Analysis of Incorporating a Phase Change Material in a Roof for the Thermal Management of School Buildings in Hot-Humid Climates

Ruey-Lung Hwang, Bi-Lian Chen and Wei-An Chen

Department of Industrial Technology Education, National Kaohsiung Normal University, Kaohsiung 82444, Taiwan; rueylung@nknu.edu.tw (R.-L.H.); ant88313@gmail.com (B.-L.C.)
* Correspondence: B0522@mail.nknu.edu.tw or vivian199038@gmail.com

Abstract: Strategies to reduce energy consumption are presently experiencing vigorous development. Phase change materials (PCMs) are novel materials that can reduce indoor temperatures via the change in material phase. Regarding the situation in Taiwan, there is no practical utilization of PCMs in school buildings at present, especially in combination with rooftops. In this paper, we discuss the feasibility and utilization potential of installing PCMs in the rooftops of school buildings. School buildings located in northern and southern Taiwan (Taipei and Kaohsiung) were selected to analyze the energy-saving potential and optimization of indoor thermal comfort by installing PCMs with different properties in rooftops over two time periods, including the air conditioning (AC) and natural ventilation (NV) seasons. Based on the simulation results, the feasible patterns of PCM simultaneity are found to be appropriate for improved indoor comfort and energy saving during the different seasons. Specifically, the efficient phase change temperature (PCT) for different PCM thicknesses is clarified to be 29 °C. The economic thickness of PCM was clarified to be 20 mm for Taipei and Kaohsiung. Through the recommendations proposed in this study, it is expected that the PCMs may be efficiently implemented in school buildings to realize the goal of energy conservation and improve thermal comfort.

Keywords: phase change materials; hybrid ventilated school building; indoor thermal comfort; thermal management; energy conservation

1. Introduction

When considering the heat insulation of buildings, the great amount of heat gain from façades and rooftops cannot be neglected. Previous studies attempted to explore various materials and techniques for improving the heat insulation of building envelopes or structures and discuss opportunities and challenges. Furthermore, researchers have suggested feasible utilization strategies [1,2]. Roofs are exposed to direct sunlight for a long period of time and thereby significantly influence the energy consumption of a building when controlling the resulting indoor temperature, especially in hot climate areas, such as Taiwan. One of the most common measures for reducing roof heat gain is to reduce the overall heat transfer coefficient, i.e., the U-value, by adding insulative materials. Phase change materials (PCMs) allow incidental heat gain to be used to change the phase of the material and thus perform heat storage, and such materials may store a significant amount of thermal energy. PCMs are considered to be an innovative technology and an effective method for improving the thermal mass of buildings, owing to the large thermal capacity within a limited temperature range, which is similar to an isothermal energy tank [3]. Incorporating PCMs into roofs can significantly enhance the heat storage ability of a structure and disperse the heat gains from the peak hours of cooling demand, consequently reducing energy consumption and improving indoor thermal comfort.
Most of the previous studies focused on the use of PCMs have primarily considered walls and have neglected the potential for roofs, even though roofs represent significant heat gain. Although most attention has been paid to the installation of PCMs in walls, the ratio of studies discussing PCMs in roofs to those in walls is approximately 1:3 [4]; however, some studies have used experimental or numerical simulation methods to investigate the energy-saving potential of installing PCMs in roofs or floors to discuss the performance of heating systems [5–7]. Studies related to the installation of PCMs can be divided into two types, including reducing energy consumption in air-conditioned buildings and improving thermal comfort in non-air-conditioned buildings. In addition, the most common parameters of PCMs that have been analyzed in previous studies are the phase-change temperature (PCT), thickness, and position of the PCM layer. Kim et al. analyzed the energy consumption of a residential building with a PCM with a specific melting temperature under different air conditioning conditions and suggested suitable PCM properties for various cooling and heating conditions in different seasons [8]. Tokuç et al. [9] evaluated roofs with and without PCMs in terms of the cooling load for the summer season in four weather zones of Turkey. They indicated that the reduction in the cooling load in May was more significant when installing thicker PCM layers. Specifically, a PCM with a thickness of 50 mm reduced the cooling load by 48.2%, 56.6%, 78.7%, and 99.1% in Izmir, Istanbul, Ankara, and Erzurum, respectively.

Regarding studies related to the combination of PCMs and rooftops, Alawadhi and Alqallaf [10] carried out numerical and experimental studies of a roof structure with PCMs. It was found that the heat transferred into the indoor space could be reduced by 39%. Mushtaq et al. [11] experimentally studied the effect of incorporating a PCM with a melting temperature of 37 °C into a roof structure with a cooling system under summer weather conditions in Baghdad, Iraq, and found that a roof structure with a PCM reduced heat transfer by 46.71% when compared to the reference roof structure. Zwanzig et al. [12] evaluated the energy-saving potential of installing a PCM layer at different positions inside the roof structure of residential buildings located in three climatic zones in the USA (Minneapolis, Louisville, and Miami). The results showed that installing a PCM in the interior surface resulted in better energy-saving potential, as the cooling loads were reduced by up to 11.4%, 8.0%, and 4.1%, respectively. Xamán et al. [13] developed alternatives with different PCM types and thicknesses for warm weather conditions in Mexico by applying PCMs on the surfaces of roof components that were closer to the indoor environment.

Previous studies also discussed the application of PCMs for promoting thermal comfort. For instance, Mourid and Alami [14] evaluated the effectiveness of combining PCMs with roof structures to improve the summer thermal comfort in lightweight buildings and investigated the influence of the thickness and position of the PCM layer on its effectiveness. Piselli et al. [15] demonstrated that a combination of cool roofing membranes and PCMs is practical and effective at lowering surface temperatures and can mitigate indoor overheating in peak summer conditions without drawbacks in the cold season. Li et al. [16] conducted an experimental study to explore the influence of the melting temperature and thickness of a PCM on the thermal performance of a glazed roof. The results showed that the peak temperature decreased by approximately 16.3 °C, and the energy consumption reduced by 47.5% when utilizing a PCM with a melting temperature of 32 °C. With an increasing thickness of the PCM layer, the energy consumption and dissatisfaction rate for an indoor thermal environment gradually declined. Parametric analysis of the thermal behavior of PCMs with different melting temperatures, layer thicknesses, and numbers of layers incorporated into building roofs was carried out in the humid tropical weather of Chennai, India, by Reddy et al. [17]. Analysis has also been carried out in the cold northeastern area of China by Dong et al. [18] and over a range of climates across the United States by Kibria et al. [19]. Besides, Yu et al. [20] have numerically investigated the phase transition temperature and thickness of a PCM layer in a roof of typical design under climatic conditions in five regions in China. Their results showed that the optimal thickness of PCM is 30 mm and that the optimum phase transition temperature increases
linearly with the increase in average outdoor solar air temperature in summer in different climatic regions. David and Javier [21] analyzed the selection of PCMs for building wall-boards and roofs via a comparison between multi-criteria decision methods and building energy simulations. The results demonstrated the importance of environment variables in appropriately assessing the performance of PCMs, and indicated that PCMs have different thermal behaviors depending on the climatic conditions. Accordingly, it is essential to assess an extensive evaluation of the climatic condition before applying this strategy.

