Case Studies in Thermal Engineering 63 (2024) 105337

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Integrating phase change materials in buildings for heating and cooling demand reduction – A global study

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A R T I C L E I N F O

Keywords:
Building energy
Phase change materials
Energy savings
DesignBuilder
Global analysis

A B S T R A C T

This study aims to analyse the integration of Phase Change Materials (PCMs) in building envelopes globally, focusing on its ability to reduce the energy demand and its economic viability. The study conducted extensive simulations using the DesignBuilder software across 5684 locations globally and utilising artificial intelligence (AI) models to extend the simulation further to 73,515 locations, evaluating the impacts of PCM properties such as melting temperature (MT) and thickness. The main findings indicate that pronounced annual energy savings, 2500 to 3000 kWh, are observed in equatorial regions including northeast Brazil, central Africa, and the Malay Archipelago. Additionally, the optimal utilisation of increased PCM thickness is contingent upon selecting the correct MT and is most effective in regions with high average maximum temperatures, while the most common effective thickness is 20 mm. The study demonstrates that MT significantly affects energy savings, more than PCM thickness, highlighting the importance of selecting appropriate MT based on climatic conditions. The 25 °C MT is most effective within lower latitude range (−15°–30°), averaging 743.2 kWh greater savings than the 21 °C option. The 21 °C MT shows superior performance outside of this range, however the advantage is marginal as the average savings is 251.0 kWh. Economically, regions such as the USA, southern Europe (Spain and Italy), Brazil, and northern Australia show the best viability for PCM integration, aligning energy efficiency improvements with substantial economic returns. This comprehensive analysis suggests that tailored PCM integration strategies are essential for maximising energy savings and advancing sustainable building practices.

Nomenclature

C	Price ($/kWh)
COP	Coefficient of Performance (−)
NS	Net savings (kWh)
Q	Heating/Cooling energy (kWh)
SPP	Simple payback period (year)
Greeks	
η	Efficiency (−)
Subscripts	
b	Boiler
c	Cooling

(*continued on next page*)

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https://doi.org/10.1016/j.csite.2024.105337
Received 15 July 2024; Received in revised form 17 October 2024; Accepted 22 October 2024
Available online 23 October 2024
2214-157X/

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e	Electricity
h	Heating
imp	Implement
ng	Natural gas

1. Introduction

To align with global climate action under the Paris Agreement, there is urgent need to reduce energy consumption in buildings, which plays a pivotal role in the global effort to mitigate climate change and enhance energy efficiency. Buildings are responsible for approximately 40 % of the total energy used worldwide [1], with a significant 50 % of this energy being used for heating and cooling [2]. This energy demand places immense pressure on improving heating and cooling technologies in buildings and/or improving energy efficiency of buildings.

Buildings energy efficiency can be improved by integration of advanced materials and technologies that can reduce the energy required for maintaining comfortable indoor environments. One of the most critical areas of focus is building insulation, which is key to regulate temperature and reducing energy loss. Traditional building envelopes, which are constructed from materials with low thermal inertia, have limited capacity to regulate indoor temperatures effectively, leading to higher energy consumption.

In this context, integration of phase change materials (PCMs) into buildings have emerged as an innovative solution. PCMs are substances with a high latent heat of fusion, capable of absorbing or releasing large amounts of heat during their phase transition at melting points. This unique property enables PCMs to store and release substantial amounts of thermal energy at a short temperature range. By integrating PCMs into building structures, such as walls and roofs, buildings can better regulate indoor temperatures, reducing the need for heating and cooling systems. Utilised in buildings, PCM works passively, it solidifies at night and releases heat to the environment. During the daytime, it melts, absorbing heat. This process not only reduces the load on heating and/or cooling systems but also stabilises indoor temperatures within a comfortable range.

A recent study by Elenga et al. [3] reported the integration of PCMs across different building envelopes, brick, cast concrete, and concrete block, in tropical climates resulted in total energy cost reductions between 31.21 % and 47.80 %. And the economic analyses of the life cycle cost indicate that the application of PCMs can save between 3.47 % and 29.62 % of building energy costs. From an environmental perspective, the use of PCMs leads to a reduction in CO_2 emissions ranging from 32.12 % to 52.96 %, dependent on the building materials and climatic conditions. The maximum reduction was observed in an earth-based building envelope in arid climates, aligning with a significant decrease in energy consumption, while the minimal impact is seen in tropical climates with concrete block constructions. Hamdani et al. [4] reported an annual energy reduction of 36.4 % was obtained by integrating PCM with 20–26 °C melting temperature range into a building envelope under Saharan climate. The simulation also showed a further 14.3 % reduction if PCMs are carefully integrated based on orientations and seasons. The indoor temperature can be reduced by 2.36–4.0 °C. Saaf and Daouas [5] reported about 13.4 % annual energy saving under Mediterranean climate condition. The integration of the PCMs was believed to lead to 5.35 °C reduction on temperature fluctuation due to the improved the thermal inertia of the wall. However, the study concluded the cost-ineffectiveness of integrating PCMs into walls through a 30-year life cycle cost analysis. Al-Yasiri and Szabó [6] experimentally studied the performance of PCM-integrated building envelop in severe hot climate conditions. PCM with phase change temperature range of 40–44 °C was integrated into roof and walls. The test results showed an average temperature reduction of 2 °C, a thermal load reduction of 8.71 %, and a reduction of 1.35 kg CO_2 per day for a scale-down 1 m^3 room. Similarly, Jiang et al. [7] experimentally investigated the cooling performance of PCM-integrated roof with a phase change temperature range of 43–49 °C. Combined with the utilisation of a solar-reflective coating layer, the room temperature was reduced by 6.4 °C and the cooling energy consumption was reduced by 14.78 %.

