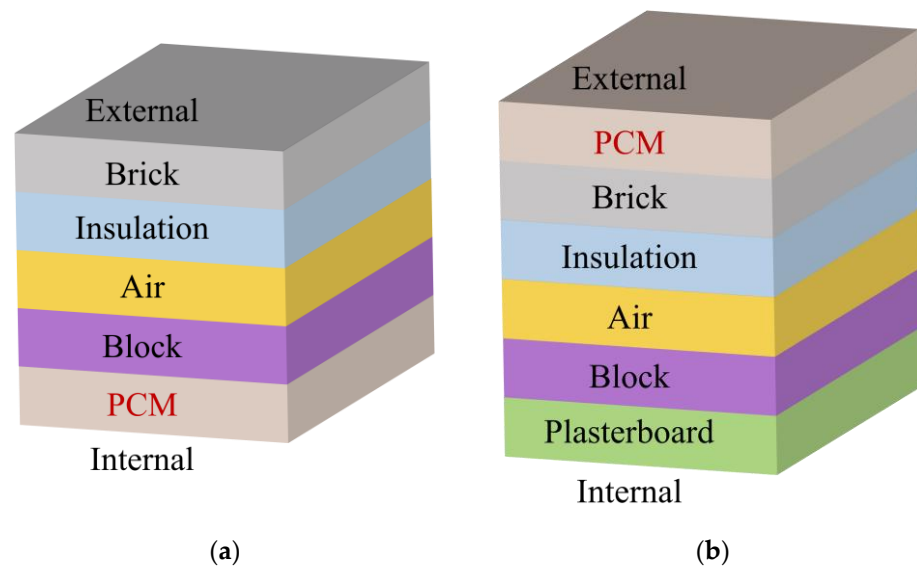
Room	Design Temperature (°C)	Setback Temperature (°C)	Infiltration Rate (ACH)	Lighting Heat Gain (W/m ²)	Occupancy Gain (W/m ²)	
					Sensible	Latent
Lounge	21	16	1	12	10	5
Bathroom	23	16	2	12	0	0
Bedroom	19	16	1	12	10	5
Circulation	19	16	1.5	12	0	0
Kitchen	19	16	1.5	12	0	0

2.3. PCM Application

The PCM used for this study was determined from the options available in the EDST Tas software. The PCM type chosen was a commercially available Rigips Alba balance 23 wall board [61], which can be applied to new or retrofitted buildings, therefore relevant for existing houses in a 2050s scenario. The PCM wall board properties are given in Table 4, and Figure 3 shows the PCM layer at different integration positions within the wall structure. The wall board consists of microencapsulated paraffins, which are able to store large amounts of thermal energy and release them when the room temperature starts to decrease [62]. This microencapsulated PCM can be added directly to building materials with a large surface area for improving heat transfer rates, and also possesses good sealing properties [63]. The full melting temperature of the wall board was designed for 23 °C, which was higher than most of the room design temperatures as seen in Table 3. As such, full phase transitioning cycles might not occur, which was something that was taken into account when the results were analysed. However, regardless of whether the PCM performed poorly, based on the real operation condition, the indoor temperature of 23 °C is relatively high for a dwelling, and the designed temperatures were more representative of a dwelling's actual temperatures.

Table 4. PCM thermal properties.

Parameter	Value
Peak melting temperature	23 °C
Latent heat storage	300 kJ/m ²
Specific heat	28.3 kJ/m ² ·K
Thermal conductivity	0.27 W/m·K
Thickness	25 mm

**Figure 3.** The PCM in wall construction: (a) internally positioned PCM, (b) externally positioned PCM.

3. Model Validation

The simulation accuracy and quality were validated by undergoing manual steady state heat loss calculations for a particular room (without PCM) within all four dwelling models with standard wall constructions. To ensure accuracy in calculation, the surface areas stated within EDSL Tas simulation report were used in the manual calculations. Similarly, infiltration and other thermal properties were all kept consistent between simulation and manual calculation. Additionally, thermal bridging losses were also calculated and applied to the overall heat losses by selecting default values for the linear thermal transmittance of the thermal bridges from the SAP 10.2 (that is, Standard Assessment Procedure version 10.2) [64]. The model validation was carried out using the appropriate steady state equations, as follows [65].

