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# Assessing the Energy Performance of Prefabricated Buildings Considering Different Wall Configurations and the Use of PCMs in Greece

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**Abstract:** Despite the multiple advantages of prefabricated compared to conventional buildings, such as significant reductions in cost and time, improved quality and accuracy in manufacture, easy dismantling and reuse of components, reduction in environmental degradation, increase of productivity gains, etc., they still share a small part of the European building stock, mainly in the Mediterranean. This paper attempts to highlight the potential of prefabricated buildings to achieve advanced levels of performance, particularly as regards their thermal and energy behavior. More specifically, in this paper the energy needs of a single-family building constructed with prefabricated elements is analyzed, considering different climate contexts. The prefabricated elements comprising the building envelope were developed in order to address specific requirements with respect to their structural, hygrothermal, energy, fire, acoustical, and environmental performance, within the research project SUPRIM (sustainable preconstructed innovative module). The new multifunctional building element, also incorporating phase change materials for increased latent thermal heat storage, has been proven to be beneficial in all the examined climate zones. The results of the relevant studies will highlight the contribution of the new prefabricated element to the sustainability of the overall construction, as well as its advantages when compared with conventional constructions.

**Keywords:** prefabricated buildings; SUPRIM; EnergyPlus; building energy performance; phase change materials

## 1. Introduction

In the Mediterranean countries, residential buildings represent almost 80% of the total building stock, with the onsite process, and reinforced concrete and brick masonry, being the dominant construction solutions [1]. Although industrialization and off-site, precast construction is a growing sector in Central Europe and a reality in many countries all over the world, such as Singapore, China, and the United States [2–4], this is not the case for the countries of the Mediterranean area, such as Greece, where the share of prefabricated buildings accounts for less than 2% [5]. It is true that for many years, the precast construction method, involving the manufacturing of the building modules off site and their transportation and assembly on site, has been regarded as of inferior quality or was dedicated to temporary constructions. However, today, things have changed; prefabricated construction methods compete with conventional ones in every aspect of performance [6]; they also present considerable reductions in cost, installation time, and noise; moreover, they are also considered as a cost effective and environmentally friendly solution that does not have to compromise the architectural design and the building shape [7,8].

To date, several studies have investigated the performance of prefabricated buildings with respect to energy consumption and waste during the construction phase [9,10], the construction quality and safety [11,12], and of course with regard to their energy and environmental performance [13–18]. However, only a small number of relevant studies, assessing the energy performance of prefabricated constructions, have been conducted in the Mediterranean area [16,19], indicating a gap in the existing literature and the need for supplementary scientific analysis. Especially for the warm Mediterranean conditions, the establishment of strategies that would further improve the thermal performance of the prefabricated buildings, generally characterized by less thermal inertia, compared to conventional heavyweight ones, is of crucial importance. In this regard, the use of latent heat storage components in the building walls, such as phase change materials (PCMs), could considerably reduce the heat transmission and control the peak cooling loads in summer, while their incorporation could also be very useful for indoor temperature regulation during the winter period [20]. Up to the present time, many scientific studies have evaluated the role of PCM in building applications in the Mediterranean area with respect to the indoor thermal comfort conditions, the heating and cooling energy savings, and the reduction of temperature fluctuations of the envelope surfaces ([21–27]). Despite this, most of them mainly focus on conventional or lightweight constructions rather than on prefabricated buildings, while the emphasis is mainly given to the summer period. Moreover, most of the existing relevant studies, assess the PCMs' application either as a combination with cement plaster for exterior/interior facades, or in the form of mats, consisting of rectangular pouches that are filled with the PCMs and installed as a single layer behind wall boards ([21–27]). On the other hand, and to the authors knowledge, the use of the phase change materials as a composite concrete layer has been far less evaluated.

Based on the above remarks, the aim of the present paper is to provide further knowledge on the energy performance and the indoor thermal conditions of prefabricated structures in the Mediterranean context, not only in summer, but also in the winter period. More precisely, the study attempts to evaluate the energy performance of a one-story, prefabricated family building compared to a conventional construction, under different climatic conditions in the Mediterranean area. For this purpose, dynamic energy performance simulations with the EnergyPlus tool were conducted. The energy performance of the building, involving the annual heating and cooling needs, and the indoor thermal conditions were examined for different wall configurations (i.e., conventional and prefabricated building elements), whereas the effectiveness of the PCMs as a latent thermal heat storage strategy was also evaluated as an alternative supporting the prefabricated construction.

In this study, the investigated prefabricated building incorporated the new prefabricated building element that was developed within the context of the research project SU.PR.I.M. (SUstainable PReconstructed Innovative Module) [28], which is co-funded by the European Union and national sources. The new building module was developed in order to satisfy specific needs as regards its mechanical strength, hygrothermal performance, energy behavior, response to sound, reaction to fire, and environmental impact. The new prefabricated building element is made of steel hollow elements, positioned vertically at a distance between 0.70 m and 1.00 m, and two concrete panels, positioned parallel to each other, on either side of the steel elements. The gap between the steel elements is filled with expanded or extruded polystyrene. Each layer (concrete panel, thermal insulation/steel hollow element) is 0.05 m thick. The whole wall element is insulated with external thermal insulation, usually extruded polystyrene, covered with organic mortar. It should be mentioned that the type and the thickness of the external thermal insulation materials may vary, in order to satisfy different needs, i.e., with regard to the climate, the requirements for acoustic insulation, or fire performance, etc.

In order to further enhance the thermal performance of the examined wall element, especially as regards its thermal mass and its dynamic behavior, the integration of PCMs into the concrete mixture was studied. Actually, as discussed in Section 2 of the paper, it was decided to add PCMs only on the inner concrete panel, in order to contribute to the control of the interior surface temperature and, as a result, to the improvement of the indoor comfort conditions and the building's energy performance. The study considered the addition of two types of powder PCMs in the concrete mixture with melting temperatures equal to 24 °C and 28 °C. The selection of the melting points was based on the recommendations of Soares et al. [29] and Ascione et al. [30] regarding the optimum phase change temperature for PCM in the Mediterranean area, targeting higher energy efficiency both in the winter and summer periods. Regarding the proper concentration of the PCMs, values ranging between 5% and 25% [31–33] have been often reported for building envelope applications, with the concentration of 20% presenting considerable energy savings and an improved indoor thermal environment. Additionally, experimental tests showed that the mechanical strength of the concrete panels is significantly reduced when the concentration of PCMs in the concrete mixture is higher than 20%. Based on the above, the proportion of the PCMs in the concrete mixture was considered equal to 20% in this study. The developed building module (with and without the addition of PCMs) was considered as the main wall element of the investigated prefabricated buildings.

The paper is organized as follows: In Section 2, an overview of previous studies, assessing the role of PCMs on the improvement of the buildings' energy performance is given, whereas the detailed description the various examined scenarios and the simulations' input parameters are presented in Section 3. Section 4 provides the presentation and justification of the simulation output and the discussion of the performance of the prefabricated building, compared to the conventional one, while in Section 5, the main conclusions are summarized.

## 2. Phase Change Materials Applications in Buildings of the Mediterranean Area

The incorporation of phase change materials into the components of the building envelope constitutes a solution that has gained increasing scientific interest, to increase the thermal heat storage and avoid overheating and increased cooling loads in summer, but also to improve the buildings' winter energy performance. Especially for lightweight buildings, PCM applications are considered as an effective solution to increase the buildings' thermal inertia, and to eliminate excessive indoor "Tair" (air temperature) fluctuations, which often compromise thermal comfort conditions [34,35]. Up to the present time, an increasing amount of literature, evaluating the improvement of the energy performance of Mediterranean buildings using latent thermal heat storage techniques has been published. Focusing on building wall applications, the respective studies generally evaluate the effect of PCMs' applications at various locations (i.e., internally, externally, and within the wall section), with the optimum position strongly depending on the combination of various parameters, including the weather conditions of the examined area, the considered melting points, the main goal of the PCMs' application (i.e., emphasis on winter or summer energy demand and indoor thermal comfort) etc. [36].

Indicatively, Saafi et al. [24] evaluated the role of PCMs integrated into conventional building envelopes under the Tunisian warm climate. Several cases of PCM integration in the building shell (inside, outside brick wall, combined with EPS insulation, roof), various peak melting temperatures between 20 °C and 30 °C, as well as different wall orientations were examined. The analysis suggested that the PCM layer, when applied on the outside face of a brick wall, provides better energy performance efficiency compared to its application on the inside, with cooling energy savings rising to 13.4% for a south orientation. In a brick wall, better efficacy of PCMs is observed in the absence of insulation, with energy reduction around 12.21%. In the same context, Panayiotou et al. [37] studied the integration of PCMs with a melting temperature of 29 °C on the envelope of a typical dwelling in Cyprus, though dynamic numerical simulations. The authors examined various PCM placements in the building shell. The obtained simulation results suggested the outside face of the external building wall as the optimum placement of the PCM layer in a typical Mediterranean building located in the warm region of Cyprus. The achieved annual energy savings due to PCMs (no insulation) ranged between 21.7% and 28.6%, with the higher efficiency being noticed in the summer rather than in the winter period. On the other hand, when PCMs were combined with thermal insulation the maximum energy savings per year reached 66.2%, while the PCMs presented higher performance in summer rather than in winter. Other studies have mainly focused on the effect of PCMs when applied at the inner face of the building walls. For example Ozdenefe et al. [38] examined, via numerical simulation means, the effect of PCMs when they are integrated into the inner side of the wallboards in a typical building in

Cyprus. The analysis focused on the cooling season, while four scenarios were considered in terms of construction styles (perforated clay brick walls with reinforced concrete slabs, and cellular concrete block walls with cellular concrete slabs) and layer thicknesses. Simulation results indicated that the PCMs were most effective in the scenario of thinner walls and lightweight cellular concrete slabs; in this case, indoor air temperatures were reduced by up to 1.7 °C, and the cooling energy needs decreased by 14.0%.