The previous studies mentioned above analyzed the energy-saving potential and the effect of improving thermal comfort resulted from the utilization of PCM; however, most of these studies are conducted under a specific season. Different from the previous research, this study aims at suggesting a feasible and economic pattern of PCMs for school buildings that can simultaneously fulfill the conditions during the AC and NV seasons to reduce energy consumption and provide a better thermal comfort condition. In view of the fact that the Taiwanese government intends to complete the installation of air-conditioning in 103,000 classrooms across the entire island by the summer of 2022, it is considered that the utilization of PCMs is helpful for raising the effect of energy-saving potential and indoor thermal condition. However, there are no existed practical cases of combining the PCMs and rooftop structure in Taiwanese school buildings. Thus, this study acts as a pioneer study to discuss the effect and feasibility of utilizing PCMs on the rooftop of Taiwanese school buildings and attempts to suggest recommendations for the utilization strategies that the energy-saving potential and indoor thermal comfort are both taken into consideration. The investigated cases in this paper were set to analyze the reducing cooling load during the air-conditioning season and improving the thermal comfort of real classrooms during the ventilation season. Based on the simulation results, it is expected to suggest the appropriate properties of PCMs for Taiwanese school buildings, including thickness and PCT. In addition, a feasible pattern of PCM, which is appropriate to be utilized throughout the entire year, is proposed to fulfill the indoor comfort and energy-saving potential.

2. Materials and Methods

2.1. Building Prototype and Simulations Procedure

The top-floor classrooms of a typical high-school building (Figure 1) located in Taiwan are selected as a model for simulation. The setting conditions of the building model are listed in Table 1. Besides, a 2.0 m deep outdoor corridor is used as a horizontal shade on the south side. Regarding the air-conditioning operation and natural ventilation period of this school building model, the air-conditioning is available for use during the weekdays in the hot-humid period from May to October. Based on the regulation, it is allowed to turn on the air-conditioning when the outdoor temperature is higher than 27 °C. Besides, the windows are always closed during the occupancy period and out of the occupancy period at night and on weekends during the AC season. The natural ventilation season is from November to April.

In order to optimize the thermal design for the classroom, including cutting down the cooling load from May to October and improving the thermal environment from November to April, the case studies of installing PCM at the inner side of the existing roof were proposed. Due to the sol-air temperature on the external roof surface varies greatly between day and night, the inner side of the roof was chosen to install the PCM, which is particularly suitable for the application of phase-change energy-storage technology. Moreover, previous studies [22–26] have confirmed that placing PCM on the inner surface of a wall can better regulate the indoor temperature and save more energy than deploying PCM on the outer surface of a wall. The PCM considered in this paper is BioPCM™, which is generally used by other previous studies; besides, the database of the BioPCM™ is complete that can be regarded as a convincing material [27–32]. BioPCM™ is non-toxic, non-corrosive, biodegradable, and has a useful life of over 100 years. In addition, BioPCM™ enables users to reduce their carbon footprint and reduce the stress on HVAC
systems in buildings, data centers, and telecom shelters [33]. In order to investigate the climate and seasonal adaptability of PCM, six types of phase-change temperature (PCT) were considered, including 23 °C (22–25 °C), 25 °C (24–27 °C), 27 °C (26–29 °C), 29 °C (28–31 °C), 31 °C (30–33 °C), and 33 °C (32–35 °C). Furthermore, four different thickness types of PCM layer were set, including 10 mm, 20 mm, 30 mm, and 40 mm. The latent heat of BioPCM is 219 kJ/kg. Figure 2 depicts the enthalpy–temperature curves for BioPCM [34].

![Image and floor plan of a typical high-school building.](https://example.com/image1.png)

**Figure 1.** Image and floor plan of a typical high-school building.

**Table 1.** Setting condition of school building model.

| Building                  | Orientation                                              | Face Toward the South                                  | 3 Stories                                                                 |
|--------------------------|----------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------|
| Classroom                | Story: Length × width × height                           | 9.0 m × 8.1 m × 3.6 m                                   | 12 W/m²                                                                  |
|                          | Lighting density                                         | 12 W/m²                                                | 30 people (including teachers and students)                              |
|                          | Room capacity                                            | 30 people (including teachers and students)             | 8:00–17:00 (weekdays)                                                   |
|                          | Occupancy period                                         | North: 29%; South: 37%                                 | North: 29%; South: 37%                                                  |
|                          | Window-wall ratio                                        | 6 mm thick clear glass                                 | North: 29%; South: 37%                                                  |
|                          | Window glass                                            | Reinforced concrete (RC)                               | North: 29%; South: 37%                                                  |
|                          | Exterior wall                                            | Exterior wall                                          | North: 29%; South: 37%                                                  |
| Material of facade and   | Roof                                                     | RC roof with 25 mm polystyrene (PS) insulation board    | North: 29%; South: 37%                                                  |
| roof structure            |                                                          | U value: 2.3 W/m² K                                    | U value: 1.0 W/m² K                                                     |

![Enthalpy–temperature curves for BioPCM.](https://example.com/image2.png)

**Figure 2.** Enthalpy–temperature curves for BioPCM.
The building energy and thermal load simulation software EnergyPlus version 9.4 was used in this study to conduct the simulation, and the weather data of a typical meteorological year (TMY3) of two major cities in Taiwan: Taipei (25.03° N, 121.50° E) and Kaohsiung (22.57° N, 120.30° E) were used. Specifically, the climatic conditions, including the outdoor temperature, cooling degree hour (CDH), and horizontal solar radiation of each month for the two selected study cities, are shown in Figure 3. Taiwan is located in the sub-tropical zone that the weather features are hot and humid. Referring to Figure 3, it is known that the outdoor temperature in Taipei during winter is much lower than that of Kaohsiung, although Taipei and Kaohsiung are both located in a hot-humid climate zone; as for the outdoor temperature in Kaohsiung, it remains at an extremely high temperature during the entire year. In addition, the heat gains from the rooftop are directly affected by the solar air temperature. As shown in Figure 4, there is a wide range of the variation of daily solar air temperature, which means the utilization potential of PCM in rooftop structure is expectable in both Taipei and Kaohsiung.

