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Marine Auzeby, Shen Wei, Chris Underwood, Jess Tindall, Chao Chen, Haoshu Ling, Richard Buswell

Date Submitted: 2019-01-07

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DOI of Published Version: https://doi.org/10.3390/en9080605 *energies*

Article

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Marine Auzeby [1,2], Shen Wei [2,*], Chris Underwood [2], Jess Tindall [2], Chao Chen [3], Haoshu Ling [3] and Richard Buswell [4]

1. Civil Engineering and Urban Planning Department, Institut National des Sciences Appliquées de Lyon, Villeurbanne F-69621, France; marine.auzeby@northumbria.ac.uk
2. Faculty of Engineering and Environment, Newcastle Upon Tyne NE1 8ST, UK; chris.underwood@northumbria.ac.uk (C.U.); jess.tindall@northumbria.ac.uk (J.T.)
3. College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China; chenchao@bjut.edu.cn (C.C.); linghaoshu@163.com (H.L.)
4. School of Civil and Building Engineering, Loughborough University, Loughborough LE11 3TU, UK; r.a.buswell@lboro.ac.uk

* Correspondence: shen.wei@northumbria.ac.uk; Tel.: +44-191-3495374

Academic Editor: Chi-Ming Lai
Received: 19 June 2016; Accepted: 28 July 2016; Published: 1 August 2016

Abstract: The UK is currently suffering great overheating issues in summer, especially in residential buildings where no air-conditioning has been installed. This overheating will seriously affect people's comfort and even health, especially for elderly people. Phase change materials (PCMs) have been considered as a useful passive method, which absorb excessive heat when the room is hot and release the stored heat when the room is cool. This research has adopted a simulation method in DesignBuilder to evaluate the effectiveness of using PCMs to reduce the overheating issues in UK residential applications and has analyzed potential factors that will influence the effectiveness of overheating. The factors include environment-related (location of the building, global warming/climate change) and construction-related (location of the PCM, insulation, heavyweight/lightweight construction). This research provides useful evidence about using PCMs in UK residential applications and the results are helpful for architects and engineers to decide when and where to use PCMs in buildings to maintain a low carbon lifestyle.

Keywords: phase change material (PCM); thermal storage; overheating; residential buildings

1. Introduction

Residential buildings in the UK can occasionally suffer serious overheating issues in the summer time, as most of them have no mechanical cooling installed [1]. This problem is not new but is increasing nowadays for several reasons: Firstly, due to the climate change, heat waves during summer are increasing the number of deaths especially among the elderly (high outdoor temperature are causing nearly 2000 death per year in the UK [2]). Secondly, by trying to refurbish old dwellings to have better thermal performance in winter, the risk of overheating in summer becomes higher. Thirdly, nowadays the population expectations for comfort are increasing too, especially with the use of air-conditioning which has become more common in non-domestic buildings [2]. This problem significantly influences people's comfort and health [3]. In order to reduce the overheating problem while retaining low carbon lifestyles, a sustainable solution is required.

Phase change materials (PCMs) have been acknowledged as an efficient solution for moderating indoor temperature variations, i.e., making the peak value lower and the minimum value higher. The specific properties of PCM make it possible to store/release a high quantity of latent heat during the phase change at constant material temperature in various applications [4], and energy efficient buildings have been considered as one of the main applications of it [5–7].

According to a number of sources [8–10], PCMs could be used either inside building structures, or as a part of the cooling or heating systems. PCMs can efficiently capture the cold energy during the nighttime in summer and reduce the fluctuation of indoor temperature by 4 °C [11,12].

Regarding its usage in residential applications, researchers in Australia have explored the use of PCMs as a passive way of reducing overheating risks in various climatic zones, such as those carried out by Alam et al. [13] and Ascione et al. [14]. Those studies have linked the effectiveness of passive heat exchange to the outdoor climatic conditions. Additionally, studies carried out in other countries have also built links between the effectiveness of the PCMs with the construction features and building properties, showing the impact of adding them to the building structure. According to Voelker et al. [15] the utilization of PCM could increase the thermal mass of the house and so consequently improve the thermal protection in summer up to a 4 °C reduction of the peak indoor temperature. Similar results were found in Portugal where a study has demonstrated that using PCM could enhance the thermal inertia of the house and so reduce the amplitude of the indoor temperature variation and increase the comfort level [16]. In Cyprus, the addition of a 0.15 m thick layer of PCM helped decrease the summer mean indoor temperature of 1.7 °C [17]. For Seong et al. [18] different kinds of PCMs were especially added to lightweight buildings and used with night ventilation to decrease the indoor air temperature of up to 0.85 °C during the summer time.

Based on the above review results, it is concluded that PCMs could be a suitable low carbon solution for the current overheating issues in UK residential buildings, reducing the need of installing mechanical cooling systems. However, questions arise, such as how efficient this solution might be to adjusting indoor temperature and what factors may influence its effectiveness. Therefore, this research has sought to address these two questions, based on the use of a dynamic building performance simulation tool. The results presented in this paper are designed to help architects, engineers and planners to make decisions about whether they should install PCMs to deal with overheating in a warming climate, while retaining a low carbon lifestyle.

2. Methodology

2.1. Case Study Building

The case study building chosen is a typical UK mid-terraced dwelling (Figure 1a), which represents 30% of the current house building stock in the UK [19]. The dwelling has two floors, and the front of the property faces north. On the ground floor, there is a living room and a kitchen, and on the first floor there are two bedrooms and a bathroom. There is a back door in the kitchen, linking the dwelling to its back yard. This room composition with corresponding sizes has been depicted in Figure 1c. All casement windows in the house have a fixed lower section with the upper part opening. The opening area has been estimated to be 30% of the total area of the upper part. There is no fixed shading on the windows but internal blinds can be used as a way to control the indoor environment or increase privacy.