Soares et al. [29] conducted multi-dimensional research on the effect of PCMs integrated in the inner side of a lightweight, steel-framed residential building on an annual and monthly base, while different case study cities in Spain, Portugal, Italy, and France were examined. Parameters that were taken into consideration were different melting temperatures ranging from 18 °C to 28 °C, as well as seven different countries (climate locations) from an energy saving point of view. The results indicated that the optimum melting point of the PCMs for the warmer Mediterranean climates ranged between 22 °C and 26 °C, while their application resulted in a peak energy efficiency gain of about 62% for Portugal's climate. Similar results have also been mentioned by Ascione et al. [30] who evaluated the effect of a PCM wallboard, positioned on the inner face of the outside building walls of an office building, with respect to indoor thermal comfort and the building's energy needs. Different melting points, ranging from 26 °C to 29 °C were considered, while dynamic energy performance simulations were conducted for Ankara, Naples, Athens, Marseille, and Seville. The obtained simulation results indicated higher summer energy savings and more favorable indoor thermal conditions for the higher melting points, with the cooling energy savings reaching 7.2% in Ankara, 4.1% in Marseille, and almost 3% in Seville and Naples. Moreover, according to the authors suggestions, when PCMs are implemented in buildings of the Mediterranean area, the optimal PCM melting point in the winter period ranges between 18 °C and 22 °C, while in summer, suitable values vary between 25 °C and 30 °C.

To continue, Guarino et al. [25] numerically assessed the effectiveness of PCMs integrated into the inner face of the exterior walls of a lightweight structure in Palermo, both during heating and cooling season. However, as the authors mention, the application of PCMs to the inner side of the exterior building walls would lead to a heat release in the indoor thermal environment during the nighttime (i.e., discharge period), increasing the overheating risk. The acquired simulation results thus highlighted the need to combine PCMs with natural ventilation in summer, so as to increase the heat discharge, effectively remove heat release, and reduce cooling energy needs; in winter, PCMs again proved an efficient solution towards the decrease of the heating energy demand, with their effect being, however, less prominent. Similarly, Costanzo et al. concluded in their research [26] that the implementation of a natural ventilation strategy at nighttime is necessary to enable a full discharge of the PCM on a daily basis in a lightweight buildings under Mediterranean conditions. More specifically, they examined the use of PCMs in a typical lightweight office building shell during the cooling period. Parameters, such as different melting peak temperatures (23 °C, 25 °C, 27 °C), thickness values, and night ventilation rates (2 ACH, 4 ACH) were considered for the cooling season. Peak cooling loads, energy needs, as well as operative temperatures were examined for all parameters stated above.

Based on the scientific evidence mentioned above, it can be generally said that:

- the applications of PCMs in the Mediterranean context mainly concerned conventional and lightweight constructions, realized onsite, rather than prefabricated buildings, while the emphasis was mainly on the cooling period.
- most of the existing studies assessed the PCMs combined with the plaster layer, either on the inner or the external part of the wall, whereas applications on composite concrete panels were rarer.
- in hot regions such as the Mediterranean area, and when the emphasis is placed on the summer period, the most favorable position of the PCM layer is the exterior face of the external building walls, as this reduces the external heat gains of the thermal zone. On the other hand, during winter the optimal PCM location is the inner part of the external building wall as this facilitates the storage and release of heat back to the thermal zone.

In this context, the present paper attempts to examine the role of PCMs in enhancing the performance of prefabricated buildings, located in the Mediterranean climate of Greece. Two building types, a prefabricated and a conventional one, made of reinforced concrete and brick masonry, are analyzed, both with respect to their annual energy performance and indoor thermal conditions, while the effectiveness of the PCMs as a latent thermal heat storage strategy in the prefabricated building is also considered. Moreover, given that the application aims at the improvement of the building's energy performance, both in winter and in summer, the PCM is applied at the internal face of the exterior wall, while summer night ventilation will be also considered to facilitate both the heat removal and the solidification process.

## 3. Materials and Methods

### 3.1. Case Study Presentation and Simulation Scenarios

The study concerns the energy performance of a small, single-family building, covering an area of 47.3 m$^2$, as shown in Figure 1. The plan is rectangular, expanded along the south-north axis, with openings only on the south and north walls. The roof is inclined and is covered with clay tiles. Below the inclined roof of the building, there is a horizontal slab, made of reinforced concrete, above which a thick layer of 10.0 cm thermal insulation (XPS) is positioned. The floor of the house, in contact with the ground, is constructed with reinforced concrete and is insulated with a 10.0 cm thick XPS layer. The windows comprise a PVC frame with a double, low-e glazing. The U-value of the transparent elements is equal to 2.0 W/(m$^2$ K).

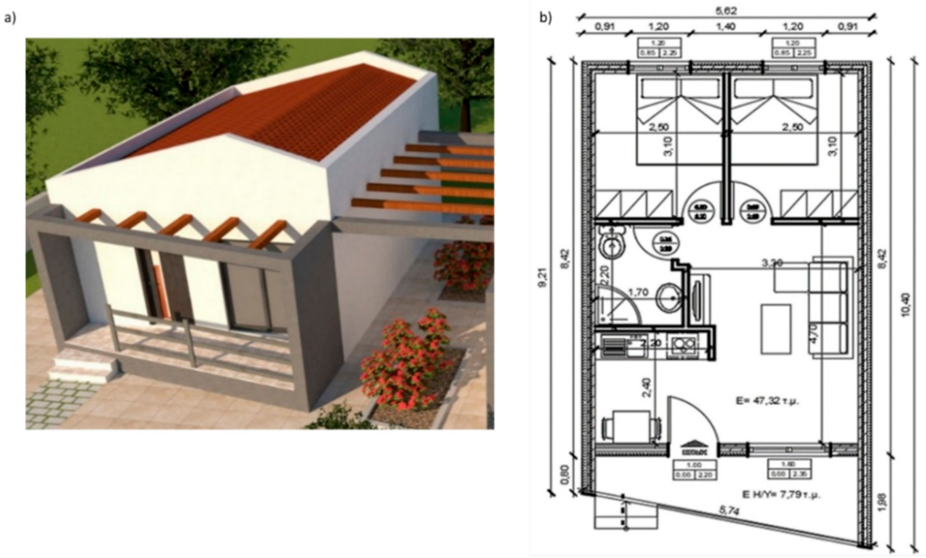


**Figure 1.** (**a**) External 3D view and (**b**) plot of the examined building.

To comparatively assess the performance of the prefabricated construction with the new module developed through the SUPRIM project, the building is examined for three different wall types:

- Considering the conventional wall construction made of reinforced concrete and hollow clay bricks (ETICS).
- Incorporating the new prefabricated module developed through the SUPRIM project, without the use of phase change materials (SUPRIM).
- Incorporating the new prefabricated module developed through the SUPRIM project, with the additional use of phase change materials (SUPRIM-PCM).

For the analysis of the energy performance, different levels of XPS thermal insulation were studied for all three wall types. More specifically, for the three types of the vertical elements' construction, the thickness of the XPS thermal insulation, positioned on the external surface of the vertical elements, was set equal to 5.0, 10.0, 15.0, and 20.0 cm. For the sake of clarity, it should be noted that the results concerning the examined configurations henceforward mentioned in the text, are named after their type and the insulation thickness. For example, "ETICS 5 cm" corresponds to a conventional wall construction of reinforced concrete and bricks, having 5 cm external thermal insulation.

The thermophysical parameters of the building envelope materials of the investigated vertical elements are given in Table 1. With regards to the 3rd configuration scenario of the building walls (i.e., SUPRIM-PCM), a mix of two PCMs has been considered, with melting points at 24 °C and 28 °C and phase change enthalpies at 140 kJ/kg and 185 kJ/kg, respectively. The PCMs are directly incorporated into the concrete mixture (including aggregates) at a concentration of 20% to further modify the energy storage capacity of the inner concrete panel. In order to define the thermal properties of the concrete panel containing PCMs accurately in the Energy Plus simulation tool, the results of a relevant experimental campaign, conducted in the context of the SUPRIM research program, were used. However, given that the focus of the present paper is mainly given to the energy performance analysis, only the basic experimental output is provided here.

**Table 1.** Geometrical and thermophysical parameters of the building envelope materials of the examined vertical walls (starting from the outside towards the inside face).

| Examined Wall Scenario | Thickness x (m) | Specific Heat Capacity Cp (J/KgK) | Thermal Conductivity λ (W/mK) |
|---|---|---|---|
| ***1) ETICS*** | | | |
| Organic plaster | 0.01 | 1100 | 0.87 |
| Insulation layer XPS | 0.05–0.20 | 1450 | 0.034 |
| Bricks | 0.19 | 1000 | 0.58 |
| Internal plaster | 0.02 | 1100 | 0.87 |
| ***2) SUPRIM*** | | | |
| Organic plaster | 0.01 | 1100 | 0.87 |
| Insulation layer XPS | 0.05–0.20 | 1450 | 0.034 |
| Concrete panel | 0.05 | 1000 | 2.1 |
| Insulation layer EPS | 0.05 | 1450 | 0.036 |
| Concrete panel | 0.05 | 1000 | 2.1 |
| Internal plaster | 0.02 | 1100 | 0.87 |
| ***3) SUPRIM-PCM*** | | | |
| Organic plaster | 0.01 | 1100 | 0.87 |
| Insulation layer XPS | 0.05–0.20 | 1450 | 0.034 |
| Concrete panel | 0.05 | 1000 | 2.1 |
| Insulation layer EPS | 0.05 | 1450 | 0.036 |
| Concrete panel with PCM | 0.05 | - | 1.95 |
| Internal plaster | 0.02 | 1100 | 0.87 |
| Organic plaster | 0.01 | 1100 | 0.87 |

More precisely, the thermal conductivity of the concrete samples (dimensions 10 × 10 × 10 cm) with and without the incorporation of PCMs were measured with a KD2 Pro handheld device, using a single needle TR-1 sensor (Figure 2). The experimental campaign was conducted according to the Standards IEEE 442, "guide for soil thermal resistivity measurements" and ASTM 5334, "standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure" [39,40]. The experimental output suggested a thermal conductivity of 1.95 W/mK for the concrete sample including the PCMs, whereas the respective value for the reference sample without PCMs was 2.1 W/mK. The latter values were considered for the energy performance simulations, while it was also assumed that the PCM is uniformly distributed throughout the thickness of the concrete panel.