For the calculation of conductive heat loss through building fabric:

$$Q_c = \sum U \cdot A \cdot (T_i - T_e) \quad (1)$$

where Q_c is the heat loss through building fabric via conduction (kW), U is the U-value (thermal transmittance) of the building fabric (W/m²·K), A is the surface area of the building fabric (m²), T_i is the indoor design temperature (°C), and T_e is the outdoor temperature (°C).

For the calculation of the infiltration heat loss through the building fabric:

$$Q_{inf} = 0.33 \cdot N \cdot V \cdot (T_i - T_e) \quad (2)$$

where Q_{inf} is the infiltration heat loss through the building fabric (kW), N is the number of air changes per hour (ACH), and V is the room volume (m³).

For the calculation of the thermal bridging heat loss through the building fabric:

$$Q_{TB} = \sum(L \cdot \Psi) \quad (3)$$

where Q_{TB} is the thermal bridging heat loss through the building fabric (kW), L is the length of the thermal bridge component (m), and Ψ is the linear thermal transmittance of the thermal bridges (W/m·K).

For the total heat loss through the building fabric:

$$Q_{total} = Q_c + Q_{inf} + Q_{TB} \quad (4)$$

The heat loss discrepancies between the simulation and the manual calculation for the selected room (that is, living room) in the different dwellings are shown in Table 5. The results displayed relatively good agreement between the thermal model results produced by EDSL Tas and the steady state heat losses carried out via the manual calculations within a good engineering tolerance [12,66]. The largest discrepancy was displayed in the semi-detached house living room with a deviation of 6.01%. On the other hand, the terraced house living room displayed the most accurate results with a deviation of 1.98%.

Table 5. Total heat loss comparisons between simulations and manual calculations.

Type of Dwelling	EDSL Tas Results (W)	Manual Calculation Results (W)	Deviation
Semi-detached house	537.71	572.1	6.01%
Terraced house	562.66	574.02	1.98%
Detached house	1620.39	1534.68	−5.29%
Apartment	2120.21	2064.23	−2.64%

Comparing the overall heat loss demonstrated the quality of agreement between simulation and manual calculation to a certain degree, which, however, is a crude way of assessing the accuracy of the simulation model. Therefore, further validation was performed by comparing the losses of the different parts of the building envelope (using the detached house living room as an example), and these results are shown in Table 6. As can be seen, windows caused the highest discrepancy between both calculations, which was due to the fact that the software accounts for winter solar transmission and absorption [67], while the manual calculation does not. As a result, the solar radiation absorbed by the opaque surfaces contributed to the room as heat gains, thereby offsetting the heat losses caused by the poor thermal performance of the windows. Other calculation disparities arose from the variation in calculation methods between the software's complex algorithms and the manually conducted steady-state heat loss calculations. For instance, the software accommodates for previous hourly heat flux as well as heat transfer by convection [68,69], which is likely another cause of the discrepancies between both results. Having said that, both the simulated and manually calculated results still show fair agreement, although a certain amount of discrepancy exists. Furthermore, EDSL Tas has undergone rigorous tests and has been validated against common standards, which has been proven to produce accurate simulation results of building thermal modelling. In summary, the EDSL Tas models were deemed validated.

Table 6. Element heat loss comparisons between simulations and manual calculations.

Medium of Heat Loss	EDSL Tas Results (W)	Manual Calculation Results (W)	Deviation
Ground floor	65.5	56.5	−15.93%
Windows	198.91	255.5	22.15%
External wall	325.06	310.35	−4.74%
Infiltration	903.22	876.28	−3.07%

4. Results and Discussion

This section presents the simulation results for comparing the effectiveness of PCMs across four different dwelling types in the UK. Specifically, it explores the relationship between PCM application effects, dwelling types, and the external wall areas. Furthermore, the optimal position for PCM integration with the external wall in the climate of North East England is identified.

4.1. Dwelling Heat Loss without PCM Integration

Figure 4 shows the results of heat losses per floor area without PCM integration, which indicated that among the four dwelling types with no PCM applied, the worst performing dwellings were the detached house and apartment with a respective total heat loss of approximately 33.9 W/m^2 and 33.7 W/m^2 . In comparison, the terraced house was the best performing dwelling, which had a total heat loss of under 30 W/m^2 . In terms of total heat loss, the detached house was the least efficient due to its large external wall area and the relatively large window area, while the apartment featured the highest window-to-wall ratio (WWR) (as per Table 6) and was the second-worst performing dwelling. As such, the glazed area on the apartment and detached house were likely to be the most influential on the overall building heat loss.