2.2. Building Performance Simulation

In this study, DesignBuilder [20] has been adopted to predict the performance of the building under various simulation scenarios. DesignBuilder provides a comprehensive user interface of EnergyPlus [21], which is a widely used simulation engine developed by the Department of Energy (DOE) in the USA. Due to its popularity, the thermal modeling using EnergyPlus has been validated under various applications, as described in the BestTest Report [22]. In EnergyPlus, PCM can be modeled as a separate layer of material and then attached to any construction components within the building. This function of EnergyPlus has been used in some existing studies [23,24] where its applicability for this study was demonstrated. To further validate its suitability for the PCM used in this study, further validation has been carried out in this work. Field measured data (both indoor and outdoor data) were collected from a greenhouse (with a length of 27.0 m, a width of 5.8 m and a height of 2.3 m) located in Beijing, China. Figure 2 shows both the predicted air temperature by EnergyPlus and the field measured temperature in the greenhouse (maximum error: 2.6 °C; mean error: 0.1 °C; standard deviation: 0.7 °C) [25]. The version of DesignBuilder used in this study is V4.2, which adopts EnergyPlus 8.1 as the engine for thermal dynamic simulations. The same as in EnergyPlus, in DesignBuilder, PCMs can be modeled using some general thermal properties, e.g., thickness, conductivity and density, with some specific properties, i.e., the material temperature-enthalpy curve.

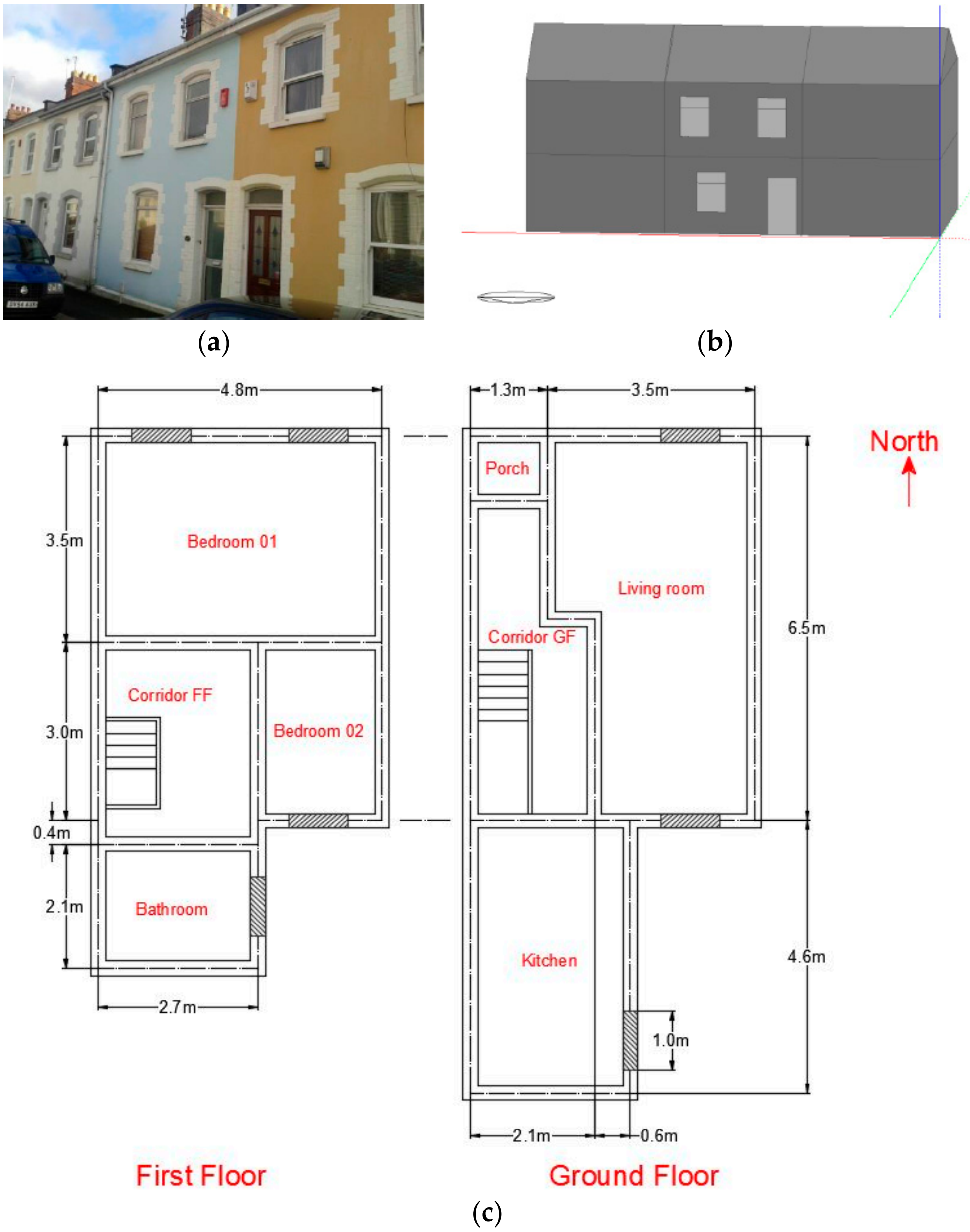

Figure 1. Case study building and the simulation model in DesignBuilder.

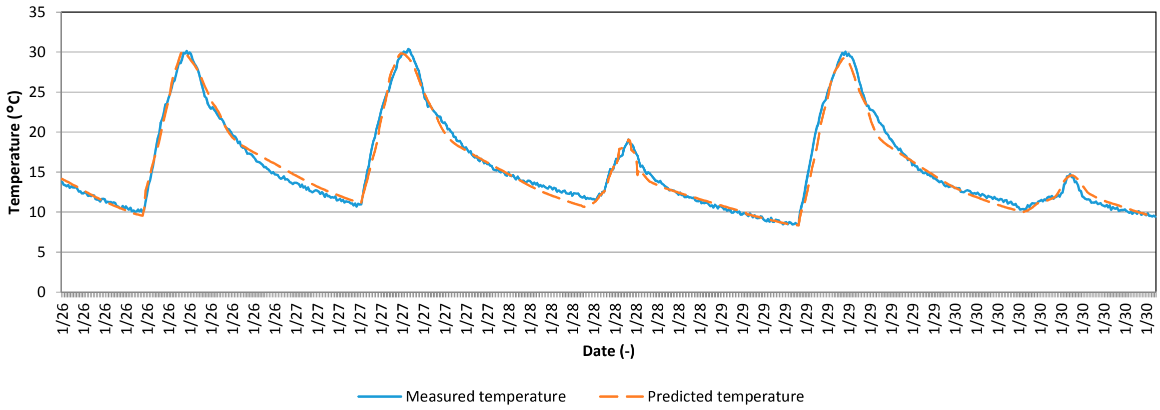

Figure 2. EnergyPlus phase change material (PCM) validation results using real measured data.