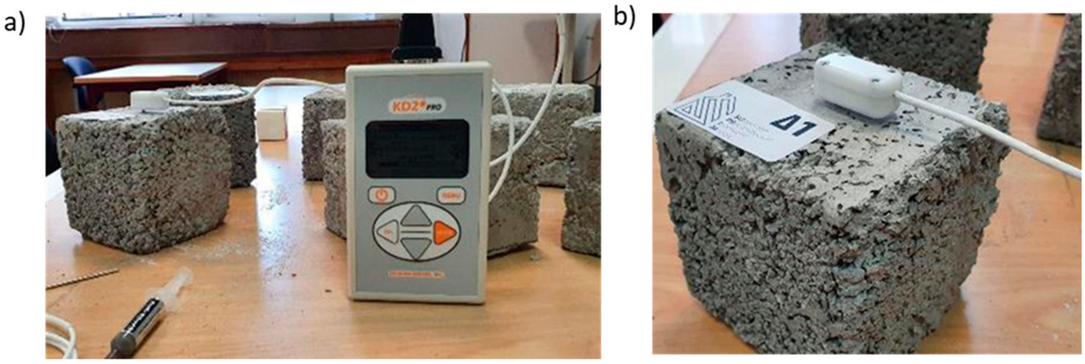


**Figure 2.** (**a**) experimental device and samples for the thermal conductivity measurements and (**b**) TR-1 sensor installation into the material.

Moreover, to evaluate the buildings' energy performance under different climatic conditions, it was assumed that the three examined building types were located in four different cities in Greece, with respect to the four climatic zones defined in the country: Heraklion (Lat. 35°19′ N; Long. 25°08′ E) for zone A (the warmest), Athens (Lat. 37°58′ N; Long. 23°42′ E) for zone B, Thessaloniki (Lat. 3740°38′ N; Long. 22°56′ E) for zone C, and Grevena (Lat. 40°05′ N; Long. 21°25′ E) for zone D (the coldest). The location of the four cities and their average monthly outdoor air temperatures are presented in Figure 3 and Table 2 respectively.

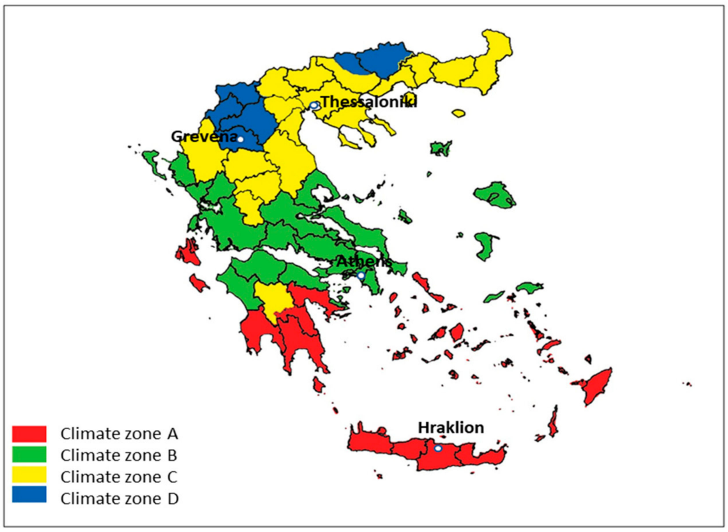


**Figure 3.** Climatic zones of Greece according to the Greek Regulation on the Energy Performance of Buildings, and locations of the case study cities [41].

**Table 2.** Monthly average air temperature (Tair) of the 4 investigated cities, corresponding to the 4 climate zones.

| City/Zone | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Heraklion** Clim. Zone A | 13.3 | 12.39 | 13.92 | 15.45 | 18.83 | 22.68 | 26.09 | 26.2 | 23.71 | 21.07 | 17.26 | 14.81 |
| **Athens** Clim. Zone B | 9.85 | 9.78 | 12.7 | 15.52 | 20.61 | 25.3 | 28.52 | 28.4 | 23.37 | 19.66 | 14.98 | 11.44 |
| **Thessaloniki** Clim. Zone C | 5.39 | 6.47 | 10.14 | 13.67 | 19.37 | 23.89 | 26.79 | 26.48 | 21.14 | 16.93 | 11.28 | 6.98 |
| **Grevena** Clim. Zone D | 3.94 | 5.33 | 9.65 | 13.38 | 19.25 | 23.42 | 26.97 | 26.71 | 20.39 | 15.73 | 9.61 | 5.31 |

Finally, aiming at a comparative assessment of the energy performance and the indoor thermal conditions of the building incorporating the SUPRIM module, an analysis was conducted: (a) for controlled indoor temperature, assuming the use of an HVAC (Heating, Ventilation, Air Conditioning) system, and (b) for free floating conditions, where the indoor temperature is free running and the PCMs are expected to improve the indoor thermal conditions.

All considered simulation scenarios are presented in the diagram of Figure 4.

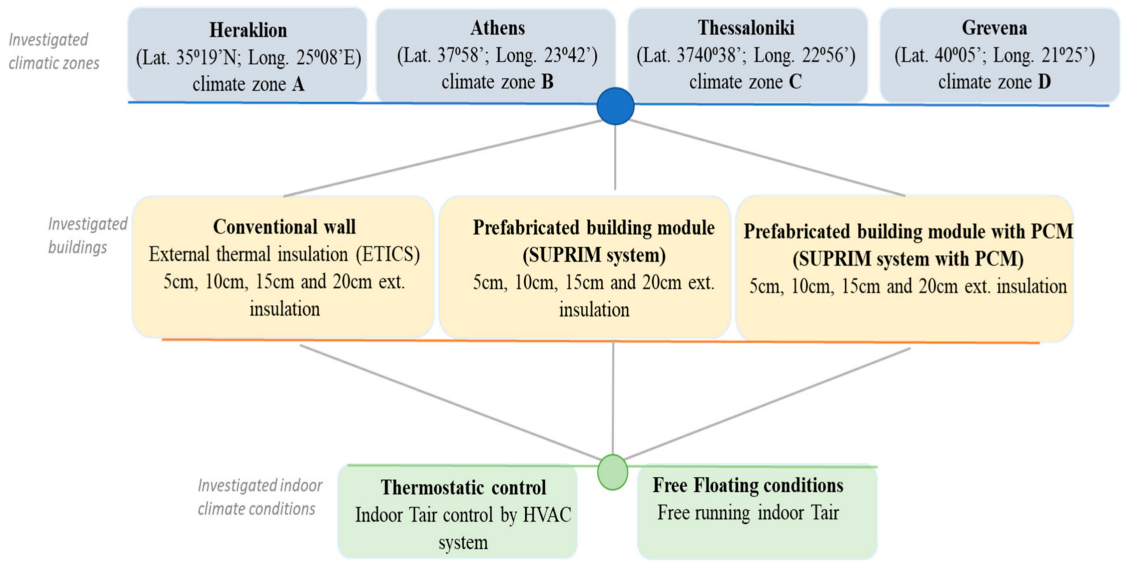


**Figure 4.** Examined simulation scenarios involving climatic conditions, building typologies, and control of indoor climate.

## 3.2. Dynamic Energy Performance Simulations and Modelling Set-Up

In this study, dynamic energy performance simulations were conducted with the EnergyPlus tool, a software developed by the US Department of Energy and continuously used and validated by many previous scientific studies worldwide [42–45]. Given its increased simulation capabilities, the model has been successfully used in several research fields, including the estimation of energy needs of residential [46–48] or tertiary buildings [49–51], indoor thermal comfort evaluation [52,53], and daylight analysis [54,55], but also in energy performance assessment of buildings with PCMs in their envelope components [30,38,56,57].

In EnergyPlus, the calculation of the thermal loads of buildings is by default based on the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) heat balance method, accounting for the heat fluxes on outdoor and indoor surfaces, and also heat conduction through the building elements [58]. The principal advantage of the conduction transfer function (CTF) method lies in the reduction of the transient heat transfer equations into simple linear equations, having constant coefficients, which can be finally easily solved for both inside and outside face temperatures and heat fluxes [38]. The CTF method can be thus efficiently applied for simulating buildings having constant material properties (i.e., ETICS and SUPRIM scenarios in this study), but this is not the case for the PCMs, the heat storage capacity of which is not constant and varies as a function of temperature.

To overcome this barrier, and accurately simulate materials with variable thermal properties, EnergyPlus has incorporated the conduction finite difference solution algorithm (CondFD) [24], a model complementing the CTF method for cases where materials with variable thermal properties are evaluated. The CondFD method has been tested and validated by previous studies [42,59], while a detailed description of the governing equations is provided in [26,38,56]. When a phase change material is thus modeled in EnergyPlus, the user needs to provide a set of temperature/enthalpy values of the PCM, by using the dedicated module "material property: phase change".