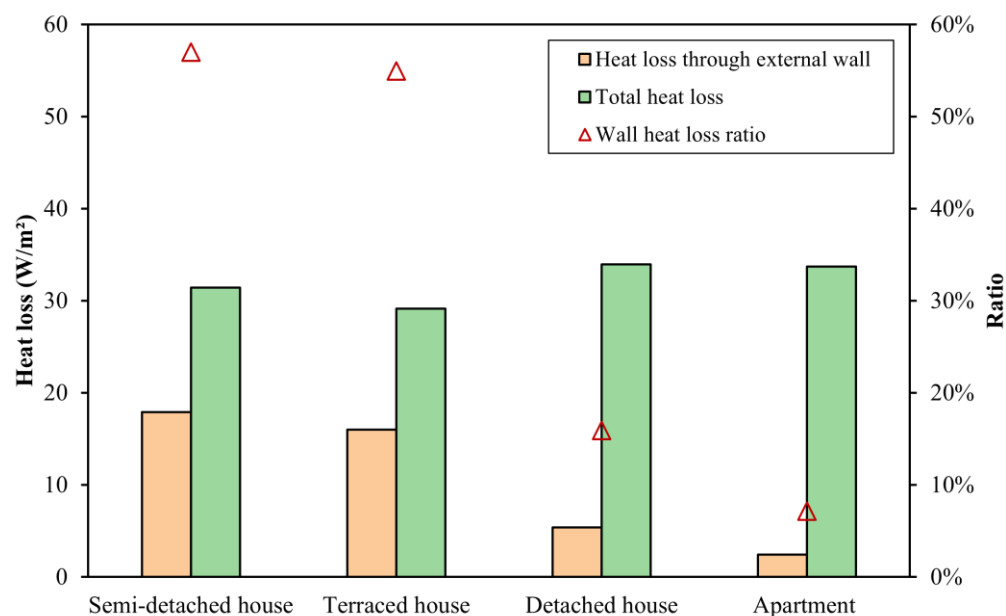


Figure 4. Dwelling heat loss without PCM integration.

However, when comparing heat losses solely through the external wall in terms of the floor area, the results were almost inverted. As can be seen, the apartment and detached house had the lowest and second-lowest heat loss values of 2.4 W/m^2 and 5.4 W/m^2 , respectively, which contributed to 7.15% and 16% of their total heat losses. In comparison, the semi-detached house was the worst performing, with a wall heat loss of 17.9 W/m^2 accounting for about 57% of the total heat loss, followed by the terraced house with a heat loss of 16 W/m^2 through the external wall, which contributed to approximately 55% of its total heat loss. This is because the apartment was land-locked with neighbouring rooms of similar temperature, and there were limited internal, ground floor, or roof-based heat losses in comparison with the other dwelling types.

Clearly, a high level of glazing was a contributing factor in making the worst performing dwellings. Therefore, it is important for building designers to achieve an equilibrium between natural daylighting and the building's energy performance with an aim to reduce heat losses in the season of winter.

4.2. Dwelling Heat Loss with PCM Integration

Figure 5 displays the effects of PCM integration methods among the different dwelling types, which revealed a consistent downward trend (from no PCM applied to interior PCM positioning) in heat losses. Basically, heat losses in all dwellings were reduced when PCMs were integrated, with the PCM situated internally being the most effective. It can be concluded that in the winter of North East England, the PCM is preferable on the internal side of the facade due to its proximity to the heat source, which aligns with the PCM transition temperatures between 15 °C and 90 °C [70]. In this study, most indoor conditions were set to a design temperature range of 19–21 °C with a setback of 16 °C, which created a 3–5 °C differential between melting and solidifying temperatures. On the other hand, almost all dwellings that placed PCM externally made little difference in comparison with internal positioning. In this case, solar gains might have somehow sped up the melting of the external PCM. Furthermore, the largest heat loss reduction improvement was seen for the detached house, from 34 W/m², with no PCM applied, to approximately 26 W/m² for the externally positioned PCM (outer PCM), which was improved further to 24 W/m² when the PCM was internally positioned.