Wang et al. [8] analysed the energy performance of a PCM-integrated office building in a cold region of China. Two layers of PCMs, with 21.6 °C and 19.5 °C phase change temperatures, were integrated into exterior and interior sides of the southern façade. The integration led to more than13 % annual energy saving, however, the static payback period was 19.7 years. Phase change temperature in the range of 19–25 °C was recommended for PCM walls. Asghari et al. [9] investigated the application of PCM-integrated walls in a cold climate city in the US. They found that PCM with phase change temperature in the range of 24–26 °C was more suitable for such climate condition, achieving 33 % reduction in heating energy consumption and 20 % reduction in cooling energy consumption. The PCM layer was more effective for cooling energy saving when installed on the outer sider of wall, however, it performed better for heating energy saving when installed in the internal side. Yin et al. [10] studied the performance of PCM-integrated building envelope under cold climate with smart heating control. It was concluded that PCM can effectively mitigate the over-heating for well-insulated buildings. With an optimal phase change temperature at 21 °C and a thickness of 75 mm, annual cost savings of 18.4 % and Spot price and 6.1 % under Time-of-Use (ToU) price.

Despite the widely acknowledged energy savings of integrating PCMs into buildings, the high initial cost and long payback period impede PCM adoption. As summarised in a review study [11], although very few research focused on economic aspects of PCM integration in buildings, the payback period is believed to be in between 10 years and 30 years. Acuña-Díaz et al. [12] concluded that the absence of subsidies or cost-effective manufacturing extends the payback period from about 8.7 years to about 14.3 years in Australia's hot arid climate, rendering PCM integration economically impractical. Cost reductions via technological improvements or government incentives could significantly decrease this period, boosting PCM's economic appeal.

Research has emphasised the importance of optimisation PCM integration based on the environment, building type, and climate, leading to the development of several guidelines. Below is a list of key optimisations for PCM integration in building design according to current literatures.

- Melting temperature (MT) - The MT of PCM should be within the indoor target temperature range. For hotter climates, a higher melting point is preferable, while cooler climates benefit from a lower melting point [13]. This allows the PCM to utilise phase change latent energy storage effectively.
- PCM thickness - The thickness of PCM layer should align with the average thermal load of the building. This ensures that the PCM can melt and solidify daily, making it cost-effective and efficient in its energy storage and release [14].
- Position within wall construction - Placing the PCM close to the average heat source, whether internal or external, enhances its effectiveness [15]. This positioning ensures optimal thermal energy transfer.
- Type of PCM - It should be non-toxic, flame-resistant, recyclable, renewable, and durable. These characteristics ensure that the PCM is safe, environmentally friendly, and provides long-term performance [16].
- Encapsulation method - The choice of PCM encapsulation impacts cost and thermal conductivities, varying with the type and location of building integration. Macro-encapsulation, using larger containers like tubes, rectangular panels or pouches, is often preferred for its ease of installation, increasing the amount of PCM and preventing any leakage [17].
- Deployment location - The effectiveness of PCM deployment varies by location within a structure, including roofs, ceilings, floors, windows, and shutters/blinds. In equatorial regions, roofs benefit most from direct solar exposure [2]. In contrast, walls,

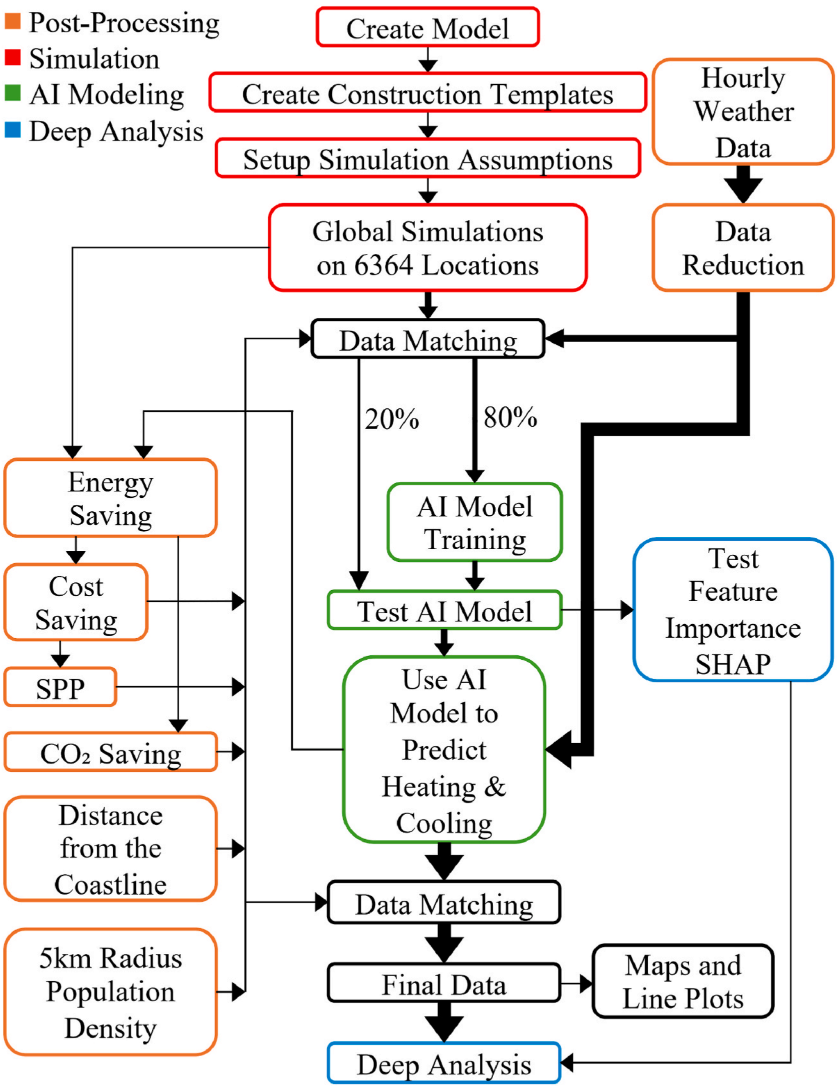


Fig. 1. Flow chart of methodology (Thickness of the arrows represents the number of locations, colours represent the sections). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

particularly south-facing ones in the southern hemisphere, are more effective location for PCM embedment due to their enhanced exposure to solar radiation [18].