2.2.1. Construction Settings

The model built for the case study building in DesignBuilder is shown in Figure 1b. The building is over 100 years old and no substantial retrofit has been carried out to promote its air tightness. Therefore, the infiltration level was set at 1 ac/h for the simulation, as suggested by the chartered institution of building services engineers (CIBSE): Guide A on Page 163 [26]. Table 1 below has listed the building construction materials forming the main building components, with the corresponding *U*-values.

Table 1. Thermal property definitions of building construction.

Construction	Name of the Material	Thickness (m)	λ (W/mK)	C_p (J/kgK)	ρ (kg/m^3)
External walls (*U*-value 1.580 W/m^{2}K)	Brickwork 1	0.100	0.84	800	1700
	Air gap	0.100	-	-	-
	Brickwork 2	0.100	0.62	800	1700
	Gypsum plastering	0.013	0.40	1000	1000
Partitions (*U*-value 1.923 W/m^{2}K)	Gypsum plasterboard	0.025	0.25	1000	900
	Air gap	0.100	-	-	-
	Gypsum plasterboard	0.025	0.25	1000	900
Ceiling element (*U*-value 3.106 W/m^{2}K)	Gypsum plastering	0.013	0.25	1000	900
Floor (*U*-value 2.574 W/m^{2}K)	Floor blocks	0.25	0.14	1200	650
Ground floor (*U*-value 1.463 W/m^{2}K)	Cast concrete	0.100	1.13	1000	2000
	Screed	0.070	0.41	840	1200
	Timber flooring	0.030	0.14	1200	650
Roof (*U*-value 0.372 W/m^{2}K)	Clay tile	0.025	1.00	800	2000
	Stone wool	0.100	0.40	840	30
	Roofing felt	0.005	0.19	837	960

A calibration of the model based on these definitions and assumed behavioral patterns (e.g., 22 °C temperature settings and windows kept open for ventilation purposes) has been carried out. This compared the model's prediction results to the Energy Performance Certificate (EPC) rating are needed whenever a property is built, sold or rented. The EPC contains: Information about a property's energy use and typical energy costs, recommendations about how to reduce energy use and save money. The EPC indicates the building's energy efficiency on a scale ranging from A for the most efficient to G for the least efficient and is valid for 10 years of the building and an acceptable variation has been confirmed. Note that with an EPC rating of D, the average UK home consumes about 20,500 kWh per year for space heating, and the predicted annual energy heating consumption for the model is 22,562 kWh, with an error of 10%, as described by Wei et al. [27]. Therefore, the model is suitable for this study. As the case study building is a mid-terraced one, the two dwellings by its sides have been assigned as adiabatic blocks in the simulation. In DesignBuilder, an adiabatic block is considered to have no heat transfer with the simulation model during the whole simulation prediction process [28]. This assumption is acceptable as these two dwellings are occupied.

2.2.2. Behaviour Settings

In this study, in order to reflect the worst case condition regarding overheating in summer, the house was assumed to be occupied by an elderly couple (note: this is not the same as the condition defined for the model calibration). This implies that the house would always be occupied during the simulation period. Additionally, elderly people are more vulnerable to the effects of overheating with consequences that can be detrimental to health. Table 2 has listed some reasonable occupancy profiles for each room, activities and equipment usage, which were used to drive the later simulation work. Internal heat gains have been defined in two main categories; people and equipment. For the heat gain from people, values suggested by CIBSE Guide A [26] were used. The existence of this gain was directly linked with the occupancy of each room as defined in Table 2. For the heat gain from equipment, suggested empirical values from CIBSE Guide A were adopted, as defined in Table 2, which represent equipment heat gain as an average value per unit room area. The existence of this gain was also directly linked with the occupancy, with one exception for the bedroom (no equipment gain was assumed between 24:00 and 07:00 + 1 when the occupants were sleeping). In the base case model, no ventilation/air-conditioning, except infiltration, has been considered to produce a worst case scenario for overheating analysis, as well as with an assumption of no blind usage for shading purpose.

Table 2. Occupancy settings for the base case model.

Room Type	Bathroom	Bedroom 1	Bedroom 2	Corridors	Kitchen	Living Room
Activity (W/person)	Standing relaxed (126)	Sleeping (72)	Sleeping (72)	Standing walking (133)	Cooking (180)	Lecture (115)
Occupancy profiles	Until: 07:00, 0 Until: 08:00, 0.5 Until: 19:00, 0 Until: 20:00, 0.5 Until: 24:00, 0	Until: 07:00, 1 Until: 23:00, 0 Until: 24:00, 1	Until: 24:00, 0	Until: 24:00, 0	Until: 08:00, 0 Until: 09:00, 1 Until: 12:00, 0 Until: 13:00, 1 Until: 17:00, 0 Until: 18:00, 1 Until: 24:00, 0	Until: 10:00, 0 Until: 12:00, 1 Until: 13:00, 0 Until: 17:00, 1 Until: 18:00, 0 Until: 23:00, 1 Until: 24:00, 0
Equipment heat gains (W/m^2)	15	0	0	0	45	20

2.2.3. Weather Data

Two sets of weather data have been used in the study. The first was obtained at a real weather station located in Nottinghamshire at the East Midlands of England. The second set of data was from the Prometheus Project [29], from which a series of design summer years (DSY) forming weather data usable by EnergyPlus/DesignBuilder have been developed. The files extracted include those for both current design applications (mean temperature between years 1961 and 1990) and future applications (predicted weather data for years 2030, 2050 and 2080). In the analysis carried out later, the former data were used as the main weather data. However, due to the lack of current data at other locations within the UK and also the data in the future, the Prometheus project data were adopted when analyzing the influence from climatic parameters (Section 3.2). Additionally, the month of July has been chosen for the study as it was found to be the hottest month of the year from the real measured data, so it was considered as the most suitable for summer overheating analysis. Additionally, July is also an official reference month for summer weather data in the UK [30].

The Nottingham dataset was monitored at Sutton Bonnington (Nottinghamshire, UK) in 2013, after the UK had started to suffer regular overheating in summer. Figure 3 displays two sets of temperature data between 1 and 31 July. One of these is the recently measured weather data at Sutton Bonnington (regarded as the current weather data), and the other is the mean temperature data measured at Watnall (Nottinghamshire), between 1961 and 1990. The latter is regarded as historical weather data, and is accessible from the Prometheus project official webpage [29]. Both Sutton Bonnington and Watnall are located at a rural site on the west side of Nottinghamshire (12 and 18 miles from the city center, respectively) and separated by approximately 15 miles.