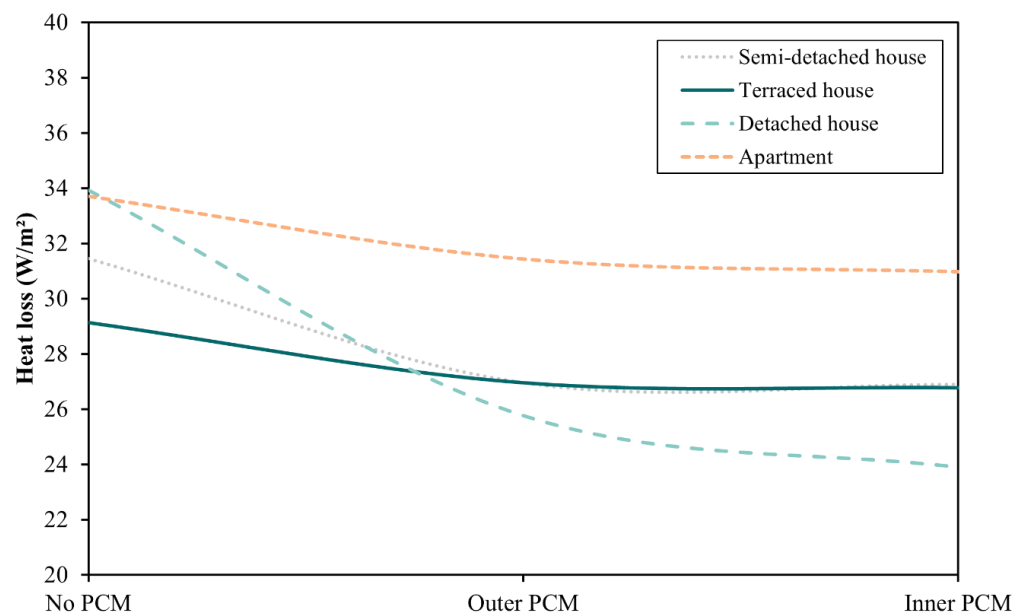


Figure 5. Dwelling heat loss due to PCM configuration.

Figure 6 shows the heat loss reduction percentage both for internally and externally positioned PCM against the no PCM scenario for different dwellings. As can be seen, all the dwellings received reductions in heat loss when the PCM was applied, no matter internally or externally. This indicated that the PCM can achieve transitioning temperatures to undergo phase change. Fundamentally, the internal air temperature coincided with the PCM melting temperature during the time of heating demand, allowing it to store heat and release it as the building started to cool down, which offset the time the room took to reach the setback temperature and reduced the peak demand in the next heating cycle. Looking at the percentage reduction in Figure 6, the detached house displayed the highest heat loss reduction when adopting PCM on external walls, in which a respective reduction of 24% and 30% was achieved for the outer and inner PCMs. This, however, demonstrates that PCM integration is most suitable for this type of dwelling.

The semi-detached house, with the largest heat loss through the external facade without PCM, was the second most responsive dwelling type for PCM integration. Figure 6 shows that the semi-detached house integrating PCM both internally and externally reduced heat loss by over 14%, with only marginal differences between the PCM positions. Comparing the initial heat loss contribution through the external wall (57%) and the overall reduced heat loss with PCM integration (14%), the performance of the semi-detached house,

although the second best, was not comparable to that of the detached house. Despite having a neighbouring dwelling, which results in lower heat gains or losses for semi-detached house, the additional external walls of the detached house provided heat gains at certain temperatures, resulting in a lower overall heating loss than all other dwelling types, especially when adopting PCM. This might change if the neighbouring building had a 24-h heating schedule, which would transmit heat to the space when the tested property operated at a setback temperature of 16 °C for improving heat loss results.