![Figure 3. Climatic conditions of selected cities.](image1)

![Figure 4. Daily range of air/solar-air temperature and daily peak radiation.](image2)

CDH 27 is a statistic value in the weather data (TMY3). Besides, owing to this value is closed to the standard value that is regulated to turn on the air-conditioning (27–28 °C); therefore, CDH 27 was set for the simulation in this study. All simulations were conducted using the conduction finite difference (CondFD) approach. During the months of May to October, air-conditioning equipment was activated to analyzing the cooling load of the classrooms; during the months of April to November, the thermal conditions of classrooms with natural ventilation opening areas such as windows were simulated (mainly for the operating temperature) through the airflow network model in EnergyPlus. The series of simulations mainly focuses on cases with PCM-installed roofs and night ventilation. Comparing to the traditional reference cases without installing PCM in the roof structure, the cooling load reduction and thermal comfort improvement resulted from the application of PCM in the roofs could be identified.

2.2. Selection of Performance Indicators

Through combining PCMs with a building’s heating, ventilation, and air-conditioning (HVAC) system, it can utilize low nighttime temperatures to store or release energy and
make use of the energy transfer for “peak shaving and valley filling”, and thereby providing all or part of the heating or cooling required during the day. In order to take better advantage of PCMs in buildings, it is essential to evaluate the usage efficiency of PCMs based on latent heat. In addition to the usage efficiency of PCMs, other indicators must be considered to evaluate the effectiveness in terms of improving indoor thermal comfort and energy savings. Therefore, three performance indicators, including the daytime heating efficiency coefficient (heat storage), the nighttime cooling efficiency coefficient (heat release), and the effective latent storage, were selected to assess the usage efficiency of a PCM roof in energy storage/releasing and the effectiveness in terms of improving the indoor thermal environment and energy saving. Each of the evaluation indicators is respectively elaborated in the following section.

2.3. Usage Efficiency of PCM

There are two main factors that influence the usage efficiency of PCM: operational period and latent storing and releasing capability of heat. Specifically, regarding the operational period, the PCM layer can reach a completely solidified or completely melted stage within a relatively short period of time; in other words, instead of operating all day, the PCM layer must be in a partially melted state for a long period time, which means that it operates effectively in daily cycles. Concerning the latent storing and releasing capability of heat, it is unpopular to utilize the PCM layer with worse performance than storing or releasing a small amount of energy during the daily cycles. Scilicet, the better performance of PCMs is that the heat-storing at night is equivalent to the heat releasing during daytime. Aforementioned, the usage efficiency of a PCM can be analyzed through its latent storing and releasing capability of heat, as well as its operational period within one daily cycle.

Ramakrishnan et al. [28] developed a method to determine the latent storing and releasing capability of heat by combining the factors mentioned above, and thereby providing more accurate predictions of the daytime heating efficiency coefficient (heat storage) and the nighttime cooling efficiency coefficient (heat release) for a PCM, named HE and CE (Equations (1) and (2)). HE and CE are used to respectively describe the operating effectiveness of the PCM during the storing and releasing latent heat period and are separately calculated for the air-conditioning season from May to October and for the natural ventilation season from November to April. Referring to Equations (1) and (2), $L_C$ and $L_{DC}$ provide information regarding the potential energy that is effectively stored and released in the PCM layer via the melting and solidification processes. In this paper, the releasing time of heat during the daytime was 600 min (08:00–17:00), and the storing time of heat at nighttime was 840 min (17:00–08:00). Besides, $T_C$ and $T_{DC}$ can be used to identify the length of time that the PCM layer is activated during the heat-storage/releasing period; a longer time period in which the PCM layer is activated can provide longer isothermal energy storage.

$$\text{HE} = \sqrt{L_C \times T_C}$$
$$\text{CE} = \sqrt{L_{DC} \times T_{DC}}$$

where $L_C$ and $L_{DC}$ are the ratios of latent heat stored/released by the PCM during daytime/nighttime over the total latent heat capacity of the PCM; $T_C$ and $T_{DC}$ are the ratios of the actual operating time of the PCM during daytime/nighttime over the storing/releasing time during daytime/nighttime; $T_C/T_{DC}$ is the interval between occurrence times of the maximum and the minimum value.

The effective latent storage ($\eta$) of the PCM layer at a specific moment is calculated by Equation (3). The value of $\eta = 1$ means that the PCM layer is completely solidified; $\eta = 0$ means that the PCM layer is completely melted.

$$\eta = \frac{\sum_{i=1}^{n} \{ H(T_i) - H(T_0) \}}{\Delta H}$$
where $\Delta H$ is the phase-change enthalpy value of PCM; $H(T_i)$ and $H(T_0)$ are the specific enthalpies of PCM at the temperature $T_i$ and the melting onset temperature $T_0$, respectively. The node temperature of the PCM can be confirmed from the simulation results of EnergyPlus, and the specific enthalpy can be obtained from the enthalpy–temperature curves.

### 2.4. Evaluation of Thermal Comfort and Energy-Saving Potential

A long-term evaluation of building performance and the criteria for determining the performance should consider the different potential susceptibilities of occupants to overheating [35]. In addition, the thermal evaluation and the design corresponding to the occupants should apply the thermal comfort standard that adapted to occupants’ thermal perception [36]. Hence, the adaptive comfort model for students in Taiwan [37] is used to evaluate the thermal environment of classrooms during the natural ventilation season from November to April. Specifically, this model is based on the experimental data of a thermal comfort survey in elementary schools and high schools. The upper limit temperature of thermal comfort ($T_{\text{max}}$) is defined by Equation (4):

$$T_{\text{max}} = 0.62 \times T_{\text{om}} + 14.5$$  

where $T_{\text{max}}$ is the upper limit temperature of thermal comfort; $T_{\text{om}}$ is the monthly moving average or the daily average of the outdoor air temperature for the past 30 days.

Regarding the long-term evaluation of indoor thermal comfort, Annex H of ISO 7730 [38] listed two types of measures for thermal discomfort to simultaneously consider the frequency and level of discomfort severity; besides, all of these two measures use the positive difference between the current operating temperature and the upper limit of thermal comfort range to evaluate the overheating discomfort. Briefly reviewing the two measures, the first measure is the number of hours in which the upper limit of thermal comfort range is exceeded; the second measure is the level of overheating severity that reflects the continuous duration and level of overheating, which is also called weighted overheating hours. The weighted measure indicates the level of thermal dissatisfaction among subjects and takes discomfort to be proportional to the non-linear ratio of the discomfort curve ($PD_h$) [37]. The two measures are defined by Equations (5) and (6). Eventually, the energy-saving potential of PCM from May to October is defined as the percentage of energy savings based on the cooling load (Equation (7)):

$$I_i = \int w f_1(\tau) \cdot d\tau \text{ if } T_{\text{op}}(\tau) \geq T_{\text{max}}, \text{ (during occupied hours)}$$  

$$PD_h(\tau) = \frac{e^{0.6802(\Delta T - 3.7690)}}{1 + e^{0.6802(\Delta T - 3.7690)}} \cdot \Delta t = T_{\text{op}}(\tau) - T_{\text{max}}$$  

$$\text{Energy-saving potential of PCM} = \frac{\text{Cooling load without PCM roof} - \text{Cooling load with PCM roof}}{\text{Cooling load without PCM roof}} \times 100\%$$

where, $I$ is the measures for thermal discomfort; for the first measure, $wf_1(\tau) = 1.0$; for the second measure, $wf_2(\tau) = PD_h(\tau)/0.2$; $T_{\text{op}}$ is the operating temperature; $PD_h$ is the discomfort curve, defined by Equation (6).