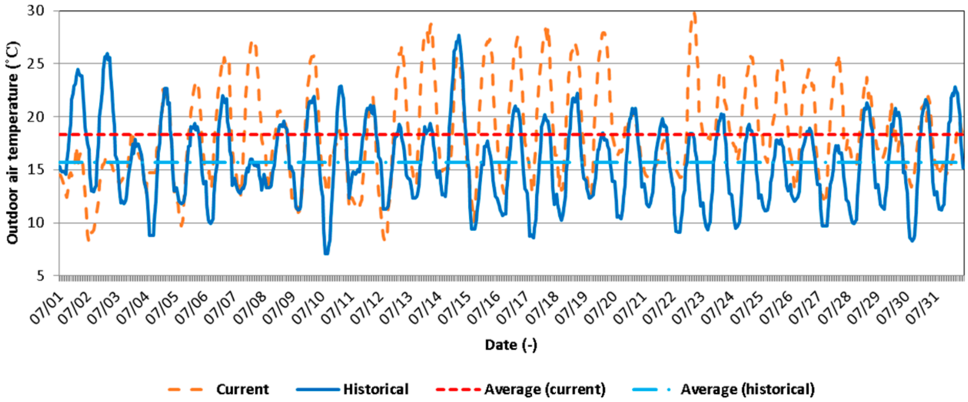

Figure 3. Outdoor air temperature in July—a comparison between current and historical data.

The comparison in Figure 3 shows that high temperatures (above 25 °C) are more frequent recently than before. This is for the mean temperature as well (the current mean temperature is 2.6 °C higher than historical), which means that the summer is much hotter now.

2.3. Experimental Phase Change Material

The PCM used in this study was developed by a partner at the Beijing University of Technology (BJUT) [31], so it is denoted as "BJUT PCM" in this paper. This type of PCM was developed for building applications, a shape-stabilized solid-liquid PCM composed of paraffin encapsulated by high density polyethylene (HDPE). This type of PCM has been successfully integrated into building fabrics and showed good performance on both promoting the thermal storage of the fabric and increasing its thermal insulation [25,32,33].

Table 3 lists some main thermal properties of the BJUT PCM and Table 4 provides its enthalpy at various temperature conditions, as reported by Chen et al. [34], with major phase changing temperatures ranging between 23.1 °C and 24.0 °C. These properties have been used to define the PCM layer in the later dynamic building performance simulation.

Table 3. Beijing University of Technology (BJUT) PCM characteristics.

Characteristics	BJUT PCM	Unit
Roughness	Rough	-
Thickness	0.2	m
λ	0.5	W/mK
ρ	900	kg/m^3
C_p	2900	J/kgK
Thermal absorbance	0.9	-
Solar absorbance	0.68	-
Visible absorbance	0.68	-

Table 4. Temperature/Enthalpy relation for the BJUT PCM.

Temperature (°C)	Enthalpy (J/kg)	Temperature (°C)	Enthalpy (J/kg)
0.0	0	20.2	70,226
7.2	10,214	22.4	73,789
8.7	13,112	23.1	77,214
10.8	18,981	24.0	86,265
15.9	42,684	25.1	92,638
17.3	52,504	25.9	95,029
18.3	61,502	31.1	104,936
19.4	68,778	41.2	122,873

As described above, the PCM panel used in the study was 0.2 m thick and it was mainly attached to the inner surface of all external walls of the building. However, in Section 3.3.1, when evaluating the impact from placement locations within the house, it was also attached to the ceiling, internal walls, roof and floors.

3. Results

The results of this study are used to answer the two main research questions raised above, i.e.,

(1) how effective is PCM in overcoming current UK residential overheating in summer; and
(2) what factors may influence its effectiveness. For this purpose, the following analysis has been split into three sub-sections.

Section 3.1 demonstrates the potential contribution of PCMs in reducing the current overheating risks in UK residential buildings, using the case study building and the field measured weather data at Sutton Bonnington, in July 2013. Then Sections 3.2 and 3.3 provide analysis of potential factors that have been grouped into two categories; climatic parameters (Section 3.2) and building-related parameters (Section 3.3).

3.1. Contribution of Phase Change Material in Reducing UK Residential Overheating Issues

Figure 4 depicts the predicted indoor air temperature for the case study building with and without PCM applied to the inner surface of all external walls (including those between houses), using the weather data measured at Sutton Bonnington (Nottinghamshire) between 1 and 31 July 2013. The solid orange line in the figure indicates the maximum indoor comfort temperature (i.e., 25 °C), and the red line defines the overheating temperature (i.e., 28 °C), both suggested in CIBSE Guide A [26]. The comparison clearly shows that PCM contributed greatly to reducing the overheating risk in the building as the frequency of high indoor temperature conditions has been reduced (31% versus 16% for 25 °C). Figure 4 suitably reflects how the heat storage characteristic of PCM helps to confine the change of indoor air temperature within a narrower range.

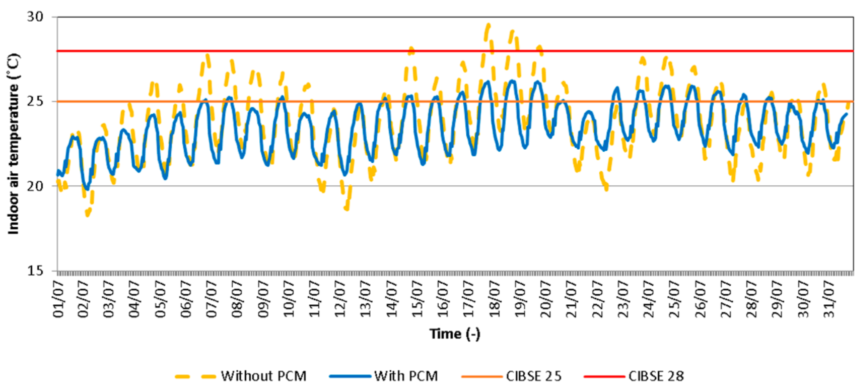

Figure 4. Predicted indoor air temperature for the case study model with and without PCM.

Figure 5 reflects the effect of narrowing indoor temperature change on the indoor thermal environment. It clearly reflects that, with PCM, the frequency of temperature above 23 °C becomes less as PCM was absorbing heat to avoid overheating, while the frequency of temperature below 23 °C becomes more as PCM was releasing absorbed heat to avoid overcooling.