In this study, the accurate determination of the thermal properties of the PCM in the SUPRIM-PCM scenario was crucial for the correct evaluation of the building's energy performance. However, given that the PCM was considered to be directly incorporated in the inside concrete panel, the enthalpy–temperature relationship of the mixture, rather than of the pure PCM, had to be known and introduced into the EnergyPlus model. In this context, the temperature-enthalpy values of the inside concrete panel of the prefabricated module were defined through the results of a measurement campaign, conducted in the context of the SUPRIM research program.

More precisely, samples of concrete incorporating microencapsulated phase change materials (manufacturer Encapsys) with melting points at 24 °C and 28 °C, and at a 20% concentration, were evaluated through differential scanning calorimetry (DSC), a widely applied method to test the phase change performance of a sample PCM [60]; the examined samples were submitted to a controlled temperature increase of 5 °C/min and the corresponding heat fluxes were recorded, providing relevant information on latent heat and specific enthalpy, with regards to the material's phase change. The heat flow (mW) at each temperature provided by the DSC was then converted to energy (J/g) and the estimated values were introduced into the EnergyPlus model [61]. It is also important to mention that, given that 2 PCMs with different melting points were considered, the phase transition did not occur at a specific temperature but a melting range was considered, starting from 21 °C to 28.5 °C. The PCMs' selection was made so as to find a suitable compromise between summer and winter period for the Mediterranean area, where the optimal melting points of the incorporated PCMs should be within the range of 24–30 °C and 18–22 °C respectively [30].

To continue, other important boundary parameters for the simulations involved:

- The infiltration rate. It was defined in accordance with the Hellenic Regulation on the Energy Performance of Buildings [41]; the respective value was set to 0.5 Air Change per Hour (ACH) and it remained constant for all the examined scenarios.
- The operational schedules concern the occupancy profile, the lighting and equipment usage, the ventilation rates, as well as the heating and cooling setpoints. They were all defined in accordance with the Hellenic Regulation on the Energy Performance of Buildings [13], as shown in Table 3.

**Table 3.** Boundary conditions and operational schedules, considered for the simulations.

| Parameter | Unit | Value | Schedule Type |
|---|---|---|---|
| Occupancy | Persons/100 $m^2$ | 5 | 7/7;<br>full occupancy: 00:00–07:00, 17:00–00:00;<br>50% occupancy: 07:00–17:00 |
| Air change/ventilation | $m^3$/s/person | 0.042 | According to the usage profile. |
| Night ventilation | ACH | 15 | During the cooling period;<br>from 00:00 till 08:00 a.m.;<br>only if the indoor air temperature is higher than the outdoor air temperature by 1.0 °C. |
| Lighting | W/$m^2$ | 6.4 | 12/12;<br>0 W/$m^2$: 00:00–08:00;<br>0.3 W/$m^2$: 08:00–17:00;<br>0.75 W/$m^2$ 17:00–00:00 |
| Heating setpoint | °C | 20 | Heating period<br>(according to the Climate zone) |
| Cooling setpoint | °C | 26 | Cooling period<br>(according to the climate zone) |
| Heat gains from occupants | W/person | 80 | Follows the usage profile |
| Heat gains from equipment | W/$m^2$ | 4.0 | Follows the usage profile |

Finally, as previously mentioned, the energy performance of the one-story house was calculated for three different types of wall, for the four climatic zones, and considering two scenarios of the indoor microclimate involving:

1. Controlled indoor temperature, where the indoor air temperature is controlled by an HVAC system. In this case, the heating setpoint is set to 20 °C, while the cooling setpoint is set to 26 °C (from 9:00 a.m. to 24:00 during the cooling season). Heating and cooling seasons are defined for each case study city, according to the recommendations of the Technical Guides of the Greek Building Energy Performance Regulation [41]. Moreover, since the aim of the study is the analysis of the performance of a building without modeling a full HVAC system, the "ideal loads air system" was used in the EnergyPlus simulations
2. Free-floating temperature, where the indoor thermal conditions are not controlled by an HVAC system and the temperature is free running. In this way, the effect of the PCMs towards the improvement of the indoor thermal conditions both in winter and summer could be evaluated. In this case, a night ventilation with a constant air change per hour (ACH) of 15 $h^{-1}$ was assumed during the cooling period to enhance the PCM discharge, provided that the outdoor temperature was lower than the indoor Tair by at least 1.0 °C

## 4. Results and Discussion

### 4.1. Thermal Performance under Controlled Indoor Temperature Conditions

The annual heating and cooling energy needs of the examined buildings are shown in Figure 5, with respect to the thermal insulation thickness, the wall configuration, and the climate zone. In parallel, Figure 6 presents the corresponding heating and cooling energy savings for the prefabricated building (with and without PCMs) compared to the conventional ETICS solution.

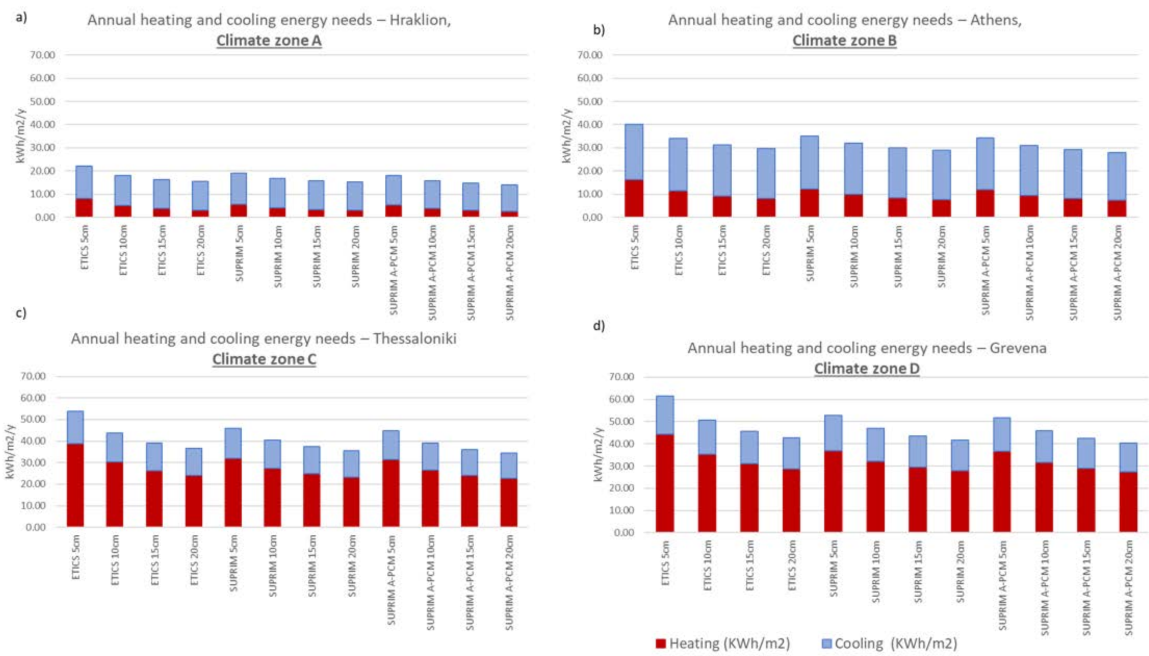


**Figure 5.** The heating and cooling needs calculated for the three examined construction types (conventional with exterior insulation, sustainable preconstructed innovative module (SUPRIM) and SUPRIM-PCM) for climate zone A, B, C, and D.

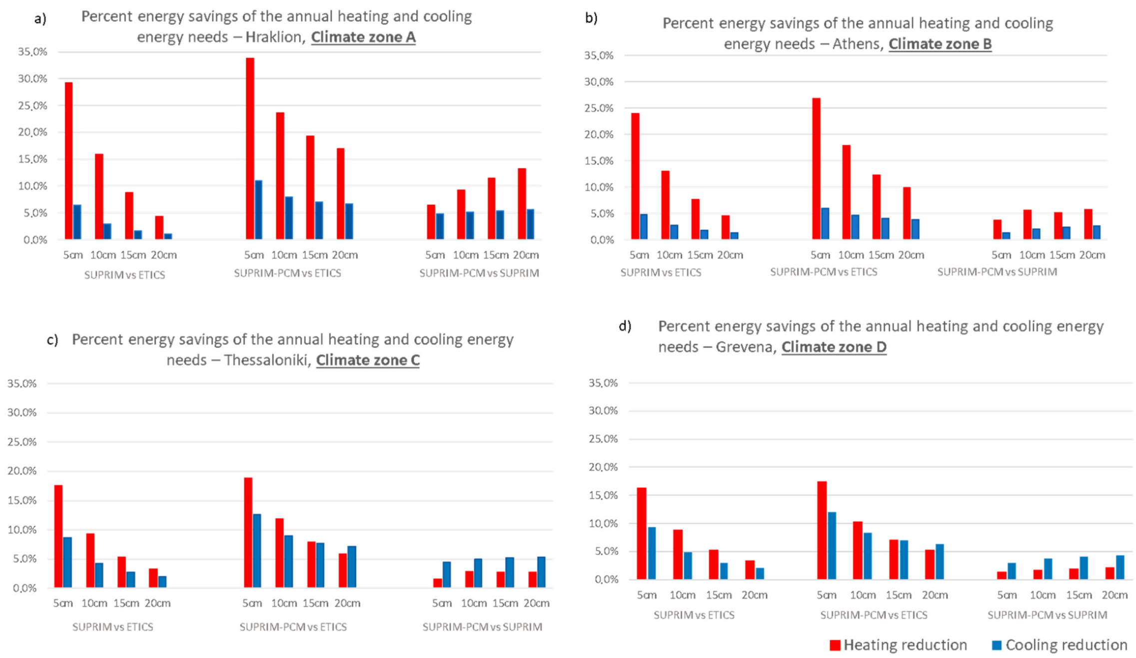


**Figure 6.** Percentage energy saving of the annual heating and cooling energy needs estimated for the various examined scenarios and for climate zone A, B, C, and D.