### 3. Results and Discussion

#### 3.1. Cooling Load and Thermal Environment with No PCM Roof

The simulation results of monthly cooling loads (CL), the number of overheating hours (I1), and the number of weighted overheating hours (I2), which represent the thermal discomfort level of the classrooms without a PCM in the roof structure in Taipei and Kaohsiung are shown in Figure 5. According to Figure 5, under the weather conditions of CDH 27, it is known that the annual cooling load is 59.0 GJ and the thermal discomfort levels of I1 and I2 are respectively 234 h and 519 h for the top-floor classrooms in Taipei.
Regarding the results of Kaohsiung, the cooling load is 79.8 GJ, and the thermal discomfort levels of I1 and I2 are respectively 344 h and 651 h. Owing to there is a higher CDH 27 and horizontal solar radiation, it is predictable that the cooling load of Kaohsiung will be higher than that of Taipei. For projects aimed at the improvement of roof structures, the ideal outcome is to reduce the cooling load and thermal discomfort in the top-floor classrooms to be the same level as in non-top-floor classrooms at the same time. Therefore, the simulation results of the non-top-floor classrooms, which had the same identical configuration with top-floor classrooms, are also shown in Figure 5 for comparing the difference. Specifically, the differences between the cooling loads and thermal discomfort levels of top-floor and non-top-floor classrooms can be regarded as being caused by the heat transferred from the roof.

![Figure 5](image-url)  
**Figure 5.** Comparison of cooling load, overheating hours, and weighted overheating hours between top-floor and non-top floor classrooms.

The contribution of heat transferred from the roof to the cooling loads and thermal discomfort levels of classrooms without PCM in the roof structure is shown in Table 2. The results show that the heat transferred from the roof accounts for 20.4% of the cooling load during the air-conditioning season in Taipei and 19.7% in Kaohsiung. The proportion of the overheating hours (I1) contributed by a roof in the ventilation season is 44.4% in Taipei and 64.2% in Kaohsiung; the proportion of the weighted overheating hours (I2) contributed by the roof is respectively 52.8% and 68.5% in Taipei and Kaohsiung. According to the results mentioned above, the importance and urgency of improving the thermal performance of the roof structure are confirmed.

| Table 2. The contribution of heat transferred from the roof to the cooling loads and thermal discomfort levels of classrooms without PCM in the roof structure. |

| May to October (Air-Conditioning Season) | November to April (Ventilation Season) |
|----------------------------------------|----------------------------------------|
| **Taipei** | **Kaohsiung** | **Taipei** | **Kaohsiung** |
| Cooling load (GJ) | 13.2 | 15.7 | 79.8 | 94.5 |
| Ratio (%) | 20.4% | 19.7% | 44.4% | 64.2% |
| I1 (hours) | 104.0 | 221.0 | 445.9 |
| Ratio (%) | 52.8% | 68.5% | 274.1 | 445.9 |

3.2. Influence of PCM on The Energy Consumption of the Air-Conditioning Season

In this paper, 30 cases of different properties of PCM are set to analyze the parameters which influence thermal performance. Specifically, six kinds of PCTs (23 °C, 25 °C, 27 °C, 29 °C, 31 °C, and 33 °C) and five types of PCM thickness (10–50 mm) were set. Figure 6 shows the energy-saving effects achieved by coupling different PCTs and PCM thicknesses during the AC season from May to October. Both PCT and thickness of PCM significantly influenced the reduction percentage of cooling load during the air-conditioning season. Within the scope of study cases, the energy-saving potential of a PCM layer on the cooling load was 1.2–7.8% in Taipei, which is equivalent to a cutback proportion of 6.3–41.6%
cooling load from the roof; and 0.9–6.2% in Kaohsiung, which is equivalent to a cutback proportion of 4.8–33.1% of the cooling load from the roof. Under the circumstance of the same PCM layer thickness during the air-conditioning season, the analysis results of the six selected PCTs show that the energy-saving effect initially increased with the increasing PCT; however, after reaching the peak of energy-saving effect, the energy-saving effect decreases as the PCT increases. In addition, it is important to match the PCT with the outdoor air temperature at night to make the PCM layer completely release the latent heat absorbed and stored during the daytime; meanwhile, it can avoid the heat storage capacity of the PCM layer becoming smaller on the next day. In other words, a higher PCT restricts the heat that can be absorbed and stored by the PCM layer during daytime and lead to a poorer energy-saving effect. Nevertheless, a lower PCT cannot release enough heat at nighttime and results in the poor ability to absorb and store heat. Therefore, it had the same effect of reducing cooling load as higher PCT.

For achieving the maximum energy-saving effect, the feasible PCTs for an air-conditioning season under different thicknesses of PCM are confirmed. Specifically, from the aspect of cost and efficiency, there is still an upper limitation that when increasing the PCT or thickness may not achieve the corresponding effect in a linear relationship. According to the results shown in Table 3, it is worth noting that only the case with a PCM thickness of 50 mm showed a better PCT at 27 °C in Taipei, all of the beneficial PCTs of a PCM layer in the air-conditioning season occurred at 29 °C both in Taipei or Kaohsiung. This result is in accordance with the previous literature reviews [39–41], which point out that it is not recommended to apply PCM with PCT > 30 °C as passive cooling for buildings.

Table 3. Feasible PCTs under different PCM layer thicknesses.

| Thicknesses of PCM (mm) | May to October (Air-Conditioning Season) | November to April (Ventilation Season) |
|-------------------------|-----------------------------------------|----------------------------------------|
|                         | 10  20  30  40  50                      | 10  20  30  40  50                      |
| PCT (°C, Taipei)        | 29  29  29  29  27                      | 27  25  25  25  25                      |
| PCT (°C, Kaohsiung)     | 29  29  29  29  31                      | 29  29  29  29  29                      |

As shown in Figure 6, when the thickness of the PCM layer in Taipei was 50 mm, the energy-saving effect of PCT = 29 °C or the beneficial PCT = 27 °C was almost the same that the differences between these two cases were negligible. Therefore, the beneficial PCT of a PCM roof in the air-conditioning season could be regarded as 29 °C. In addition, the results also show that though the solar radiation in Kaohsiung was higher than in Taipei; however, there is no need to apply the PCM layer with higher PCT in Kaohsiung to create a better energy-saving effect.