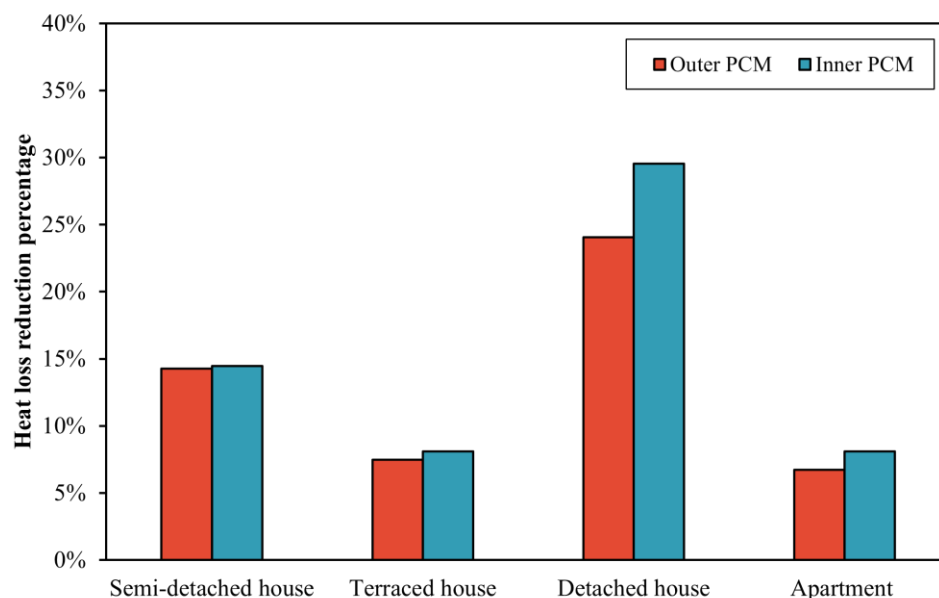


Figure 6. Comparison of dwelling heat loss reduction percentages.

On the other hand, the two poorest performing dwellings were the apartment and the terraced house. Both showed similar heat loss reductions of around 8% when the PCM was integrated internally. However, external PCM positioning had more influence on the terraced house compared to the apartment, with approximate heat loss reductions of 7.5% and 6.7%, respectively. This variation in heat loss reduction was possibly due to the apartment being north-facing, while the terraced house also had a south-facing facade benefiting from solar radiation that assisted in PCM phase transitioning, thereby reflecting the heat loss reduction.

It has been discussed in the literature review how multiple parameters affect PCM performance and are often interlinked, but this study maintained consistent parameters throughout all the dwellings with the exception of the external walls area. Specifically, the relationship between external wall area and heat loss reduction was explored, showing a consistent positive correlation as per Figure 7. Basically, it displayed a linear relationship where the heat loss reduction increased with the increase in the external wall area, while the increased wall area of the internal wall PCM (that is, outer PCM) correlated with a greater heat loss reduction than that of the external wall PCM. In addition, as external wall area increased, the PCM heat loss reduction improved at a consistent rate when the PCM was located internally; similarly, when the PCM was integrated externally, heat loss reduction increased exponentially with the increase in the wall surface area, which was particularly evident in the scenario of the detached house. This was possibly due to the higher level of latent heat storage available and the overall increased thermal mass, particularly for the detached and semi-detached houses which had the largest external wall areas. In Figure 7, although the apartment and the terraced house showed a slight anomaly with lower heat loss reductions than expected, both were limited by their small wall areas. Despite the preference for internal PCM positioning, Figure 7 shows that all dwellings except the detached house had a nearly parallel performance between the PCM positions. As the two performance lines for heat loss reduction approached the detached house, the area between

both lines increased, indicating that the effect of the outer PCM was beginning to weaken whereas the inner PCM continued to perform effectively.