While these guidelines provide a framework for optimising PCM integration, however, every case is unique and requires a custom study and simulation [19]. This is due to the diverse nature of locations and building designs. Each situation needs individual optimisation to ensure maximum efficiency and effectiveness. The effectiveness of PCMs depends on their thermal properties, integration methods, and climate conditions. Current literature primarily focuses on case studies in limited geographic locations and optimisation features, offering a narrow view of PCM potential in diverse climates and building types. Economic and practical considerations, such as total life cycle cost, payback period, market potential, long-term durability, and compatibility with existing building designs, also have limited research.

This study aims to obtain and analyse the global performance of integrating PCMs in building envelops for heating and cooling demand reduction. It directly simulates 5684 locations worldwide with 'Brick and Block' and 'Timber Frame' construction types to predict the energy saving and therefore economic viability of PCM integration. Artificial intelligence (AI) was then employed to extend the simulation to 73,515 geographic locations, covering almost all possible locations in this world. This method enhances understanding and provides a detailed view of PCM applications across different climates. Additionally, this study seeks to identify optimal PCM properties, like MT and thickness, providing tailored solutions for each location and different climates. Furthermore, this study encompasses an economic analysis to assess the viability of integrating PCM in different regions. By integrating the energy-saving data with current gas and electricity prices, this analysis aims to provide the PCM industry with a clearer direction for technology deployment. This is particularly important to increase market adoption by identifying where and how PCM can be most effectively integrated.

2. Modelling approach

2.1. Overall methodology

The overall methodology of current study is shown in Fig. 1. The entire process consists of simulation, AI modelling, post-processing and deep analysis, as explained below.

- DesignBuilder software [20] was employed to construct realistic building models with different construction templates, with and without integrating PCMs. Simulations were initiated for all 6364 locations provided by the software, however incomplete weather data resulted in only 5684 useable outcomes. The disparity between the simulated locations and the total available raw weather data of 73,515 locations, sourced from EnergyPlus [21] and Climate One Building [22], left a significant gap which would later be addressed using predictions from the AI modelling.
- The primary objective of the AI model was to expand the simulated dataset to a broader geographic scope, providing detailed insights into regional energy savings and economic viability across locations without direct simulation. Additionally, AI model aimed to analyse the significance of various features in predicting energy savings when integrating PCMs into buildings. AI model was trained with 80 % of the simulation results then tested by the other 20 % simulation results to get satisfactory accuracy.

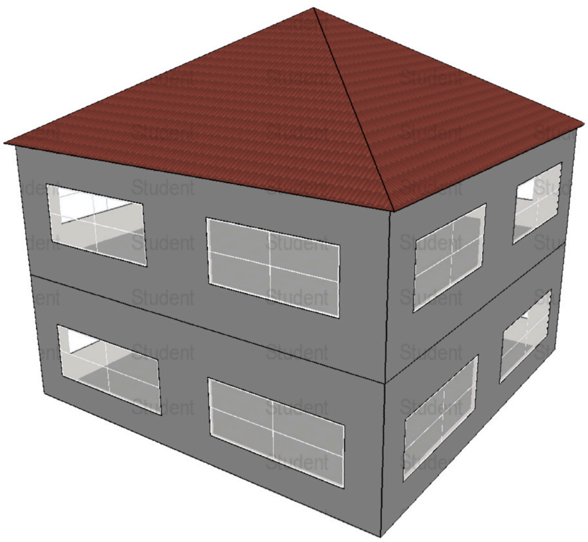


Fig. 2. Building model in DesignBuilder.

- The post-processing takes all results and conducts more data processing to obtain essential performance indicators including energy savings, cost savings and CO_2 savings.
- To gain a deeper understanding of why specific locations yield higher energy and/or cost savings through PCM integration, the AI model was leveraged, focusing on identifying critical variables driving these savings and understanding their impact. To conduct this deep analysis, SHAP (SHapley Additive exPlanations) values [23] were calculated and used as a robust tool for feature assessment.

2.2. Building model

DesignBuilder software was employed to construct a realistic building model, mirroring the average structure and size of Western style detached single-family homes seen in Fig. 2. This model has a square footprint, encompassing 2383 square feet, reflective of the average size of newly sold residential single-family homes in the United States, as given the latest U.S. Census data [24]. The decision to model after the United States was driven by the availability of detailed construction data and the significant market size, ensuring the relevance and applicability of the analysis.

Twenty construction templates are presented in Table 1 with details presented in Appendix 1, varying in PCM MT, thickness, and construction types. Two templates serve as benchmarks without PCM for energy savings calculations. Fig. 3 illustrates the composition of external walls and internal ceilings, including 'Brick and Block' and 'Timber Frame' constructions, both with and without PCMs. Modelled on traditional U.S. construction practices, PCM layers are positioned externally to optimise for hotter climates, as suggested by the literature [25]. While aiming to reflect global practices, these templates may not fully account for local variations in building materials, designs, or climatic conditions, which could influence energy consumption estimates.