Figure 6 also shows the expected trends: the energy-saving effect increases with the increasing thickness of the PCM layer, and the increasing trend became moderate when the
thickness of the PCM layer decreased. Taking a beneficial PCT as an example, according to the simulation results, when the thickness of the PCM layer increases from 10 mm to 20 mm, the energy-saving effect increased from 5.21% to 6.86% in Taipei, which was an increment of 1.65%; increased from 4.74% to 5.91% in Kaohsiung, with an increment of 1.16%. Regarding the thickness of the PCM layer increases from 40 mm to 50 mm, the energy-saving effect increases from 7.45% to 7.6% in Taipei, for which the increment was 0.15%; as for the results of Kaohsiung, the energy-saving effect increased from 6.17% to 6.22%, for which the increment was barely 0.05%. It is worth noting that the thickness of the two circumstances increased the same by 10 mm, but the increment of the energy-saving effect differs by nearly 11 times and 24 times. It is because of the low thermal conductivity of PCM (0.2 W/m·K) and a thicker PCM layer, the required time for complete melting of PCM is prolonged. If the time required for melting lasts too long, part of the PCM may remain in a solid state at the end of the daytime period of the endothermic process. Under the circumstance of a thicker PCM layer, the full capacity of PCM has not yet been utilized; therefore, the relationship between the energy-saving effect and the thickness of PCM was not linearly related.

3.3. Influence of PCM on Thermal Comfort in the Ventilation Season

The roof structure with PCM creates a more comfortable environment during the ventilation season from November to April, which can reduce the number of overheating hours and weighted overheating hours under the situation of classroom operating temperatures exceeding 80% of the acceptable upper limitation. Figure 7 shows the difference in the number of overheating hours (I1) between the baseline case of a roof without PCM and the case of a roof with different kinds of PCM. In Figure 7, the overheating hours (I1) are represented by a dashed line, and the weighted overheating hours (I2) are represented by a solid line. The reduction percentage in the number of overheating hours was 3.7–45.5% in Taipei and 8.1–47.4% in Kaohsiung, which were equivalent to 9–110 h and 28–163 h less than the case of not using PCM. As shown in Figure 7, among all the analyzed cases, the decrements in weighted overheating hours (I2) were higher than those in the number of overheating hours (I1).

Figure 8 explains how the PCM layer enhances the level of thermal comfort during the ventilation season. Specifically, it shows the operating temperatures of classrooms using and not using PCM in Taipei from 22–24 April. In this case, a PCM layer with a melting point of 25 °C and a thickness of 40 mm was set for simulation. As revealed in Figure 8, PCM begins to solidify by releasing heat at nighttime, and since the nighttime temperature of the ventilation season is low, most of the PCM layer was solidified by early morning. As the temperature rises during the daytime, the PCM begins to melt and store the heat transferred to the roof as latent heat, preventing it from being transferred into the interior space and thereby inhibiting the rise in indoor operating temperature. Moreover, there was no extremely high temperature during the ventilation season, so the PCM layer would melt slowly and makes the operating temperature during the day close to the comfort upper limit of 29 °C or within the comfort range. On average, the operating temperature during daytime was reduced by 1.0 °C, and the PD$_h$ was decreased by 0.11, while the temperature of the hottest noon period (12:00–14:00) was reduced more by 1.8 °C, and the PD$_h$ decreased by 0.23. Although in some high-temperature periods at noon, the PCM layer was not able to reduce the operating temperature to a comfortable range or reduce the number of overheating hours, it did reduce the PD$_h$ significantly, which would help to improve the comfort level of classrooms. Furthermore, within the three days shown in Figure 8, the length of time periods in which the operating temperature was outside the comfort zone had also been decreased by installing PCM in the roof structure. Under the situation without PCM, the temperature exceeded the comfort zone for 14 h; while under the situation of using PCM, the continuous time was shortened to 8 h. Simultaneously, referring to the result of the previous night of 23 April, it showed that when the temperature
was low enough for a complete solidification of the PCM, the greatest improvement in indoor comfort could be achieved.

![Graph]

Figure 7. Effects on thermal comfort of different thicknesses of PCM roofs during the ventilation season from November to April.

![Graph]

Figure 8. Comparison of simulating operative temperatures of classrooms with and without PCM roofs during the ventilation season.

According to the results shown in Figure 6 and Table 3, it is worth noting that for achieving the maximum comfort effect in the ventilation season under different thicknesses
of PCM, it did not matter if the analysis was based on the number of overheating hours or the weighted overheating hours, the beneficial PCTs were identical. For instance, when the thickness of PCM was 10 mm, the beneficial PCTs were 27 °C in Taipei and 31 °C in Kaohsiung; when the thickness of PCM was over 20 mm, the beneficial PCTs were 25 °C in Taipei and 29 °C in Kaohsiung. In addition, the beneficial PCTs for the ventilation and air-conditioning seasons were identical in Kaohsiung; but in Taipei, the beneficial PCT for the air-conditioning season was 4 °C higher than that for the ventilation season. The main reason for this difference is because the outdoor air temperature of the air-conditioning season was higher than that of the ventilation season; ideally, dual-layer PCM roofs with different PCTs would be expected to be selected according to the outdoor climate features of the ventilation and air-conditioning seasons. Specifically, the outer PCM layer, which possesses a higher melting temperature, would be active in summer, and the inner PCM layer, which possesses lower melting temperatures, would be active in winter. Through this measure, the energy-saving effect and indoor thermal comfort of a building could be improved in both summer and winter [42, 43]; however, it may increase construction costs and construction difficulties.

3.4. Efficiency of PCM

The corresponding efficiency coefficients for the PCM roof with the closest feasible PCT for applying to school buildings in Taiwan are listed in Table 4. According to the table, it could be concluded that the efficiency coefficients of CE (daytime heating) and HE (nighttime cooling) tended to be low for the selected PCM layers of various thicknesses in the two seasons. Regarding the air-conditioning season, CE and HE in Taipei, respectively, lay within 0.58–0.39 and 0.50–0.38, and those in Kaohsiung were within 0.45–0.73 and 0.43–0.55. For the ventilation season, CE and HE in Taipei, respectively, lay within 0.33–0.24 and 0.35–0.27, and those in Kaohsiung were within 0.35–0.48 and 0.38–0.53. It is predictable that the CE and HE of both cities in the two seasons were close to each other. In addition, it is worth mentioning that CE in the air-conditioning season was slightly higher than HE, particularly for the thinner PCM layer. This is because during the air-conditioning season, the outer surface temperature of the roof at 7:00–8:00 in the morning led to the PCM to start melting instead of continuously solidifying, offsetting part of the cold energy charged at nighttime. This could also be corroborated by the lower nighttime latent heat-storing ratio \( L_C \), as compared to the daytime latent heat-releasing ratio \( L_{DC} \). The reasons for the low CE and HE could be clarified by observing the latent heat charging ratio and operating time ratio of the PCM layer. Taking the simulation results of Taipei as examples, for various selected thicknesses of PCM, it was found that the nighttime operating time ratio \( T_C \) and latent heat charging ratio \( L_C \) from May to October were respectively 0.62–0.74 and 0.21–0.57.