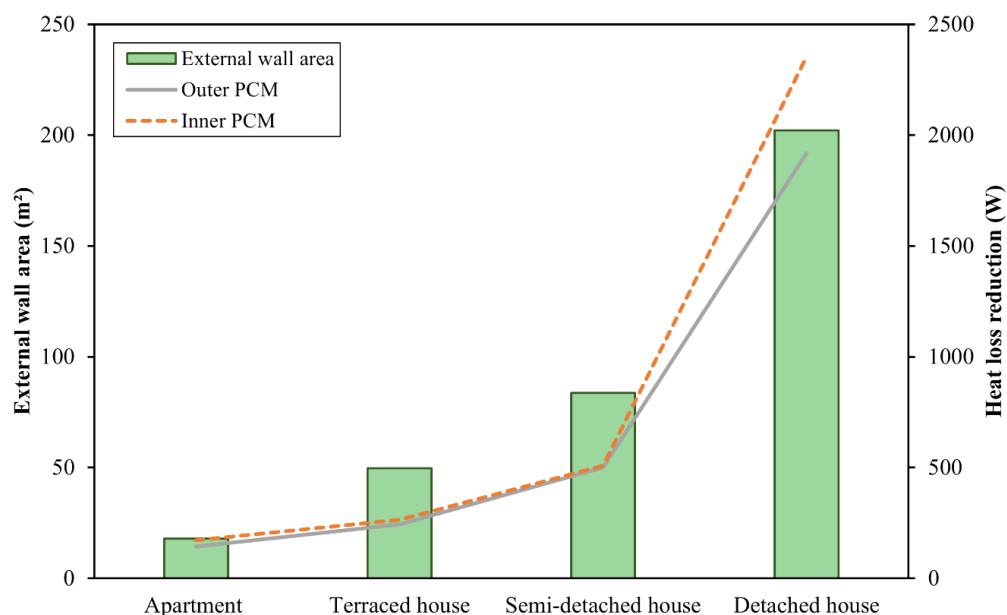


Figure 7. Correlation between external wall area and heat loss reduction when using PCM.

5. Conclusions

This study conducted a numerical analysis to understand how PCMs can be effectively implemented in building facades and thus improve the thermal performance of four different types of dwellings in the UK context. Specifically, it examined the characteristics and parameters necessary for PCM integration into facades and assessed how different dwelling types affect the feasibility and performance of the PCM. This study also investigated the impact of PCM integration on heat loss through dwelling facades and identified the most suitable position for PCMs in the external wall constructions of buildings in North East England. Our findings showed that, under the projected 2050 weather conditions in North East England, PCMs generally performed better when situated internally to reduce heat losses in cold climates. In this case, the PCM benefitted from the room's heating emitters warming the soffit of the walls, allowing the PCM to transition its energy when the room cooled down. In terms of thermal improvement via PCMs, the detached house, in particular, exhibited a significant heat loss reduction of 30%, starting as the worst performing dwelling (34 W/m^2) for heat loss without PCMs to the best performing for heat loss with PCM integration among the four dwellings. This improvement was primarily due to the large external wall area, allowing for substantial PCM integration and maximising heat storage capacity, thereby enhancing the building's thermal mass. In comparison, the apartment performed the poorest by achieving only 8% heat loss reduction with the PCM internally positioned, mainly due to its low external wall area with a large portion of glazing; therefore, PCM implementation might not be suitable for this type of dwelling. Furthermore, both terraced and semi-detached houses also saw minor reductions in heat loss (8% and 14%, respectively), due to their smaller external wall areas, limiting PCM integration and thermal storage capacity. This study, however, demonstrated that PCMs can play a vital role in North East England, particularly in housing retrofit scenarios where existing dwellings require thermal improvements to assist in achieving the UK's aim of net zero by 2050.

6. Limitations and Future Research

Since dwellings in North East England predominantly require heating, cooling conditions were not investigated in this study, though an extension to this study could be made to determine the PCM's performance in the summer for an all-year-round performance review, and that of different climate contexts is also of interest. In addition, the dwellings

used in this study were selected from real-life buildings, which, however, might not be representative of other dwellings of the same type due to various sizes, shapes, and the WWR. Thus, future research can focus on a larger group of dwelling types to ensure consistency and to further validate the results. On the other hand, due to future demographic changes, PCM performance in other residential buildings such as retirement homes and care homes should be worthy of study. This paper is, however, focused on the facade-integrated PCMs; further research can also look at PCM applications on ceilings and floors within the dwellings especially for multi-story apartments, where thermal performance may be affected by adjacent floors.

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Nomenclature

Symbols

A	surface area of the building fabric [m^2]
L	length of the thermal bridge component [m]
N	number of air changes per hour [-]
Q_c	heat loss through the building fabric via conduction [kW]
Q_{inf}	infiltration heat loss through the building fabric [kW]
Q_{TB}	thermal bridging heat loss through the building fabric [kW]
Q_{total}	total heat loss through the building fabric [kW]
T_e	outdoor temperature [$^{\circ}\text{C}$]
T_i	indoor design temperature [$^{\circ}\text{C}$]
U	thermal transmittance [$\text{W}/\text{m}^2\cdot\text{K}$]
V	room volume [m^3]

Greek symbols

Ψ	linear thermal transmittance of the thermal bridges [$\text{W}/\text{m}\cdot\text{K}$]
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Abbreviations

ACH	air changes per hour
HVAC	heating, ventilation, and air conditioning
PCM	phase change material
SAP	standard assessment procedure
TES	thermal energy storage
WWR	window-to-wall ratio

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