First, it can be generally seen that the energy needs of the prefabricated building are always lower when the innovative module (i.e., SUPRIM) is incorporated, compared to the respective values for the conventional ETICS construction. More precisely, in the warmest climate zone (i.e., Zone A), the energy required for covering the total heating and cooling needs is higher by 2–15% for the ETICS scenario compared to SUPRIM, with the difference varying as a function of the thermal insulation thickness; it is interesting to notice that as the thickness of the thermal insulation increases, the difference in energy needs between the two wall configurations becomes lower. Furthermore, it can be seen that in Zone A, the cooling needs are significantly higher than the heating ones. In fact, the cooling needs can be even four times higher than the heating ones. The gap becomes larger as the thermal insulation thickness increases. This can be attributed to the fact that the maximization of the thermal resistance of the walls leads to the minimization of heat losses during winter, but it does not cause an equivalent decrease of the cooling needs, as the solar heat gains, its major component, stem mainly from the transparent building elements. For the same reason, the maximum differences between the cooling needs for the two construction types (i.e., SUPRIM and ETICS) hardly exceed 6%, while for the heating loads the maximum difference reaches 29% (see Figure 6a). Again, the difference on the heating needs between the two examined construction types is not the same for every thickness of thermal insulation. As the thermal insulation thickness increases, its impact on heating load reduction weakens.

For Climate Zone A, it can also be seen that the differences on the total energy needs are rather moderate when the PCMs are integrated in the inner concrete panel. In fact, when comparing SUPRIM with SUPRIM-PCM, the observed reductions range between 5 and 6% and 6 and 13% in cooling and heating loads, respectively. Especially for the cooling needs, the monthly analysis of the derived results showed that the PCMs perform better in June, when a reduction of up to 16% is observed for all insulation thicknesses, while their performance falls in the following months and does not exceed 5%. In more detail, the city of Heraklion is characterized by warm summers, with an average daily maximum temperature in June and July close to 32 °C and average daily minimum close to 21 °C. Thus, in spite of the frequent activation of the phase change, the warm climatic conditions do not permit a full heat discharge of the materials, a phenomenon that has also been observed by Ascione et al. in relevant research in the Mediterranean area [30]. Additionally, as can be seen in

Figure 5a, the PCMs can have a more significant impact on the formation of the cooling needs for lower insulation levels. This can be attributed to the heat discharge and recharge phases that are more intense when the thermal insulation is not increased.

Similar trends are observed when the examined buildings are located in the second warmest zone of Greece, Zone B. Again, the annual energy needs are lower for the building that integrates the SUPRIM element compared to the ETICS, but the differences range over lower levels, i.e., between 2% and 12%. Higher differences are observed for the heating loads (4.7% to 24%, with regard to the thermal insulation thickness), while the difference in cooling needs are lower (1.3% to 4.7%), although the cooling needs are almost doubled (Figure 6b). As in the case of Heraklion, SUPRIM-PCM presents marginally lower cooling energy needs compared to the SUPRIM case, ranging between 1.3 and 3%, depending on the insulation thickness. On a monthly basis, the derived results showed that the SUPRIM-PCM again performed better in June, when a reduction of up to 6% and 7% for insulation thicknesses of 10 cm and 15 cm, respectively, was observed compared to the SUPRIM building. The performance, in the case of SUPRIM-PCM, falls considerably in August, probably because the PCM does not perform a complete discharge. Again, the PCMs present a more significant impact on the formation of the cooling needs for the lower insulation levels, and similar magnitudes of energy savings have also been reported in a previous study in Athens [30].

To continue, the energy need profile changes drastically when the buildings are located in a colder location, such as Thessaloniki in zone C (Figure 5c). The amount of energy needs increases significantly, and the heating needs prevail, as they are almost doubled with respect to cooling. Again, the SUPRIM building always performed better than the conventional ETICS one, as its energy needs are always lower. The difference on total energy needs ranges between 3% and 15%, with the heating loads being reduced by 3% to 17.5% with respect to the thickness of thermal insulation (Figure 6c). As with the previous climatic zones, it can be seen that the maximization of thermal resistance of the walls (as the insulation thickness increases) would contribute to lower heat losses during winter, but the decrease of the cooling needs are of lower importance, again due to the prevailing role of the solar heat gains; the maximum differences between the cooling needs for the two construction types (i.e., SUPRIM and ETICS) is close to 6%. Similarly, in zone D, the coldest of Greece, the energy needs reach their highest levels, with the cooling loads accounting for only one third of the heating ones (Figure 5d). The performance of the SUPRIM wall elements is better in the colder climate of zone D compared to the ETICS construction, as the decrease on the energy needs ranges from 3% to 14%. Again, the heating reduction is more substantial, reaching 16%. Interestingly, the incorporation of the PCMs seems to provide higher cooling energy savings in the two colder zones, ranging between 4.0 and 5.3% and 3.2 and 4.3% for climate zone C and D, respectively. This is mainly attributable to the milder summer conditions in the two colder zones, enabling the full discharge of the PCMs.

### *4.2. Thermal Performance under Free Floating Conditions*

As the next step, the thermal performance of the examined buildings under free floating conditions was evaluated. Then, the assessment of the annual performance of the three examined buildings types was performed (i.e., ETICS, SUPRIM and SUPRIM-PCM). In this case, the lower limit of the thermal comfort (i.e., in the winter period) was 18 °C, while the upper acceptable limit was set to 28 °C (i.e., in the summer period). Figure 7 depicts the percentage period of the total occupancy time that the indoor Tair was within the comfort range (i.e., 18 °C ≤ Tzone ≤ 28 °C) for the four examined climatic zones, and accounting for 10 cm external thermal insulation for all three building configurations.

First, it can be seen that the prefabricated building, SUPRIM, performed marginally better than the ETICS one, regarding the percent time that the Tair of the zone was within the comfort range. However, in all climatic zones, the incorporation of PCMS can further improve the thermal response of the prefabricated building under free floating conditions. Especially in the two warmer climatic zones (i.e., A and B), the addition of PCMs allows for a longer duration of comfort conditions of around 3%, corresponding to 250 h and 150 h, respectively. However, the PCMs' positive effect was of lower importance in the two colder zones (i.e., C and D). Given the low winter temperatures and the absence of a heating system, the resulting indoor Tair values very often fell below 15 °C, even, which cannot be compensated by the PCMs incorporation.

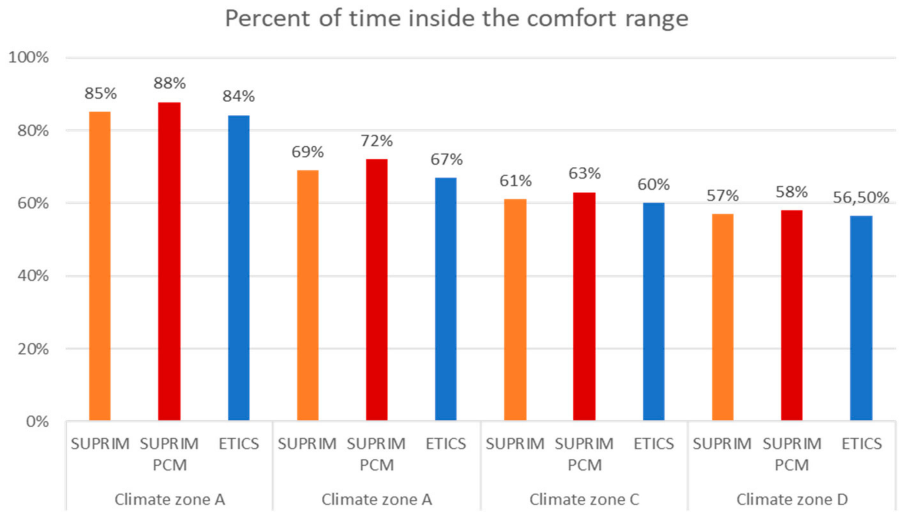


**Figure 7.** Annual percentage of the total occupancy time inside the comfort conditions for the three examined wall types, assuming 10 cm external thermal insulation.

Given the above mentioned results it should be emphasized that, in spite of the positive effect of PCMs, there is still an important part of the total occupancy period when the indoor Tair value is out of the comfort range, a fact that has to be taken into account when PCMs are considered in the design process of the buildings and their HVAC systems. Still, the beneficial effect of the PCMs could have been considerably higher if different melting points had been examined, depending on the climatic conditions. In this study, a mixture of two PCMs was evaluated (i.e., melting points at 24 °C and 28 °C), for all the climatic zones; while a future analysis of multiple melting points would provide the optimal solution for each climatic zone, also enhancing the performance of the SUPRIM building.

To continue, as previously mentioned, the performance of the phase change materials did not present similar characteristics during the summer months, with higher performance rates being reported for all climate zones in June. For the following months (i.e., July and August) the daytime and nighttime temperatures were higher, suggesting unfavorable conditions for a full discharge of the PCMs. In this context, and in order to better evaluate the impact of PCMs on the indoor thermal environment under free running conditions, the indoor Tair and Tsurf (surface temperature) profiles during typical weeks in June were analyzed. More precisely, Figures 8–11 depict the profiles of the indoor air temperature and the surface temperature on the internal side of the southern walls of the three examined building types and with reference to each climatic zone.