Figure 9 reveals the efficiency of PCM for the four days in May. A high \( T_C \) indicates that the PCM layer was solidifying and releasing heat at night for most of the time. On the other hand, a low \( L_C \) indicates that the PCM layer had not completely solidified before sunrise; as shown in Figure 9, the latent heat capacity could not be fully utilized. The daytime latent heat-releasing ratio \( L_{DC} \) of the PCM layer was usually close to the nighttime value \( L_C \), but the daytime operating time ratio lay within 0.44–0.67, which means that they only operated for half of the time during the daytime, even becoming entirely liquid by noon.

According to the analysis mentioned above that the utilization efficiency barely lay within 0.44–0.67, which means that although the roof with PCM significantly improves indoor thermal comfort from November to April, it does not accompany by high efficiency. In the same manner, we also evaluated the operating time ratio \( T_C \) and latent heat-storing ratio \( L_{DC} \) for the operation of the PCM layer through the entire ventilation season (November to April). Unlike the air-conditioning season, the nighttime operating time ratios are not high (0.30–0.42 for Taipei, 0.37–0.54 for Kaohsiung) from November to April. Moreover, as revealed by comparing Figures 9 and 10, on those four days of February, the
daytime latent heat discharging ratio \((L_{DC})\) of the PCM was 0.0 at 08:00 and did not reach 1.0 until 17:00; besides, the PCM layer even started solidification after 15:00. According to the results, it means that the lack of demand was the main reason for the PCM not operating for the entire day and could not make full utilization of the latent heat effect, and accordingly lead to the poor CE or HE. Overall, the lack of demand during the daytime was the main reason for the low usage efficiency of the PCM layer in the ventilation season. This result was different for the situation during the air-conditioning season as the PCM was not able to completely solidify at nighttime. However, for the better utilization of storage capacity, the PCM must be fully melted during daytime and fully solidified during nighttime; in other words, the PCM must complete its daily phase change cycle to reach greater performance.

Table 4. Corresponding efficiency coefficients for PCM roofs for school buildings in Taiwan.

| Thickness (mm) | May to October (Air-Conditioning Season) | November to April (Ventilation Season) |
|---------------|-----------------------------------------|----------------------------------------|
|               | Storing | Releasing | PCT \(^\circ\)C | Storing | Releasing | PCT \(^\circ\)C |
| Taipei        |         |           | \(T_C\) | \(L_C\) | CE | \(T_{DC}\) | \(L_{DC}\) | HE | \(T_C\) | \(L_C\) | CE | \(T_{DC}\) | \(L_{DC}\) | HE |
| 10            | 29      | 0.62      | 0.57    | 0.58    | 0.44 | 0.62 | 0.50 | 25 | 0.30 | 0.38 | 0.33 | 0.43 | 0.35 | 0.35 |
| 20            | 29      | 0.71      | 0.42    | 0.53    | 0.57 | 0.45 | 0.49 | 25 | 0.37 | 0.29 | 0.32 | 0.40 | 0.32 | 0.34 |
| 30            | 29      | 0.73      | 0.31    | 0.47    | 0.61 | 0.34 | 0.44 | 25 | 0.39 | 0.21 | 0.29 | 0.44 | 0.25 | 0.32 |
| 40            | 29      | 0.74      | 0.25    | 0.42    | 0.65 | 0.27 | 0.41 | 25 | 0.41 | 0.17 | 0.26 | 0.46 | 0.20 | 0.29 |
| 50            | 29      | 0.74      | 0.21    | 0.39    | 0.67 | 0.23 | 0.38 | 25 | 0.42 | 0.14 | 0.24 | 0.47 | 0.17 | 0.27 |
| Kaohsiung     |         |           | \(T_C\) | \(L_C\) | CE | \(T_{DC}\) | \(L_{DC}\) | HE | \(T_C\) | \(L_C\) | CE | \(T_{DC}\) | \(L_{DC}\) | HE |
| 10            | 29      | 0.79      | 0.69    | 0.73    | 0.46 | 0.72 | 0.55 | 29 | 0.37 | 0.62 | 0.47 | 0.45 | 0.68 | 0.53 |
| 20            | 29      | 0.85      | 0.49    | 0.64    | 0.60 | 0.51 | 0.54 | 29 | 0.48 | 0.49 | 0.48 | 0.56 | 0.51 | 0.52 |
| 30            | 29      | 0.86      | 0.37    | 0.56    | 0.67 | 0.39 | 0.49 | 29 | 0.51 | 0.36 | 0.43 | 0.60 | 0.38 | 0.46 |
| 40            | 29      | 0.86      | 0.30    | 0.50    | 0.71 | 0.31 | 0.45 | 29 | 0.53 | 0.28 | 0.38 | 0.62 | 0.30 | 0.42 |
| 50            | 29      | 0.86      | 0.25    | 0.45    | 0.75 | 0.26 | 0.43 | 29 | 0.54 | 0.23 | 0.35 | 0.63 | 0.24 | 0.38 |

Figure 9. Operating efficiency of the PCM during the air-conditioning season.
The energy-saving and thermal comfort efficacy of different thicknesses of PCM layers under the beneficial PCT.

As revealed in the analysis above, the beneficial PCT during the air-conditioning season in Taipei was 4 °C higher than the PCT during the ventilation season. Under the thermal management approach of schools in Taiwan, the feasible selection of PCM roofs must simultaneously consider the energy consumption during the air-conditioning season and the annual benefit of thermal comfort during the ventilation season. The issue of whether to prioritize thermal comfort during the ventilation season or to prioritize energy consumption during the air-conditioning season may not alter by the 4 °C temperature difference when selecting a feasible PCT. Under the economic PCM thickness of 20 mm, the benefits of a PCT of 25 °C or 29 °C in the air-conditioning season and the ventilation season can be observed according to Table 5. Specifically, when 29 °C is selected as the feasible PCT, only an additional 29 h of overheating and 22 h of weighted overheating hours are added in the ventilation season, which does not significantly increase the level of thermal discomfort. Besides, it can achieve an additional 2.5 GJ (3.7%) energy-saving potential of cooling load compared with selecting 25 °C as the beneficial PCT. Even if
the air conditioner is turned on for an additional 22 h during the ventilation season, the percentage of increasing cooling load is much less than 3.7%. Thus, we can confirm that the most economical PCM layer in Taipei was $PCT = 29^\circ C$ and a thickness of 20 mm, which was the same as that in Kaohsiung.