The used 'Brick and Block' and 'Timber Frame' construction types reflects prevalent global methods. The former one is traditional, and the latter becomes increasingly popular for its cost-efficiency and rapid build time. The PCM MTs chosen were 21 °C, 25 °C and 29 °C, slightly above typical comfort levels to create temperature difference for heat transfer, aligning with the literature and targeting hotter climates with significant energy savings. PCM thicknesses of 10 mm, 15 mm, and 20 mm were selected to balance cost and effectiveness, echoing prior studies [18] allowing outcomes to be compared. Thermal properties of used PCMs are presented in Table 2.

The simulation setup was meticulously configured with key parameters to ensure accuracy. Occupant activity was simulated using the TM59_Studio profile in DesignBuilder for three occupants. Thermal comfort was constant and assumed to be maintained between 21 °C and 25 °C using setpoints within DesignBuilder, although comfort temperature can vary significantly due to local climate and cultural preferences. The HVAC system, operational continuously, included a Fan Coil Unit (4-pipe), Air-cooled Chiller, and Co-efficients of Performance (COP) for heating is set at 0.85 with natural gas and cooling COP is 1.8 with grid electricity, typical of systems in western countries. COP values are assumed to remain constant regardless of external temperatures and internal loads and are representative of systems worldwide, which might not reflect all local technologies or efficiencies. More detailed information on the used models and simulation methodology can be referred to EnergyPlus Documentation [27].

Each construction template was simulated using the optimiser in the DesignBuilder software for all 6364 locations templates provided within the software. Due to memory constraints, this could not be scheduled in one go so it was broken down into small batches selecting and exporting each manually.

Table 1
Construction templates simulated.

	Construction type	PCM thickness	PCM MT
No PCM	Brick and block	–	–
No PCM	Timber frame	–	–
PCM	Brick and block	10 mm	21 °C
PCM	Brick and block	10 mm	25 °C
PCM	Brick and block	10 mm	29 °C
PCM	Brick and block	15 mm	21 °C
PCM	Brick and block	15 mm	25 °C
PCM	Brick and block	15 mm	29 °C
PCM	Brick and block	20 mm	21 °C
PCM	Brick and block	20 mm	25 °C
PCM	Brick and block	20 mm	29 °C
PCM	Timber frame	10 mm	21 °C
PCM	Timber frame	10 mm	25 °C
PCM	Timber frame	10 mm	29 °C
PCM	Timber frame	15 mm	21 °C
PCM	Timber frame	15 mm	25 °C
PCM	Timber frame	15 mm	29 °C
PCM	Timber frame	20 mm	21 °C
PCM	Timber frame	20 mm	25 °C
PCM	Timber frame	20 mm	29 °C

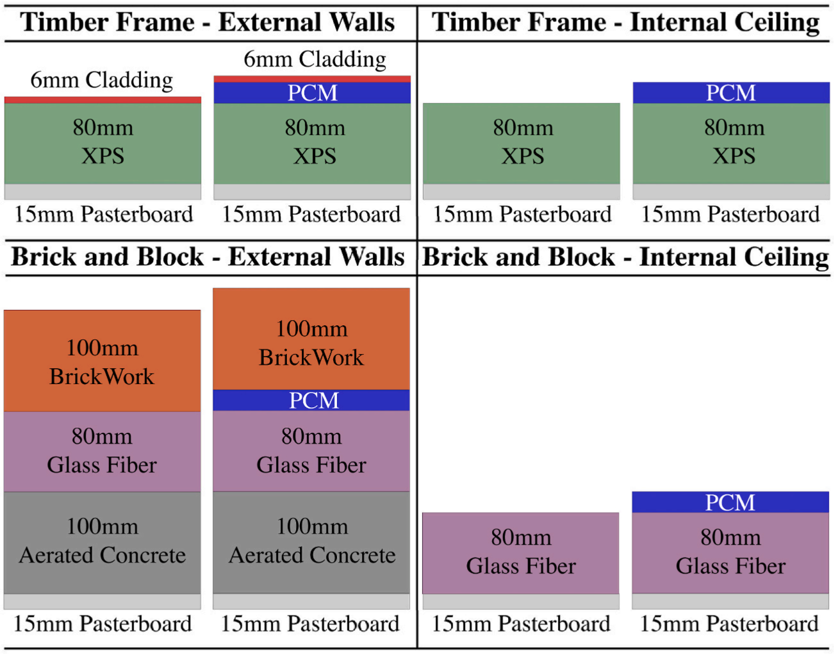


Fig. 3. Layers of each construction type with and without PCM.

Table 2
Properties of used PCMs [26].

	PCM21	PCM25	PCM29
Latent heat (kJ/kg)	200	200	200
Density (kg/m^3)	1540	1540	1540
Specific heat (J/(kg K))	3140	3140	3140
Liquid state thermal conductivity (W/(m K))	0.54	0.54	0.54
Solid state thermal conductivity (W/(m K))	1.09	1.09	1.09

2.3. Post-processing

Accurate climate analysis was critical for each location, given that the weather data files contained 34 hourly-recorded variables. To manage this vast dataset within computational limits, a Python script was used to condense the data into weekly aggregates. This process focused on key parameters like maximum, minimum, average, and diurnal variations. This approach effectively reduced the dataset to 6240 values per location, enabling efficient training of the AI model.

To give each location a 'population density' value, which was deemed to affect microclimates within urban areas due to the urban heat island effect, a population density dataset was used from SEDAC (Socioeconomic Data and Applications Centre) [28] to calculate the average population density in a circular 5 km radius around each location's coordinates using a Python script.