For every climatic zone, the provided surface and air temperature profiles corresponded to typical weeks during June, when no extreme heat wave phenomena and extreme temperatures are observed. In all cases, free floating conditions are considered, while the scenario of the 10 cm external insulation is here analyzed for all building configurations. It can be generally seen that during the examined days, in all climatic zones, the air temperature profiles of the SUPRIM-PCM building were always lower compared to the SUPRIM and the conventional ETICS building. More precisely, in Heraklion, the PCMs incorporation resulted in lower indoor Tair values by 0.2–0.8 °C compared to the prefabricated building without PCMs, with the peak daily indoor Tair values not exceeding 27.5 °C (Figure 8a).

***Hraklion, Climate Zone A***

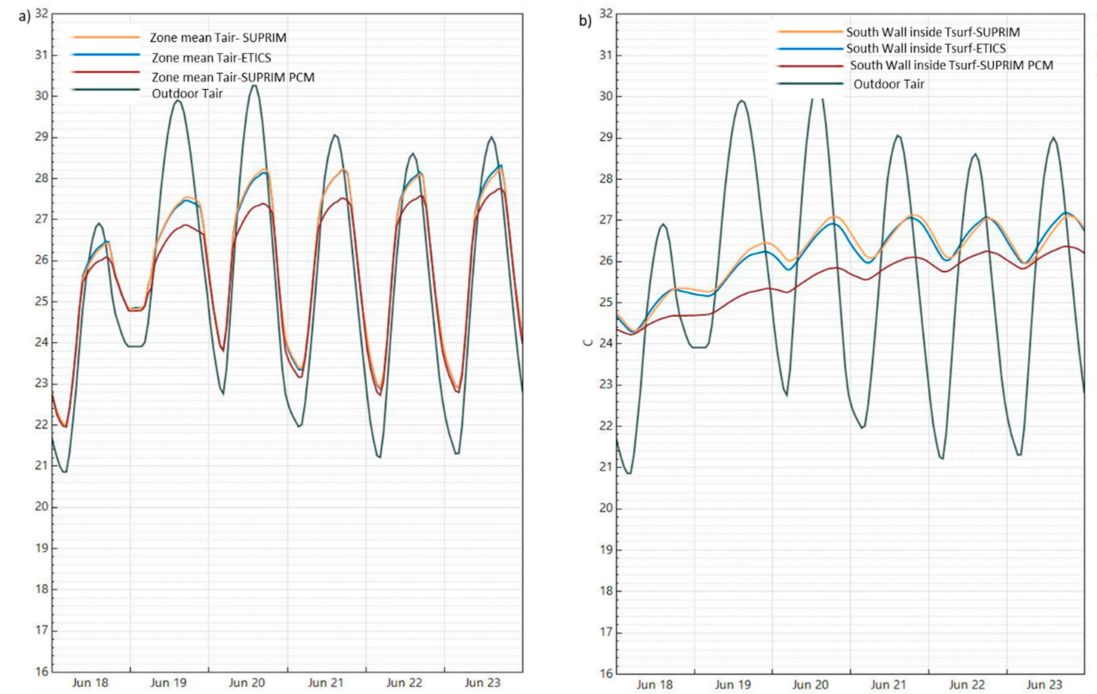


**Figure 8.** Climate zone A: (**a**) outdoor Tair and indoor Tair and (**b**) outdoor Tair and Tsurf evolution of the south facing wall during a typical week in June for the three investigated wall configurations and for 10 cm external insulation.

***Athens, Climate Zone B***

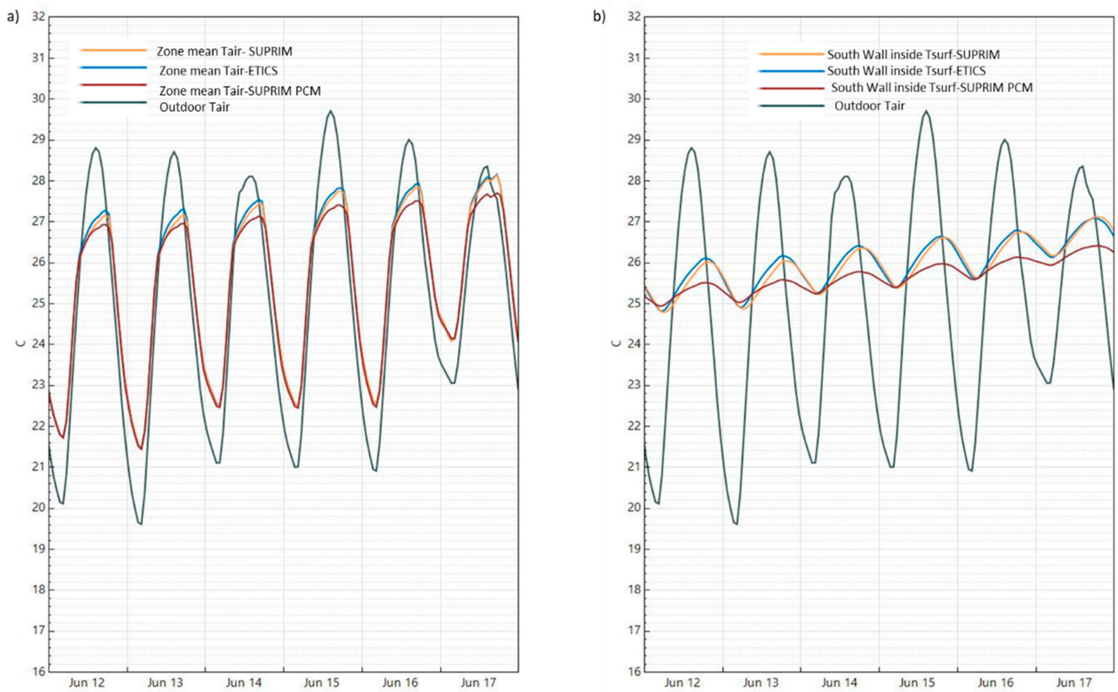


**Figure 9.** Climate zone B: (**a**) outdoor Tair and indoor Tair and (**b**) outdoor Tair and Tsurf evolution of the south facing wall during a typical week in June for the three investigated wall configurations and for 10 cm external insulation.

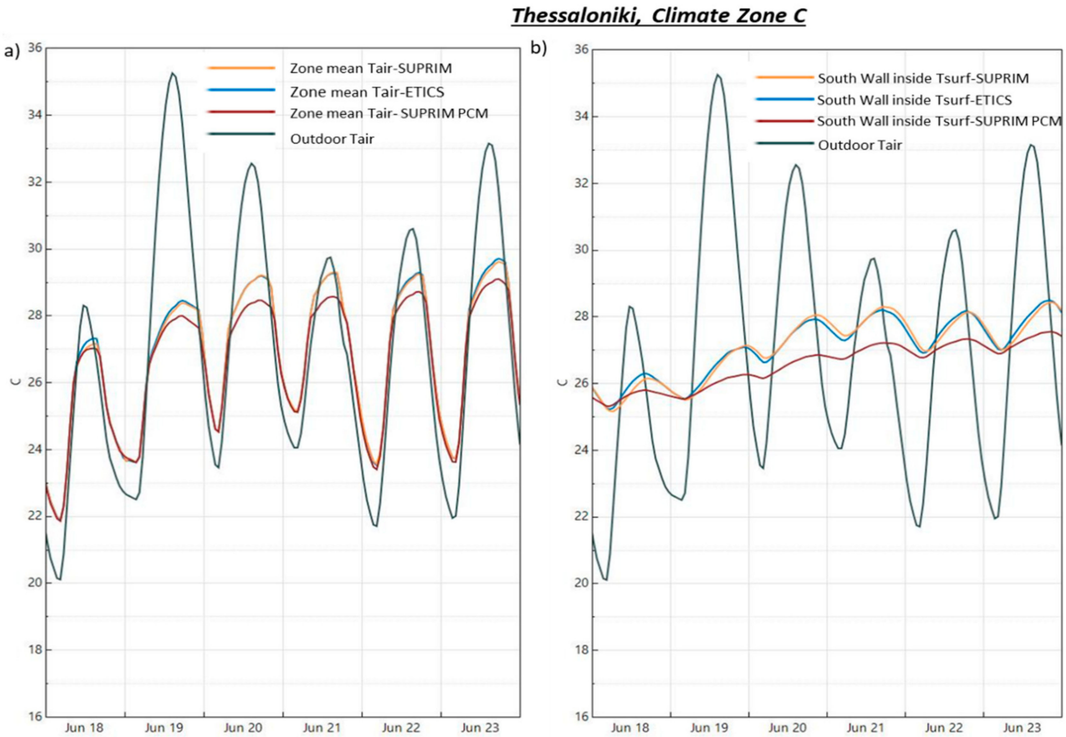


**Figure 10.** Climate zone C: (**a**) outdoor Tair and indoor Tair and (**b**) outdoor Tair and Tsurf evolution of the south facing wall during a typical week in June for the three investigated wall configurations and for 10 cm external insulation.