Table 5. Comparison of annual efficacy of a $PCT$ of 25 °C or 29 °C in Taipei.

| $PCT$ ($°C$) | Overheating Hours, $I_1$ (hr) | Weighted Overheating Hours, $I_2$ (hr) | Energy-Saving Potential (GJ) |
|-------------|-------------------------------|-------------------------------------|-----------------------------|
| 25          | 80                            | 206                                 | 2.5 (3.7%)                  |
| 29          | 51                            | 184                                 | 4.7 (6.9%)                  |
| Difference  | 29                            | 22                                  | $-2.2 (-3.2\%)$             |

4. Conclusions

Owing to the undergoing policy of broadly installing the air-conditioning in school buildings in Taiwan, it is essential to draw up energy-saving strategies that not only reduce energy consumption but create better indoor comfort. This paper selected the school buildings located in Taipei and Kaohsiung as target buildings to discuss their cooling load in air-conditioning season and thermal discomfort in natural ventilation season under the circumstance of installing PCM on rooftops. In order to confirm that combining the rooftop structure and PCM brings benefits to building energy-saving, this study firstly revealed the importance of heat insulation from the rooftop by simulating the incoming heat from the rooftop. Secondly, thirty cases of different setting parameters of PCM, including thickness and $PCT$, were set to simulate their energy-saving effect and thermal discomfort. Eventually, the recommended feasible utilization patterns of PCM for better indoor comfort and energy-saving potential was proposed.

According to the simulation results of incoming heat from a rooftop in AC season, it is known that the ratio of cooling load resulting from the rooftop is significant and cannot be ignored. Regarding the NV season, the ratio of overheating hours resulting from the rooftop should not be overlooked either. As aforementioned, the urgency of heat insulation from the rooftop could be confirmed. The investigated cases of different $PCT$ and thicknesses of PCM show that the features of PCM make noticeable influences on the reducing potential of cooling load. Specifically, regarding the relationship between different $PCT$ and energy-saving effects in the AC season, when the thickness of PCM is fixed, it is worth noting that the energy-saving effect increases as the $PCT$ increase. However, when reaching the peak of the energy-saving effect, the energy-saving effect decreased as the $PCT$ increased. Furthermore, based on the simulation results, for achieving the maximum energy-saving potential, the beneficial $PCT$ for all different thicknesses of PCM was clarified as 29 °C. Additionally, this study also analyzed the relationship between the thickness of PCM and the energy-saving effect. The results show that the energy-saving effect increased as the thickness of the PCM increased, whereas the increasing trend becomes moderate when the thickness of PCM keeps increasing. Briefly, the relationship between the energy-saving effect and the thickness of PCM was not linear.

Concerning the relationship between PCM and thermal discomfort in the NV season, the results showed that installing the PCM on the rooftop apparently cut down the weighted overheating hours in both Taipei and Kaohsiung. Furthermore, the feasible $PCT$ under the conditions of different thicknesses of PCM was suggested. In addition, it is worth noting that the beneficial $PCT$ in AC season and NV season was the same value in Kaohsiung; as for Taipei, the beneficial $PCT$ in the air-conditioning season was 4 °C higher than in the NV season. After confirming the feasible $PCT$, the most economical thickness of PCM for improving the energy-saving effect and thermal comfort is clarified as 20 mm.

According to the aforementioned, this study suggests the feasible selection of PCM, including its thickness and $PCT$ for the school buildings during different seasons. In addition, based on the simulation conducted respectively in the AC season and NV season,
the feasible pattern of PCM through the year is proposed to fulfill the whole year indoor comfort and energy-saving potential. Through the recommendations proposed in this study, it is expected to efficiently utilize the PCM in school buildings to reduce the additional energy consumption and eventually realize the goal of energy conservation.

**Author Contributions:** Conceptualization, R.-L.H. and B.-L.C.; Methodology, R.-L.H. and W.-A.C.; Formal Analysis, R.-L.H. and W.-A.C.; Investigation, B.-L.C.; Resources, R.-L.H.; Data Curation, R.-L.H. and B.-L.C.; Writing—Original Draft Preparation, R.-L.H. and W.-A.C.; Writing—Review and Editing, W.-A.C.; Supervision, R.-L.H.; Project Administration, W.-A.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

**References**

1. Wang, X.; Sun, X.; Yu, C.W.F. Building envelope with variable thermal performance: Opportunities and challenges. *Indoor Built Environ.* 2018, 27, 729–733. [CrossRef]
2. Zhou, Y.; Yu, C.W. The year-round thermal performance of a new ventilated Trombe wall integrated with phase change materials in the hot summer and cold winter region of China. *Indoor Built Environ.* 2019, 28, 195–216. [CrossRef]
3. Madad, A.; Mouhib, T.; MouhSEN, A. Phase Change Materials for Building Applications: A Thorough Review and New Perspectives. *Buildings* 2018, 8, 63. [CrossRef]
4. Al-Yasiri, Q.; Szabó, M. Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. *J. Build. Eng.* 2021, 36, 102122. [CrossRef]
5. Stamatiadou, M.E.; Katsourinis, D.I.; Founti, M.A. Computational assessment of a full-scale Mediterranean building incorporating wallboards with phase change materials. *Indoor Built Environ.* 2016, 26, 1429–1443. [CrossRef]
6. Ramakrishnan, S.; Sanjayan, J.; Wang, X. Experimental Research on Using Form-stable PCM-Integrated Cementitious Composite for Reducing Overheating in Buildings. *Buildings* 2019, 9, 57. [CrossRef]
7. Bravo, J.P.; Venegas, T.; Correa, E.; Álamos, A.; Sepúlveda, F.; Vasco, D.A.; Barreneche, C. Experimental and Computational Study of the Implementation of mPCM-Modified Gypsum Boards in a Test Enclosure. *Buildings* 2020, 10, 15. [CrossRef]
8. Kim, T.; Ahn, S.; Leigh, S.-B. Energy consumption analysis of a residential building with phase change materials under various cooling and heating conditions. *Indoor Built Environ.* 2014, 23, 730–741. [CrossRef]
9. Tokuc, A.; Yesügey, S.C.; Başaran, T. An evaluation methodology proposal for building envelopes containing phase change materials: The case of a flat roof in Turkey's climate zones. *Arch. Sci. Rev.* 2017, 60, 408–423. [CrossRef]
10. Alqallaf, H.J.; Alawadhi, E.M. Concrete roof with cylindrical holes containing PCM to reduce the heat gain. *Energy Build.* 2013, 61, 73–80. [CrossRef]
11. Mushtaq, T.H.; Ahmed, Q.M.; Hasanain, M.H. Experimental and Numerical Study of Thermal Performance of a Building Roof Including Phase Change Material (PCM) for Thermal Management. 2013. Available online: http://ijersonline.org/HTML_Papers/ResearchJournalofEngineeringandTechnology_PID_2013-4-3-7.html (accessed on 31 October 2013).
12. Zwanzig, S.D.; Lian, Y.; Brehob, E.G. Numerical simulation of phase change material composite wallboard in a multi-layered building envelope. *Energy Convers. Manag.* 2013, 69, 27–40. [CrossRef]
13. Xamán, J.; Rodríguez-Ake, A.; Zavala-Guillén, I.; Hernández-Pérez, I.; Arce, J.; Saucedo, D. Thermal performance analysis of a roof with a PCM-layer under Mexican weather conditions. *Renew. Energy* 2020, 149, 773–785. [CrossRef]
14. Mourid, A.; El Alami, M. Thermal Behavior of a Building Provided With Phase-Change Materials on the Roof and Exposed to Solar Radiation. *Sol. Energy Eng.* 2017, 139, 061012. Available online: https://asmedigitalcollection.asme.org/solarenergyengineering/article-abstract/139/6/061012/379777 (accessed on 24 December 2019). [CrossRef]
15. Piselli, C.; Castaldo, V.L.; Pisello, A.L. How to enhance thermal energy storage effect of PCM in roofs with varying solar reflectance: Experimental and numerical assessment of a new roof system for passive cooling in different climate conditions. *Sol. Energy* 2019, 192, 106–119. [CrossRef]
16. Beltrán, R.D.; Martínez-Gómez, J. Analysis of phase change materials (PCM) for building wallboards based on the effect of environment. *J. Build. Eng.* 2019, 24, 100726. [CrossRef]
17. Reddy, K.S.; Mudgal, V.; Mallick, T.K. Thermal Performance Analysis of Multi-Phase Change Material Layer-Integrated Building Roofs for Energy Efficiency in Built-Environment. *Energies* 2017, 10, 1367. [CrossRef]
18. Li, D.; Zheng, Y.; Liu, C.; Wu, G. Numerical analysis on thermal performance of roof contained PCM of a single residential building. *Energy Convers. Manag.* 2015, 100, 147–156. [CrossRef]