Similarly, give each location a 'distance from the nearest coastline' value, deemed to affect microclimates due to the large thermal mass of the ocean, a shapefile of the global coastlines from Ref. [29] was used and calculated using a Python script.

To calculate yearly cost savings from total energy savings, natural gas (for heating) and electricity (for cooling) prices were sourced from the International Energy Agency [30] and Global Petrol Prices [31] for 2022, assumed to be stable over time. Total annual energy costs, C, were computed by the following equation,

$$C = C_{ng} Q_h / \eta_b + C_e Q_c / \mathrm{COP} \tag{1}$$

where C_{ng} is the natural gas prices at \$/kWh, Q_h is the annual heating load at kWh, η_b is the boiler efficiency, C_e is the electricity prices at \$/kWh, Q_c is annual cooling load at kWh.

Total CO_2 savings were determined similarly to cost savings, using carbon intensity data for electricity generation from Ref. [32] and a standard value of 0.185 kg/kWh for natural gas [33]. These data were combined to calculate CO_2 emissions from heating and cooling loads, thus deriving total CO_2 emission savings.

Next, to calculate the cost of integrating PCM insulation at varying thicknesses, a price of \$22.53/m^2 was sourced for 20 mm thick plastic pouches [34] as used and matched with the thermal properties within the DesignBuilder software. This price was converted into a volumetric cost of \$1126.50/m^3. Using DesignBuilder, the total area required for insulation was established. The area and the volumetric cost used to calculate the insulation costs for each thickness can be seen in Table 3. This assumes that the PCM material is integrated into new builds with no additional installation challenges compared to conventional insulation types omitting installation and maintenance costs. It is also manufactured in bulk at a single location and the MT, location or variations in material cost do not affect the price.

To assess the economic feasibility of integrating PCMs into buildings, cumulative net savings (NS) and simple payback periods (SPP) were calculated for each location and construction template. NS was derived by subtracting integration costs from annual energy savings over 50 years, the expected lifespan of the building envelope, as shown in the following equation,

$$NS = \sum_{i=1}^{50} (C_{NoPCM} - C_{PCM}) - C_{imp} \tag{2}$$

where C_{NoPCM} and C_{PCM} are the annual heating and cooling costs of building without and with integrating PCMs, C_{imp} is the implementation cost given in Table 3. SPP is calculated by the following equation,

$$SPP = \frac{C_{imp}}{C_{NoPCM} - C_{PCM}} \tag{3}$$

Though SPP offers a quick assessment of cost recovery, it isn't the primary metric due to its failure to reflect the full benefits accrued over the PCM's lifespan, where thicker PCMs may yield greater long-term savings despite longer paybacks. These economic evaluations excluded considerations like the time value of money, inflation, cost of capital, or subsidies, which could significantly affect financial outcomes.

2.4. AI modelling

The AI model was trained with a supervised random forest regression algorithm from the scikit-learn library in Python. Input and output variables for the 5684 simulated locations, detailed in Fig. 4, were used for AI model training and testing.

Separate models were developed for each combination of the three output variables and construction templates. This separation of heating and cooling energy calculations was crucial for post-processing steps. Additionally, a model specifically for total energy savings was created to analyse features significant in the deep analysis. The modelling process involved splitting the data into training (80%) and testing (20%) sets, with the training set, further split for cross-validation to iteratively improve model accuracy whilst still reserving the testing set for final evaluation.

After the training phase, each model was evaluated using its testing set with performance indicators like R-squared Score and Actual *vs* Predicted plots. Models achieving satisfactory results, with R-squared scores between 0.962 and 0.982 for heating and cooling, were used to predict values for the 73,515 unsimulated locations. These output variables were then post-processed to expand the dataset as shown in Fig. 4. Notably, only the heating and cooling energy models, due to their high R-squared scores, were used in post-processing to avoid potential errors when comparing heating and cooling energy models with total energy saving model.

The trained model was utilised to predict the outputs for 73,515 locations, where only input variables were available, This AI modelling expanded the dataset significantly, enabling the creation of detailed maps and line plots. These maps identify regions where PCM integration notably reduces the energy consumption and detail its environmental and economic impacts.

2.5. Deep analysis

Fig. 5 shows the flow diagram of the deep analysis. SHAP (SHapley Additive exPlanations) values were first calculated for each input variable at every location using the total energy saving model. These values measure how much each feature contributes, in kWh, to the energy savings of a specific location compared to the average. The mean absolute SHAP values for each variable were then computed to quantify their average impact across all locations. The analysis aggregated weekly data for each variable and reduction method, enabling a comparative analysis against variables such as latitude and population density. Aggregated values were visualised

Table 3
Implementation cost calculation.

	Thickness (mm)	Area (m^2)	Volume (m^3)	Cost ($)
Semi exposed ceiling	0	114.5	0	0
External wall	0	215.4	0	0
Total				0
Semi exposed ceiling	10	114.5	1.145	1289.84
External wall	10	215.4	2.154	2426.48
Total				3716.32
Semi exposed ceiling	15	114.5	1.7175	1934.76
External wall	15	215.4	3.231	3639.72
Total				5574.49
Semi exposed ceiling	20	114.5	2.290	2579.69
External wall	20	215.4	4.308	4852.96
Total				7432.65

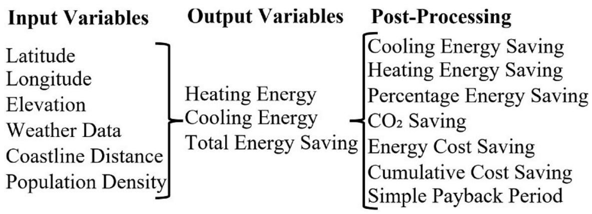


Fig. 4. AI model input and output variables.