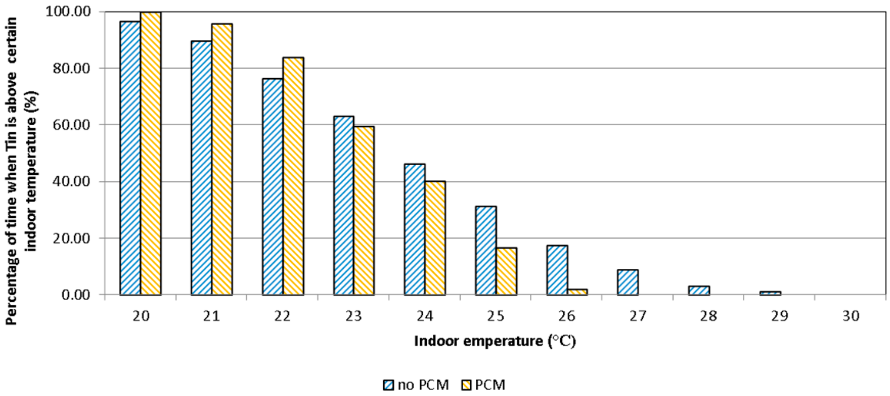

Figure 5. Predicted indoor air temperature for the case study model with and without PCM.

3.2. Climatic Parameters

After confirming the positive contribution of PCM in reducing indoor overheating issues of UK residential buildings, this section evaluates the impact of two factors that affect the outdoor climatic conditions of the building. Specifically, these are the geographical location within the UK and the impact of climate change/global warming.

3.2.1. Geographical Location within the UK

Although the UK is not as big as China or the US, there is still a difference at various locations with respect to outdoor climatic conditions. Therefore, it is important to justify whether PCM is currently needed in all parts of the UK or only some warmer parts. The conclusion obtained from this analysis will help to decide whether the implementation of PCM in UK residential buildings needs to be considered as a national priority or can be planned more gradually dependent on the geographical location of the building. When evaluating the influence from this factor, three locations have been chosen to drive the simulation, and they were Aberdeen (57°15′ N), Newcastle (54°93′ N) and Southampton (50°54′ N). They are typical cities in the northern, middle and southern parts of the UK, respectively, and, as can be seen in Figure 6, belong to different summer mean temperature ranges in the UK. The weather data used in this section were downloaded from the Prometheus project official webpage [29], as they provide a comprehensive number of weather data around the whole UK. The data chosen for this analysis were those measured between 1961 and 1990, which were developed for current design applications.

Figure 7 compares the predicted indoor air temperatures when placing the case study building without PCM at the above three locations respectively. From the comparison, it clearly shows that overheating is much more serious at Southampton than at Aberdeen. However, at Aberdeen, there are still some cases when the indoor air temperature is going beyond the indoor maximum comfort temperature (i.e., 25 °C), which would cause thermal discomfort. However, the frequency was not very high so the overheating issue in the northern part of the UK may be solved by other passive cooling techniques such as natural ventilation, which requires no cost (or a much lower cost than PCM).

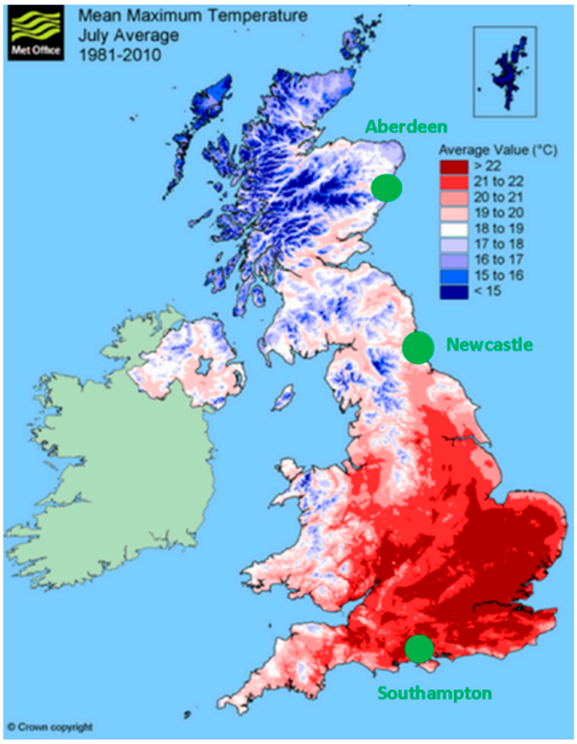

Figure 6. Mean UK maximum outdoor temperature in July between 1961 and 2010 [30].

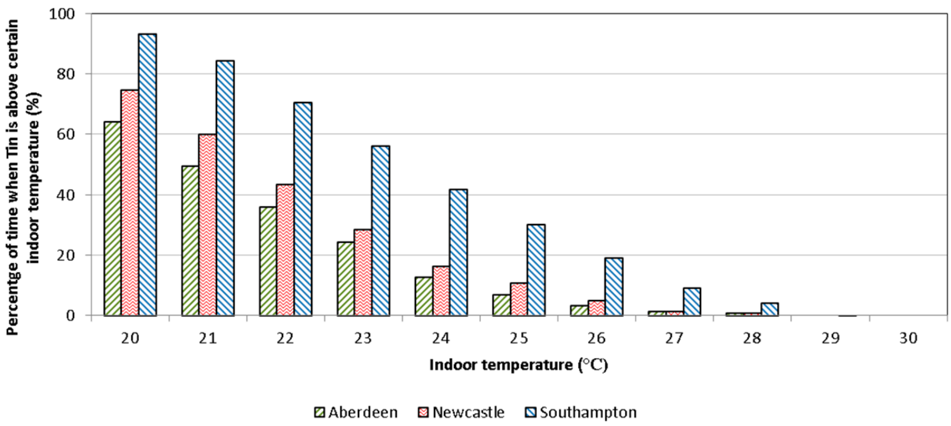

Figure 7. Predicted indoor air temperatures at three different locations within the UK.

3.2.2. Climate Change/Global Warming

The analysis above reflects that some cities in the UK may not currently need PCMs to address the overheating issue. However, due to climate change/global warming, it is anticipated that the local climate for those cities will be increasingly hotter in the coming decades. This section, therefore, has analyzed the impact of climate change/global warming on the house indoor thermal environment in the future and pointed out its contribution to the requirement of PCMs. The weather data used here were also downloaded from the Prometheus project official webpage [29], and Aberdeen was chosen for this analysis as it is the coolest among the above three cities.

Figure 8 shows the predicted indoor air temperatures when placing the case study building at Aberdeen under both current and future climate conditions. It clearly reflects that overheating will not become a serious issue for this city until sometime between 2030 and 2050, as there will be a big jump during this period regarding the indoor air temperature. Therefore, although PCM may not be needed currently for houses in Aberdeen, it will be needed at some time between 2030 and 2050.