19. Roman, K.K.; O’Brien, T.; Alvey, J.; Woo, O. Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities. *Energy* 2016, 96, 103–117. [CrossRef]

20. Yu, J.; Yang, Q.; Ye, H.; Luo, Y.; Huang, J.; Xu, X.; Gang, W.; Wang, J. Thermal performance evaluation and optimal design of building roof with outer-layer shape-stabilized PCM. *Renew. Energy* 2020, 145, 2538–2549. [CrossRef]

21. Li, D.; Wu, Y.; Zhang, G.; Aricci, M.; Liu, C.; Wang, F. Influence of glazed roof containing phase change material on indoor thermal environment and energy consumption. *Appl. Energy* 2018, 222, 343–350. [CrossRef]

22. Jin, X.; Medina, M.A.; Zhang, X. Numerical analysis for the optimal location of a thin PCM layer in frame walls. *Appl. Therm. Eng.* 2016, 103, 1057–1063. [CrossRef]

23. Heim, D.; Wierprzkonczew, A. Positioning of an isothermal heat storage layer in a building wall exposed to the external environment. *J. Build. Perform. Simul.* 2015, 9, 542–554. [CrossRef]

24. Murathan, E.K.; Manioglu, G. Evaluation of phase change materials used in building components for conservation of energy in buildings in hot dry climatic regions. *Renew. Energy* 2020, 162, 1919–1930. [CrossRef]

25. Yang, L.; Qiao, Y.; Liu, Y.; Zhang, X.; Zhang, C.; Liu, J. A kind of PCMs-based lightweight wallboards: Artificial controlled condition experiments and thermal design method investigation. *Build. Environ.* 2018, 144, 194–207. [CrossRef]

26. Cascone, Y.; Capozzoli, A.; Perino, M. Optimisation analysis of PCM-enhanced opaque building envelope components for the energy retrofitting of office buildings in Mediterranean climates. *Appl. Energy* 2018, 211, 929–933. [CrossRef]

27. Muruganantham, K. Application of Phase Change Material in Buildings: Field Data vs. EnergyPlus Simulation. Arizona State University, December 2010; p. 84. Available online: http://repository.asu.edu/attachments/56138/content/Muruganantham_asu_0010N_10151.pdf (accessed on 1 December 2010).

28. Jamil, H.; Alam, M.; Sanjayan, J.; Wilson, J.L. Investigation of PCM as retrofitting option to enhance occupant thermal comfort in a modern residential building. *Energy Build.* 2016, 133, 217–229. [CrossRef]

29. Liu, J.; Liu, Y.; Yang, L.; Liu, T.; Zhang, C.; Dong, H. Climatic and seasonal suitability of phase change materials coupled with night ventilation for office buildings in Western China. *Renew. Energy* 2020, 147, 356–373. [CrossRef]

30. Berardi, U.; Soudian, S. Benefits of latent thermal energy storage in the retrofit of Canadian high-rise residential buildings. *Build. Simul.* 2011, 4, 709–723. [CrossRef]

31. Sage-Lauck, J.; Sailor, D. Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building. *Energy Build.* 2014, 79, 32–40. [CrossRef]

32. Ramakrishnan, S.; Wang, X.; Alam, M.; Sanjayan, J.; Wilson, J.L. Parametric analysis for performance enhancement of phase change materials in naturally ventilated buildings. *Energy Build.* 2016, 124, 35–45. [CrossRef]

33. Biopcm Webpage.Pdf. Available online: https://phasechange.com/biopcm/ (accessed on 12 May 2021).

34. Biopcm Webpage.Pdf. Available online: https://phasechange.com/biopcm/ (accessed on 12 May 2021).

35. What is BioPCM®? Available online: https://phasechange.com/biopcm/ (accessed on 12 May 2021).

36. Lomas, K.J.; Porritt, S.M. Overheating in buildings: Lessons from research. *Build. Res. Inf.* 2016, 45, 1–18. [CrossRef]

37. Teli, D.; Bourikas, L.; James, P.; Bahaj, A.S. Thermal Performance Evaluation of School Buildings using a Children-based Adaptive Comfort Model. *Procedia Environ. Sci.* 2017, 38, 844–851. [CrossRef]

38. Liang, H.-H.; Lin, T.-P.; Hwang, R.-L. Linking occupants’ thermal perception and building thermal performance in naturally ventilated school buildings. *Appl. Energy* 2012, 94, 355–363. [CrossRef]

39. ISO. ISO 7730:2005 Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. Available online: https://www.iso.org/standard/39155.html (accessed on 1 November 2005).

40. Pomianowski, M.; Heiselberg, P.; Zhang, Y. Review of thermal energy storage technologies based on PCM application in buildings. *Energy Build.* 2013, 67, 56–69. [CrossRef]

41. Waqas, A.; Din, Z.U. Phase change material (PCM) storage for free cooling of buildings—A review. *Renew. Sustain. Energy Rev.* 2013, 18, 607–625. [CrossRef]

42. Zhou, D.; Zhao, C.; Tian, Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. *Renew. Sustain. Energy Rev.* 2020, 117, 35–45. [CrossRef]

43. Zhu, N.; Hu, N.; Hu, P.; Lei, F.; Li, S. Experiment study on thermal performance of building integrated with double layers shape-stabilized phase change material wallboard. *Energy* 2019, 167, 1164–1180. [CrossRef]