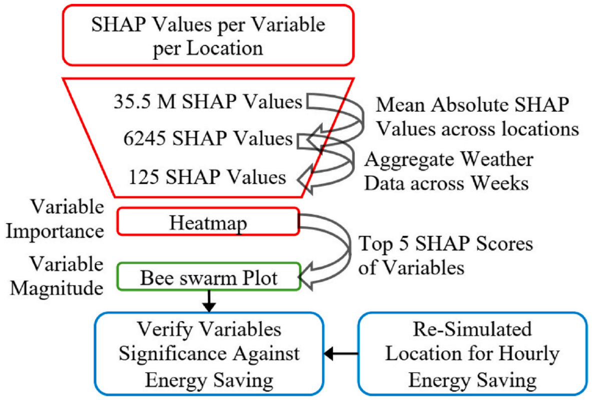


Fig. 5. Flow diagram of deep analysis.

in a heatmap to clearly compare each variable's importance, highlighting those with the highest aggregated SHAP values. To understand the extent of these significant variables, beeswarm plots were created for the top five variables, illustrating the trend and impact of each feature across simulated locations.

While SHAP values provide a robust tool for feature assessment, it is important to remember that they reflect correlations learned by the model rather than direct causations in the real world. AI models prioritise correlation, which can sometimes lead to high SHAP values for proxy variables that may not be directly causing the observed outcomes.

To confirm these findings, a case study was conducted at a location showing high energy savings, re-simulating both control (Brick and Block) and optimal construction templates. The hourly energy consumption data from this simulation were then analysed to provide a detailed view of energy savings over the year. This data is plotted against the most significant features identified by SHAP values to examine real-world correlations and validate the AI model's findings.

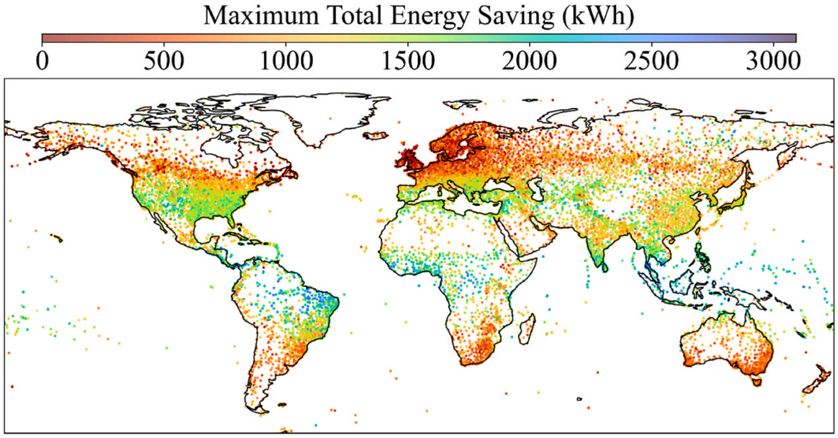
3. Results and discussion

3.1. Geographical distribution of energy savings

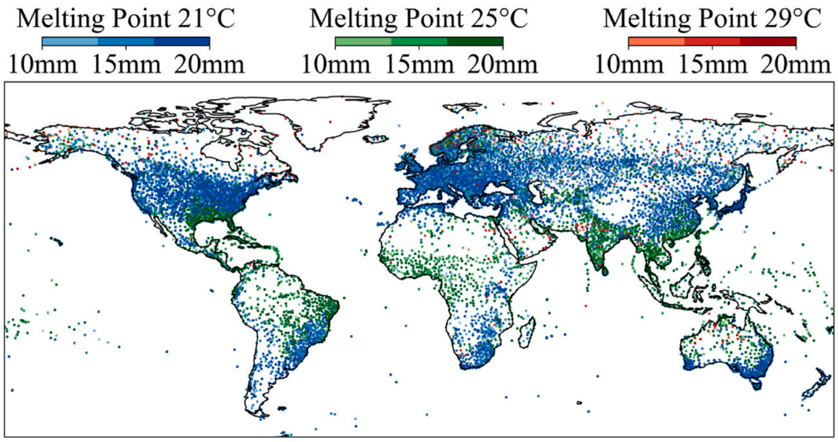
Fig. 6(a) highlights the highest total energy savings achieved using the 'Brick and Block' construction templates, with the corresponding specific configuration shown in in Fig. 6(b). These values, predicted using the AI model, are mapped for all locations in the dataset. The figure highlights pronounced energy savings in equatorial regions, including northeast Brazil, central Africa, and the Malay Archipelago, where savings range from 2500 kWh to 3000 kWh.

Significant savings, between 1250 kWh and 2000 kWh, are also evident between latitudes 40° N and 20° S, encompassing central America, the USA, northern South America, southern Europe, northern Africa, Asia (excluding Russia), and northern Australia. These observations correlate with regions known for substantial direct solar radiation during the day and cooler temperatures at night. This diurnal cycle facilitates the daily phase change of the PCMs, utilising its high thermal storage capabilities and reducing the peak and overall cooling load. In contrast to this, the majority locations of the EU, Canada, south Africa, south America and Australia has low energy savings, mostly lower than 1000 kWh, attributing to relatively lower day temperatures.

The focus on total energy savings, rather than percentage savings, is intentional for assessing the commercial viability of PCMs integration. While cooler regions further from equator exhibit higher percentage savings, their absolute energy savings are minimal due to relatively lower total energy demand for heating and cooling. This results in modest monetary benefits from PCM integration in building constructions, highlighting the need to target regions with higher energy expenditures to maximise return on investment.