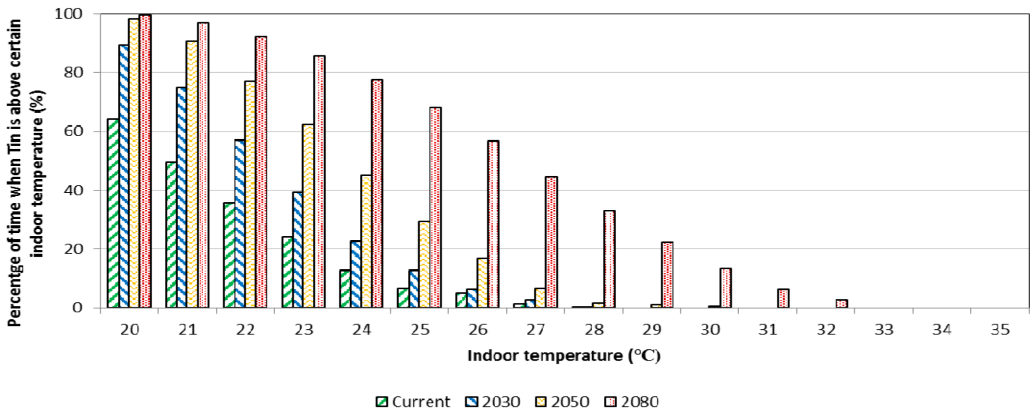

Figure 8. Predicted indoor air temperatures in Aberdeen with a consideration of climate change/global warming without PCM.

Figure 9 shows the potential contribution of PCM to reducing overheating risks in 2050, by which time a significant increase in indoor air temperature is predicted to have happened. The analysis focused on conditions with temperature beyond the maximum indoor thermal comfort temperature, where thermal discomfort happens. It shows that the highest temperature above the 25 °C limit has been significantly reduced by the PCM to an acceptable level with no more than 10% of temperature above it for the whole month.

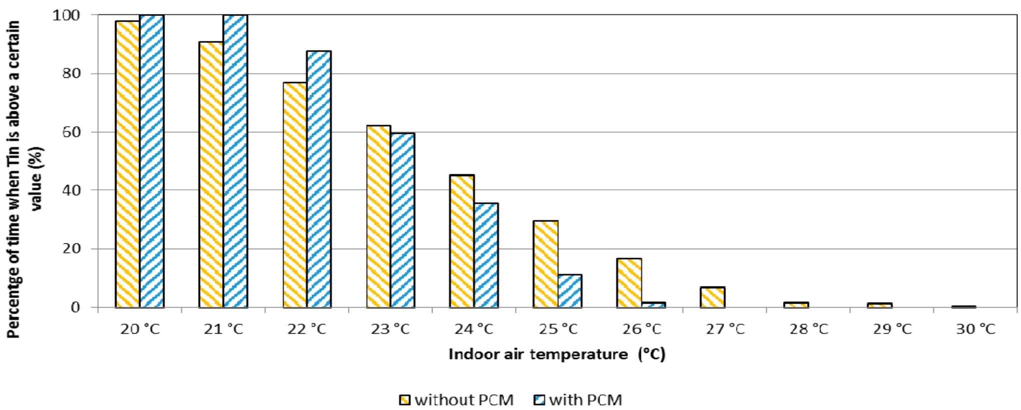

Figure 9. Predicted contribution of PCM in Aberdeen for 2050.

3.3. Building-Related Parameters

Besides outdoor climatic conditions, many building-related parameters (e.g., *U*-value, and building thermal capacity) may also influence the thermal performance of a building. This section, therefore, analyzed their influences on the PCM performance. The analysis was composed of three parts:

(1) the location within the building where the PCM layer is added to;
(2) various insulation levels of the external façade; and
(3) whether the structure type is lightweight or heavyweight. In the following analysis, the weather data measured at Sutton Bonnington (Nottinghamshire) was used, as it reflects the current summer condition in the UK (at the East Midlands).

3.3.1. Placement Location of the Phase Change Material inside the Building

Various locations inside the building may result in different PCM performance due to variations in the available area for PCM placement, zonal temperatures and heat gains from both internal sources (due to heat convection) and external conditions (due to both solar radiation and heat conduction). To evaluate this influence, the PCM was attached to the inner surfaces of various construction components sequentially, including external walls, internal partitions, ceiling, floors and the roof of the house. The indoor thermal environment under these various scenarios was then compared.

The predicted indoor thermal environment under the above scenarios has been depicted and compared in Figure 10. The comparison reflects that putting PCM onto external walls and partition walls performed much better compared with the other options, as the maximum indoor temperature reached is lower than in the other cases. That result may come from a combinational effect of several factors, e.g., the zonal temperature condition around each component and the available surface area of each component, and a more in-depth analysis would be needed to have a better understanding on the individual influences of those parameters.

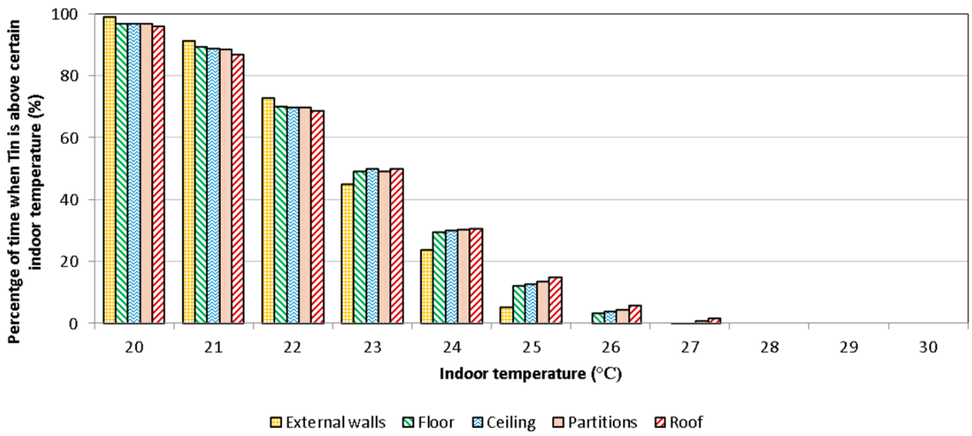

Figure 10. Influence from the location inside the building for July month.