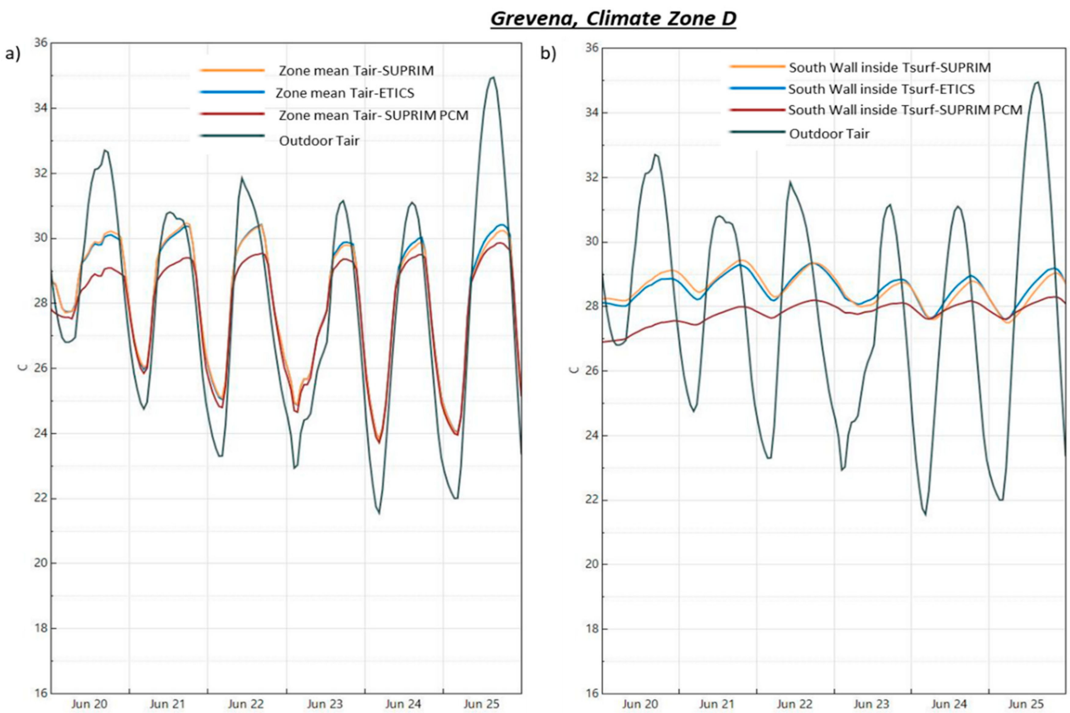


**Figure 11.** Climate zone D: (**a**) outdoor Tair and indoor Tair and (**b**) outdoor Tair and Tsurf evolution of the south facing wall during a typical week in June for the three investigated wall configurations and for 10 cm external insulation.

In Athens, the respective reduction due to PCMs ranged between 0.4 and 0.7 °C, and the indoor Tair fluctuated between 21.2 °C and 27.6 °C, whereas in the SUPRIM building, the zone Tair range fluctuated between 21.1 °C and 28.8 °C, with peak differences reported in the early afternoon (Figure 9a). In both cases, the lower indoor air temperatures were mainly attributed to the lower surface temperatures of the inner face of the building walls; indicatively, in climate zone A, during daytime and given the selected melting points of the PCM mixture (i.e., 24 °C and 28 °C), the phase change was activated and the south wall inside face temperature was lower by almost 1.0 °C compared to the no PCM building, thus leading to reduced convective heat transfer into the building.

Similar tendencies were also noticed in the colder climatic zones of Greece, with the beneficial effect of PCMs being slightly lower compared to the findings in Heraklion and Athens. More precisely, in the case of Thessaloniki, in climate zone C, the indoor Tair in the SUPRIM-PCM building was lower by 0.12–0.51 °C compared to the prefabricated building without PCMs during the examined week in June, with the peak daily indoor Tair values ranging between 27.2 °C and 28.9 °C (Figure 10a). A similar tendency was also noticed in Grevena, zone D, where the respective reduction due to PCMs, ranged between 0.12 and 0.8 °C. As with the two warmer zones, the PCM activation during the daytime, when the Tsurf exceeded 21 °C (a melting range is considered for the PCM mixture, starting from 21 °C to 28.5 °C), contributed to lower surface temperatures (Figures 10b and 11b) compared to the two other examined building configurations, and thus, to lower sensible heat transfer into the zone.

## 5. Conclusions

This paper evaluated the energy performance of a prefabricated building, incorporating the innovative SUPRIM building module in comparison to a conventional heavyweight construction under Mediterranean climatic conditions. The incorporation of PCMS, as a way to improve both the energy needs and the indoor thermal conditions, was also considered. A numerical simulation analysis with the EnergyPlus simulation model was conducted for a precast small family house, considering different thermal insulation thicknesses and various climatic zones in Greece.

The obtained simulation results suggested that the building constructed with the new prefabricated building elements had a better energy performance than the conventional one, made of reinforced concrete and bricks. This behavior was observed regardless of the thickness of the external thermal insulation, which was common for both constructions. More specifically, the improved energy performance concerned mainly the heating loads, while the cooling loads were not significantly reduced. Although the heating loads can be further reduced, through additional measures on the building envelope, such as windows with lower U-values, or thicker insulation on the roof, it is questionable whether the cooling loads can be similarly decreased.

As this work showed, the decrease of cooling loads cannot be achieved by further increasing the thermal resistance of the building envelope. Other, non-conventional measures should be introduced, which can be efficient in excessive heat management through the warmer periods of the year. Apart from solar shading, which is nevertheless beneficial, the heat capacity of the structure plays an important role. To this aim and to further increase the heat storage capacity of the examined prefabricated building, the incorporation of phase change materials into the concrete mix of the inside concrete panel was evaluated. The numerical results presented in this study indicated the potential of the PCMs incorporation to reduce the energy needs, both for heating and cooling periods on the one hand, and to improve the indoor comfort conditions on the other hand. However, their efficiency was found to be higher in warmer than in colder climatic zones. In light of the above, it is important to mention that the proper selection of the melting point of the PCMs, depending on the climatic conditions, would be necessary for the optimization of their performance, indicating a new field for future research. In other words, even if Greek cities are generally characterized by Mediterranean climatic conditions, important deviations still occur among them during the year, from the northern to the southern part of the country. More specifically, selecting the PCM melting temperature for each city, in line with the evolution of the ambient air temperature could further improve the energy performance and the indoor thermal comfort conditions of the examined buildings.

In parallel, to obtain a global perspective of the PCMs efficiency on the buildings' overall environmental and energy performance, a cost effectiveness analysis should be performed in the future, evaluating the pay-back periods, as well as the durability of PCMs after years of charging and discharging.

Finally, even if the conducted analysis was inevitably not exhaustive, the obtained results are expected to be a significant contribution on the respective scientific field. Considering that the share of prefabricated buildings and the relevant scientific studies are today very low in the Mediterranean area, despite their advantages, the present paper provides additional information on their performance, highlighting their enhanced energy behavior, especially when combined with latent heat storage systems such as PCMs.

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## References

1. EU Building Stock Observatory. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/eu-bso_en (accessed on 29 July 2020).
2. Mao, C.; Xie, F.; Hou, L.; Wu, P.; Wang, J.; Wang, X. Cost analysis for sustainable off-site construction based on a multiple-case study in China. *Habitat Int.* **2016**, *57*, 215–222. [CrossRef]
3. Steinhardt, D.A.; Manley, K. Exploring the beliefs of Australian prefabricated house builders. *Constr. Econ. Build.* **2016**, *16*, 27–41. [CrossRef]
4. Generalova, E.M.; Generalov, V.P.; Kuznetsova, A.A. Modular buildings in modern construction. *Proc. Eng.* **2016**, *153*, 167–172. [CrossRef]
5. Apaydin, F. Effectiveness of prefabricated house industry's marketing activities and Turkish consumers' buying intentions towards prefabricated houses. *Asian Soc. Sci.* **2011**, *7*, 267. [CrossRef]
6. Tam, V.W.; Tam, C.M.; Zeng, S.; Ng, W.C. Towards adoption of prefabrication in construction. *Build. Environ.* **2007**, *42*, 3642–3654. [CrossRef]
7. Jaillon, L.; Poon, C.S. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Autom. Constr.* **2009**, *18*, 239–248. [CrossRef]
8. Pan, W.; Gibb, A.G.; Dainty, A.R. Strategies for integrating the use of off-site production technologies in house building. *J. Constr. Eng. Manag.* **2012**, *138*, 1331–1340. [CrossRef]
9. Lu, N. The current use of offsite construction techniques in the United States construction industry. In Proceedings of the Construction Research Congress 2009: Building a Sustainable Future, Seattle, WA, USA, 5–7 April 2009; pp. 946–955.
10. Lawson, R.; Ogden, R. Sustainability and process benefits of modular construction. In Proceedings of the TG57-Special Track 18th CIB World Building Congress, Salford, UK, 10–13 May 2010; p. 38.
11. Lopez, D.; Froese, T.M. Analysis of costs and benefits of panelized and modular prefabricated homes. *Proc. Eng.* **2016**, *145*, 1291–1297. [CrossRef]
12. Knyziak, P. The impact of construction quality on the safety of prefabricated multi-family dwellings. *Eng. Fail. Anal.* **2019**, *100*, 37–48. [CrossRef]
13. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
14. Hong, J.; Shen, G.Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model. *J. Clean. Prod.* **2016**, *112*, 2198–2207. [CrossRef]