(a)



(b)

Fig. 6. (a) Maximum total energy saving among 'Brick & Block' construction templates; (b) corresponding construction templates those result in maximum energy saving.

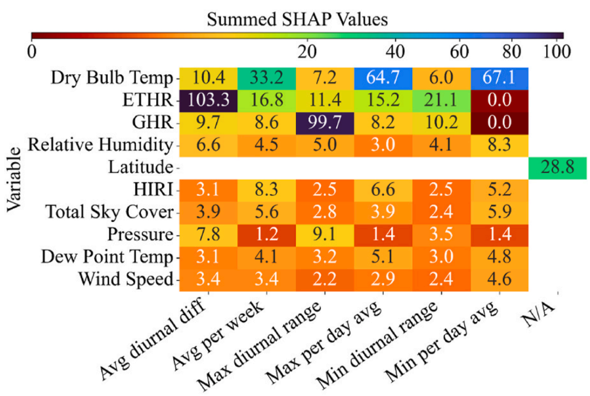


Fig. 7. SHAP value heatmap for total energy saving using the 'Brick & Block', 20 mm thick 21 °C PCM.

3.2. SHAP values

To identify the critical variables influencing energy savings, Fig. 7 displays a heatmap of the top 10 most significant variables from the input data, ranked by summed SHAP values for 'Brick & Block' construction template with 20 mm thick 21 °C PCM. These values quantify each variable's impact on the model's output. This specific construction template was selected due to its widespread effectiveness across all the locations in the dataset. A more comprehensive version of this heatmap, which includes all variables, can be found in Appendix 2.

The finding indicates that dry bulb temperature, particularly its maximum and minimum temperatures are critical for energy savings, with SHAP values of 64.7 and 67.1 respectively. Extraterrestrial horizontal radiation (ETHR), which measures the solar radiation outside Earth's atmosphere, also play a key role, specifically highlights the average diurnal difference within a week, with a top SHAP score of 103.3. This metric is directly linked to ambient surface temperature.

Other variables, such as relative humidity, pressure, and dew point, act as proxy variables influenced by temperature fluctuations. They correlate with causal variables but do not directly impact energy savings. In contrast, latitude is a key driver, as it determines the amount of ETHR, and subsequently, global horizontal radiation (GHR) that reaches the Earth's surface. This transformation of ETHR into GHR is moderated by total sky cover, which determines how much solar radiation penetrates the atmosphere, affecting surface temperature.

Building on the insights from the SHAP heatmap, the SHAP values of the top 5 most significant variables are presented in Fig. 8. The figure reveals a positive correlation between energy savings and variables such as ETHR, with its average diurnal difference per week, and GHR, with its maximum diurnal difference, suggesting that larger diurnal variations in solar radiation can lead to greater energy conservation. Additionally, both the average and maximum daily dry bulb temperatures show a significant positive effect, indicating that environments with higher daily temperatures optimise the PCM's thermal regulation capabilities. In contrast, a negative correlation is observed with the minimum average daily temperature of dry bulb temperature, indicating higher value of minimum dry bulb temperature leading to less energy saving, emphasising the need of enough temperature difference for PCM phase changing.

To validate the insights derived from the SHAP value analysis, Fig. 9 provides a direct comparison between daily total energy savings and key variables: maximum dry bulb temperature, and extraterrestrial horizontal radiation (ETHR) diurnal difference. This plot aimed to exam the relationships between these variables and energy savings, offering empirical evidence to either support or challenge the causative links suggested by the SHAP values. The observation from the plot reveals that the maximum dry bulb temperature closely follows the trends in energy savings, confirming its significant positive correlation, as suggested by the SHAP value analysis. This alignment suggests that higher maximum temperatures are indeed conducive to increased energy savings, validating the PCM's effectiveness in thermally regulated environments. On the other hand, while the ETHR diurnal difference also shows a general alignment with the trends in energy savings over the year, its correlation is not as pronounced as that of the temperature, indicating that while important, ETHR may have a more secondary role in driving energy savings.

3.3. Optimisation of PCM integration

Fig. 10 highlights the influence of PCM MT and thickness on energy savings. This analysis is pivotal in understanding the dynamic interaction between PCM properties and climate conditions.

3.3.1. Thickness

The analysis generally favours thicker PCM applications, with 20 mm often yielding the highest energy savings across all latitudes and melting temperatures. For example, 5 mm thicker can lead to maximumly around 210 kWh more energy saving (21 °C MT, 10 °N). However, the benefit of increased thickness becomes less significant and more variable in cooler regions farther from the equator, e.g. only 38 kWh more energy can be saved if using 20 mm instead of 15 mm PCM around 40 °N (21 °C MT). In these cooler climates, PCM often fails to fully transition phase daily, primarily due to the lower heat transfer rate, which is proportional to the temperature differences between the building interior and exterior. As a result, additional PCM thickness does not enhance the daily thermal energy

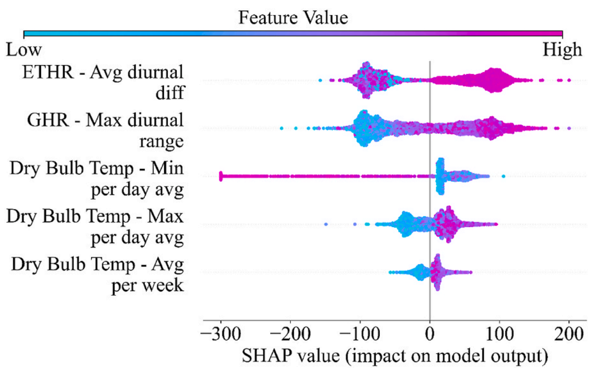


Fig. 8. SHAP beeswarm plots for the top 5 most significant variable.