3.3.2. Thermal Insulation of External Façade (*U*-Value)

Buildings are mainly used to separate indoor environment and outdoor environment so a thermally stable and comfortable indoor living space can be provided. Therefore, the thermal insulation of the external façade may well influence the indoor thermal environment and, hence, influence the performance of the PCM. This section analyzed the impact of this parameter by giving two different levels of thermal insulation (i.e., low and high) to the building external fabric and identified the influence on the PCM.

The approved document L1B for conservation of fuel and power [35] has provided the maximum *U*-value of 0.7 $W/(m^2K)$ for UK refurbished buildings but has also recommended an ideal value close to 0.3 $W/(m^2K)$ in the case of insulated external walls. The base model was considered as the low level of insulation while the insulated model described in Table 5 is considered as the highly insulated one as it follows the L1B document prescriptions. The insulation material chosen is made of glass fiber, and its thickness is made to be as close as possible to the recommended *U*-value for the wall.

Figure 11 compares the predicted indoor air temperature of the case study building under the three scenarios: low insulation, high insulation and high insulation with PCM. It clearly shows that well insulated houses will result in a more serious overheating issue, although it may greatly help to reduce the energy used to heat the house in winter [27]. Therefore, a well-insulated building will need PCM more than a poor-insulated one. The contribution of PCM can be found by the last column of data shown in Figure 11 (the overheating reduction is nearly 20% for 25 °C between the insulation alone and the insulation with PCM).

Table 5. Definitions of uninsulated and insulated building external wall.

Construction	Name of the Material	Thickness (m)	λ (W/mK)	C_p (J/kgK)	ρ (kg/m^3)
External walls–Low Insulation (U-value = 1.580 W/m^{2}K)	Brickwork 1	0.100	0.84	800	1700
	Air gap	0.100	-	-	-
	Brickwork 2	0.100	0.62	800	1700
	Gypsum plastering	0.013	0.40	1000	1000
External walls–High Insulation (U-value = 0.287 W/m^{2}K)	Brickwork 1	0.100	0.84	800	1700
	Air gap	0.100	-	-	-
	Brickwork 2	0.100	0.62	800	1700
	Gypsum plastering	0.013	0.40	1000	1000
	Glass fibre slab	0.100	0.035	1000	25

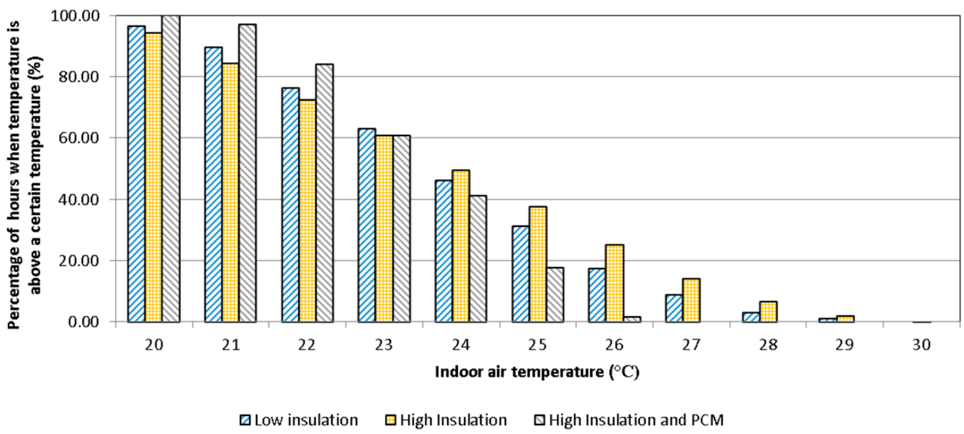

Figure 11. Predicted indoor air temperatures with a consideration of the level of insulation for July month.

3.3.3. Lightweight and Heavyweight Building

"Lightweight" buildings are those with low thermal storage capacity inherent in their construction, comparing to "heavyweight" buildings [36,37]. Implementing PCM in buildings increases the building's thermal storage capacity, so making a "lightweight" building closer to a "heavyweight" one. Therefore, if the building is already a "heavyweight", adding PCM may not be as helpful as for a lightweight building. The analysis in this section attempts to demonstrate the difference.

DesignBuilder has provided usable definitions for lightweight and heavyweight buildings [20] so these definitions have been adopted in this study. The construction templates proposed by DesignBuilder are part of the ASHRAE 90.1-2007 [38] and the heavyweight and lightweight definitions are presented for early design of the buildings. Considering the influence from the building insulation, the uninsulated model has been used for both scenarios. The construction specifications are detailed in Table 6.

Table 6. Description of the materials used in lightweight and heavyweight models.

Construction	Name of the Material	Thickness (m)	λ (W/mK)	C_p (J/kgK)	ρ (kg/m^3)
Lightweight-External Walls	Metallic cladding	0.006	0.29	1000	1250
	Air gap	0.050	-	-	-
	Gypsum plastering	0.013	0.40	1000	1000
Heavyweight-External Walls	Brickwork	0.105	0.84	800	1700
	Air gap	0.050	-	-	-
	Concrete	0.100	0.51	1000	1400
	Gypsum plastering	0.013	0.40	1000	1000

Heavyweight and lightweight buildings can be distinguished using a thermal time constant. Figure 12 depicts the answer of lightweight, heavyweight and the base case model to an exterior surface step of temperature (from 0 °C to 30 °C). The time constant of the model is calculated according to Hagentoft [39] as the time required to reach 63% of the indoor temperature change.

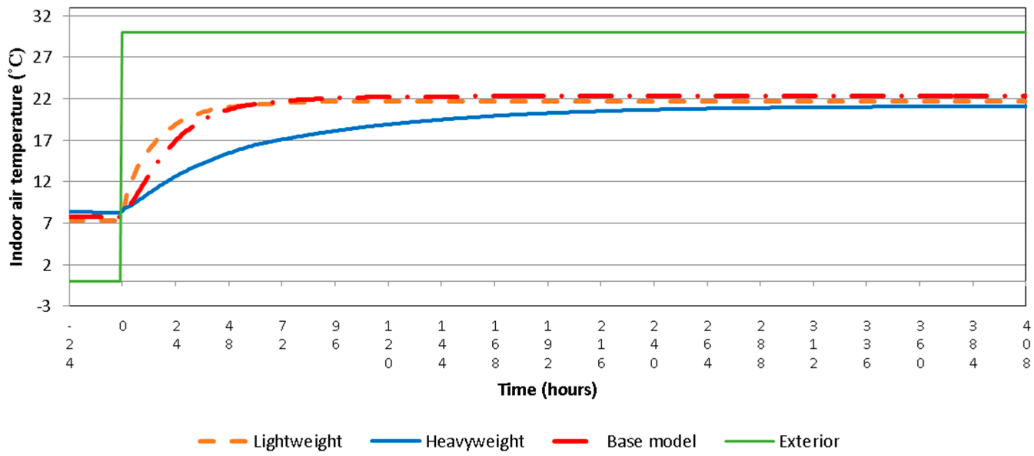

Figure 12. Indoor air temperature for determination of the Thermal Time Constant.