15. Tumminia, G.; Guarino, F.; Longo, S.; Ferraro, M.; Cellura, M.; Antonucci, V. Life cycle energy performances and environmental impacts of a prefabricated building module. *Renew. Sust. Energy Rev.* **2018**, *92*, 272–283. [CrossRef]
16. Silva, P.C.; Almeida, M.; Bragança, L.; Mesquita, V. Development of prefabricated retrofit module towards nearly zero energy buildings. *Energy Build.* **2013**, *56*, 115–125. [CrossRef]
17. Gunawardena, T.; Ngo, T.; Aye, L.; Mendis, P. Innovative Prefabricated Modular Structures–An Overview and Life Cycle Energy Analysis. In Proceedings of the International Conference on Structural Engineering Construction and Management, Kandy, Central, Sri Lanka, 16–18 December 2011.
18. Yin, X.; Dong, Q.; Zhou, S.; Yu, J.; Huang, L.; Sun, C. Energy-Saving Potential of Applying Prefabricated Straw Bale Construction (PSBC) in Domestic Buildings in Northern China. *Sustainability* **2020**, *12*, 3464. [CrossRef]
19. Bruno, R.; Bevilacqua, P.; Cuconati, T.; Arcuri, N. Energy evaluations of an innovative multi-storey wooden near Zero Energy Building designed for Mediterranean areas. *Appl. Energy* **2019**, *238*, 929–941. [CrossRef]
20. Da Cunha, S.R.L.; de Aguiar, J.L.B. Phase change materials and energy efficiency of buildings: A review of knowledge. *J. Energy Storage* **2020**, *27*, 101083. [CrossRef]
21. Nghana, B.; Tariku, F. Phase change material's (PCM) impacts on the energy performance and thermal comfort of buildings in a mild climate. *Build. Environ.* **2016**, *99*, 221–238. [CrossRef]
22. Ascione, F.; Bianco, N.; De Masi, R.F.; Mastellone, M.; Vanoli, G.P. Phase change materials for reducing cooling energy demand and improving indoor comfort: A step-by-step retrofit of a Mediterranean educational building. *Energies* **2019**, *12*, 3661. [CrossRef]
23. Tenpierik, M.; Wattez, Y.; Turrin, M.; Cosmatu, T.; Tsafou, S. Temperature Control in (Translucent) Phase Change Materials Applied in Facades: A Numerical Study. *Energies* **2019**, *12*, 3286. [CrossRef]
24. Saafi, K.; Daouas, N. Energy and cost efficiency of phase change materials integrated in building envelopes under Tunisia Mediterranean climate. *Energy* **2019**, *187*, 115987. [CrossRef]
25. Guarino, F.; Longo, S.; Cellura, M.; Mistretta, M.; La Rocca, V. Phase change materials applications to optimize cooling performance of buildings in the Mediterranean area: A parametric analysis. *Energy Proc.* **2015**, *78*, 1708–1713. [CrossRef]
26. Costanzo, V.; Evola, G.; Marletta, L.; Nocera, F. The effectiveness of phase change materials in relation to summer thermal comfort in air-conditioned office buildings. In Proceedings of the Building Simulation, Cambridge, UK, 11–12 September 2018; pp. 1145–1161.
27. Karaoulis, A. Investigation of energy performance in conventional and lightweight building components with the use of phase change materials (PCMs): Energy savings in summer season. *Proc. Environ. Sci.* **2017**, *38*, 796–803. [CrossRef]
28. SUPRIM. Available online: https://suprim.gr/?lang=en (accessed on 29 July 2020).
29. Soares, N.; Gaspar, A.; Santos, P.; Costa, J. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. *Energy Build.* **2014**, *70*, 411–421. [CrossRef]
30. Ascione, F.; Bianco, N.; De Masi, R.F.; de'Rossi, F.; Vanoli, G.P. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. *Appl. Energy* **2014**, *113*, 990–1007. [CrossRef]
31. Kośny, J. Short history of PCM applications in building envelopes. In *PCM-Enhanced Building Components*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 21–59.
32. Kosny, J.; Yarbrough, D.W.; Miller, W.A.; Petrie, T.; Childs, P.W.; Syed, A.M. *2006/07 Field Testing of Cellulose Fiber Insulation Enhanced with Phase Change Material*; Oak Ridge National Lab.(ORNL), Building Technologies Research and Integration Center: Oak Ridge, TN, USA, 2008.
33. Zhang, M.; Medina, M.A.; King, J.B. Development of a thermally enhanced frame wall with phase-change materials for on-peak air conditioning demand reduction and energy savings in residential buildings. *Int. J. Energy Res.* **2005**, *29*, 795–809. [CrossRef]
34. 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]
35. Cabeza, L.F.; Castell, A.; Barreneche, C.d.; De Gracia, A.; Fernández, A. Materials used as PCM in thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1675–1695. [CrossRef]

36. Al-Absi, Z.A.; Mohd Isa, M.H.; Ismail, M. Phase Change Materials (PCMs) and Their Optimum Position in Building Walls. *Sustainability* **2020**, *12*, 1294. [CrossRef]
37. Panayiotou, G.; Kalogirou, S.A.; Tassou, S.A. Evaluation of the application of Phase Change Materials (PCM) on the envelope of a typical dwelling in the Mediterranean region. *Renew. Energy* **2016**, *97*, 24–32. [CrossRef]
38. Ozdenefe, M.; Dewsbury, J. Thermal performance of a typical residential Cyprus building with phase change materials. *Build. Serv. Eng. Res. Technol.* **2016**, *37*, 85–102.
39. IEEE STANDARD. IEEE Std 442-IEEE Guide for Soil Thermal Resistivity Measurements. *EUA IEEE* **1981**. [CrossRef]
40. ASTM. Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure. *ASTM Data Ser. Publ.* **2008**, *5334*, 1–8.
41. TOTEE20701-1/2017. Technical Guides of the recast of the Hellenic Thermal Regulation of the Energy Assessment of Buildings. 2017. Available online: http://portal.tee.gr/portal/page/portal/SCIENTIFIC_WORK/GR_ENERGEIAS/kenak/files/TOTEE_20701-1_2017_TEE_1st_Edition.pdf (accessed on 10 July 2020). (In Greek).
42. Tabares-Velasco, P.C.; Christensen, C.; Bianchi, M. Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. *Build. Environ.* **2012**, *54*, 186–196. [CrossRef]
43. Yu, S.; Cui, Y.; Shao, Y.; Han, F. Research on the Comprehensive Performance of Hygroscopic Materials in an Office Building Based on EnergyPlus. *Energies* **2019**, *12*, 191. [CrossRef]
44. Shrestha, S.; Maxwell, G. Empirical validation of building energy simulation software: EnergyPlus. In Proceedings of the Building Simulation; Iowa State University: Ames, IA, USA, 2006; pp. 2935–2942.
45. Goia, F.; Chaudhary, G.; Fantucci, S. Modelling and experimental validation of an algorithm for simulation of hysteresis effects in phase change materials for building components. *Energy Build.* **2018**, *174*, 54–67. [CrossRef]
46. Shabunko, V.; Lim, C.; Mathew, S. EnergyPlus models for the benchmarking of residential buildings in Brunei Darussalam. *Energy Build.* **2018**, *169*, 507–516. [CrossRef]
47. Bojić, M.; Yik, F. Application of advanced glazing to high-rise residential buildings in Hong Kong. *Build. Environ.* **2007**, *42*, 820–828.
48. Dávi, G.A.; Caamaño-Martín, E.; Rüther, R.; Solano, J. Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil. *Energy Build.* **2016**, *120*, 19–29. [CrossRef]
49. Boyano, A.; Hernandez, P.; Wolf, O. Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. *Energy Build.* **2013**, *65*, 19–28. [CrossRef]
50. Korolija, I.; Zhang, Y.; Marjanovic-Halburd, L.; Hanby, V.I. Regression models for predicting UK office building energy consumption from heating and cooling demands. *Energy Build.* **2013**, *59*, 214–227.
51. Vujošević, M.; Krstić-Furundžić, A. The influence of atrium on energy performance of hotel building. *Energy Build.* **2017**, *156*, 140–150. [CrossRef]
52. Hong, S.H.; Lee, J.M.; Moon, J.W.; Lee, K.H. Thermal comfort, energy and cost impacts of PMV control considering individual metabolic rate variations in residential building. *Energies* **2018**, *11*, 1767. [CrossRef]
53. Yao, J.; Chow, D.H.C.; Zheng, R.-Y.; Yan, C.-W. Occupants' impact on indoor thermal comfort: A co-simulation study on stochastic control of solar shades. *J. Build. Perform. Simul.* **2016**, *9*, 272–287. [CrossRef]
54. Ramos, G.; Ghisi, E. Analysis of daylight calculated using the EnergyPlus programme. *Renew. Sust. Energy Rev.* **2010**, *14*, 1948–1958. [CrossRef]
55. Motamedi, S.; Liedl, P. Integrative algorithm to optimize skylights considering fully impacts of daylight on energy. *Energy Build.* **2017**, *138*, 655–665. [CrossRef]
56. Váz Sá, A.; Almeida, R.; Sousa, H.; Delgado, J. Numerical analysis of the energy improvement of plastering mortars with phase change materials. *Adv. Mater. Sci. Eng.* **2014**, *2014*. [CrossRef]
57. Zastawna-Rumin, A.; Kisilewicz, T.; Berardi, U. Novel Simulation Algorithm for Modeling the Hysteresis of Phase Change Materials. *Energies* **2020**, *13*, 1200. [CrossRef]
58. Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.F.; Huang, Y.J.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J. EnergyPlus: Creating a new-generation building energy simulation program. *Energy Build.* **2001**, *33*, 319–331. [CrossRef]

59. Tabares-Velasco, P.C.; Griffith, B. Diagnostic test cases for verifying surface heat transfer algorithms and boundary conditions in building energy simulation programs. *J. Build. Perform. Simul.* **2012**, *5*, 329–346. [CrossRef]
60. Jin, X.; Xu, X.; Zhang, X.; Yin, Y. Determination of the PCM melting temperature range using DSC. *Thermochim. Acta* **2014**, *595*, 17–21. [CrossRef]
61. Castellón, C.; Günther, E.; Mehling, H.; Hiebler, S.; Cabeza, L.F. Determination of the enthalpy of PCM as a function of temperature using a heat-flux DSC—A study of different measurement procedures and their accuracy. *Int. J. Energy Res.* **2008**, *32*, 1258–1265. [CrossRef]