According to the prediction results, the heavyweight construction template had a thermal time constant more than 4 times higher than the lightweight one, highlighting the difference in behavior for the two construction types (Lightweight model: 14 h; Heavyweight model: 61 h and Base case model: 25 h). Concerning the base case model, its time constant shows that it performs somewhere between the two extreme models, but its similarity to the lightweight model justifies the requirement of suitable PCM.

Figures 13 and 14 show the results predicted for both lightweight and heavyweight constructions, with and without PCMs. As expected, the lightweight building tends to suffer more from overheating with a difference between maximum and minimum indoor air temperature of 14.5 °C, while that difference is only of 8.5 °C for the "heavyweight" construction. According to the contribution of PCM to the overheating reduction, the mean difference between the daily peak temperatures (the average value of peak temperature difference for each simulation day) for a building with and without PCM has been determined. From the data shown in Figures 13 and 14, the mean difference between the daily peak temperatures for the "heavyweight" building is 0.74 °C, while it is 0.16 °C for the "heavyweight" building. This confirms that PCMs are more effective in reducing overheating in lightweight buildings than in heavyweight buildings.

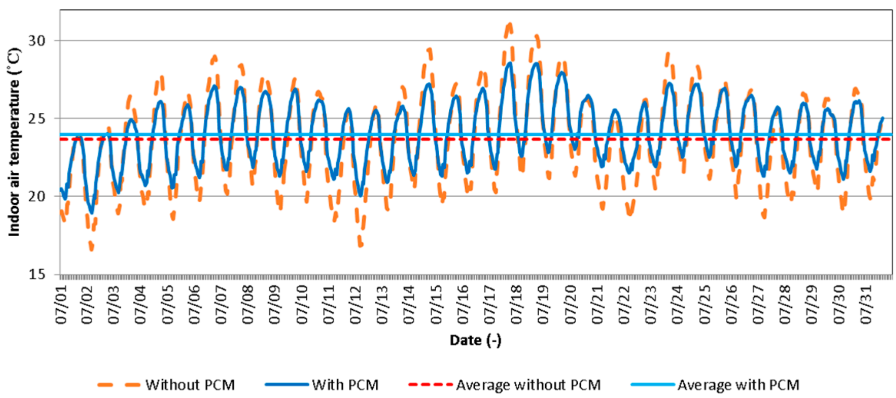

Figure 13. Predicted indoor air temperatures for a "lightweight" construction.

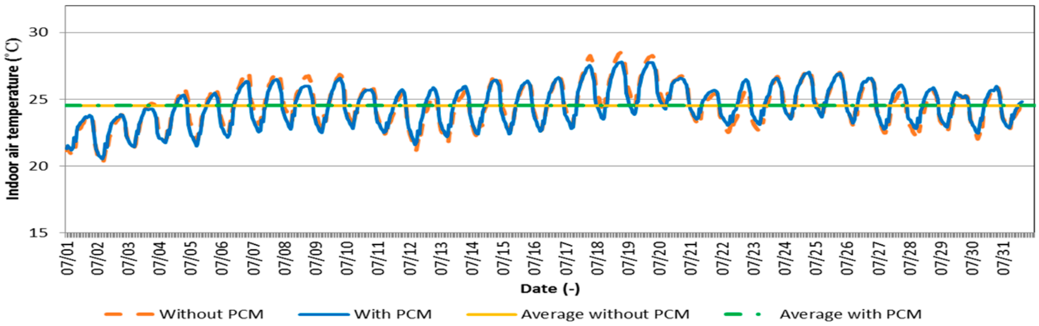

Figure 14. Predicted indoor air temperatures for a "heavyweight"construction.

4. Conclusions

Residential buildings in the UK frequently suffer from summer overheating which is especially problematical when residents are elderly, disabled or very young. With a consideration of low carbon lifestyles, a passive method to reduce this problem, rather than using air-conditioning, has been explored in this paper. The focus was on the use of structurally-integrated PCM. This study applied a dynamic building performance simulation to a typical UK mid-terraced house: (1) demonstrated the contribution of PCMs to reducing overheating risks; and (2) identified potential factors that will influence its effectiveness. From the simulation results, the following conclusions can be drawn:

- Results show that the PCM has a significant impact in mitigating overheating in UK residential buildings.
- The impact on reducing overheating depends on prevailing weather patterns (i.e., geographical location).
- Due to the climatic change/global warming, PCMs will benefit all UK regions, even for those not experiencing severe overheating issues now.
- Placement of PCMs affects their performance but the reasons for this need further exploration.
- Building thermal insulation may also influence the need of PCMs, and well-insulated houses need PCMs more than those poor-insulated ones.
- Installing PCMs is mainly to increase the thermal mass of the house so 'lightweight' buildings enjoy a greater benefit from the use of PCMs than "heavyweight" buildings.

This study treated building occupants as passive objects as no adaptive actions that can also influence people's thermal perception has been considered, e.g., opening windows to increase ventilation, or adjusting clothing insulation to adjust thermal sensation. By doing this the contribution of PCMs to adjusting the indoor thermal environment has been maximized. However, other passive methods, especially occupants' adaptive actions, will also help to decrease the residential overheating risks and future studies should consider them as suitable measures as well.

It is expected that the results described in this paper will help UK building stakeholders (i.e., architects, engineers, policy-makers and building owners) decide on best strategies for the use of this promising new class of materials to alleviate summer overheating in a sustainable way.

Author Contributions: Marine Auzeby, Shen Wei, Chris Underwood and Jess Tindall conceived and designed the experiments and analysed the data. Chao Chen and Haoshu Ling provided data of BJUT PCM and carried out the validation work of modelling PCM in EnergyPlus/DesignBuilder. Richard Buswell provided field measured climatic data at Nottinghamshire and got involved in the analysis of parts linked with that data.

Conflicts of Interest: The authors declare no conflict of interest.

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