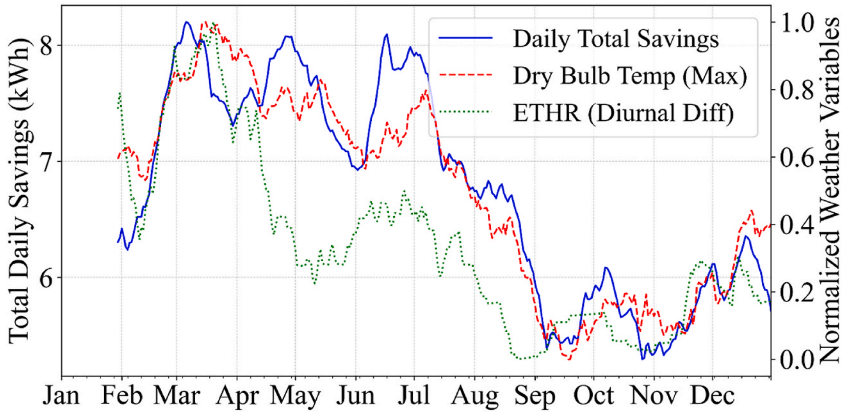


Fig. 9. Validation of significant SHAP variables using year-long simulated data, location: Phuket, Thailand.

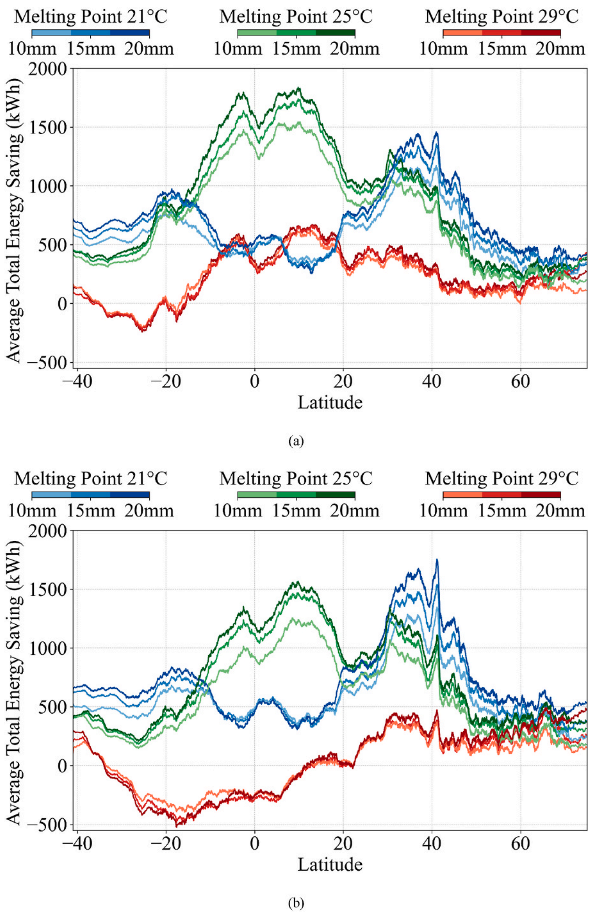


Fig. 10. Average total energy saving against latitude for (a) 'Brick & Block' construction templates; (b) 'Timber Frame' construction templates.

stored, consequently, the advantage of increasing PCM thickness in these colder climates diminishes.

In warmer climate, thicker PCMs tend to produce greater energy savings, particularly for the 21 °C and 25 °C MTs. However, an exception is observed around 10 °N latitude, where thinner 21 °C PCMs occasionally outperform. This anomaly occurs in extremely hot climates because ambient temperatures may remain above the 21 °C melting point, preventing the PCM from solidifying and completing its phase change. Additionally, the 29 °C MT does not show a consistent benefit from increased thickness, underscoring the complexity of tailoring PCM integration across different geographic locations.

3.3.2. Melting temperature

The effectiveness of energy savings varies significantly with changes in PCM MT across different latitudes. Within the latitude range of 15 °S to 30 °N, the 25 °C MT dramatically outperforms the 21 °C option, delivering an average of 743.2 kWh more in energy savings. This makes the 25 °C option especially effective in warmer regions such as South America (excluding the Brazilian highlands and the Andes), the Caribbean, Southeastern USA, Central Africa, Southern Asia, and Northern Australasia.

Conversely, the 21 °C melting point shows higher performance outside the 15 °S to 30 °N latitude range, which covers the majority of the remaining regions worldwide. These areas likely benefit from the cooler conditions that match this lower melting point. The performance difference between the 25 °C and 21 °C options is not as pronounced here, with the 21 °C only marginally outperforming the 25 °C option by 251.0 kWh on average. This suggests that MT above 21 °C may be too high to effectively utilise phase change for thermal storage under these cooler climates.

The 29 °C MT, on the other hand, often fails to achieve effective phase transitions, resulting in minimal or even negative energy savings, especially for the 'Timber Frame' templates. Although some energy savings are observed near the equator (less than 200 kWh for 'Brick & Block' templates), they are significantly lower than those achieved with the 25 °C MT, indicating only sporadic phase changes throughout the year. This MT only shows superior performance in desert climates with significant diurnal temperature variations, such as in Saudi Arabia, UAE, Pakistan, Myanmar, and Northern to Central Australia, as seen in Fig. 6(b). Given the limited effectiveness of the 29 °C option even in hotter climates, this further suggests that it may be too high for practical thermal storage.

These results emphasise that selecting the optimal MT is more important than simplifying increasing PCM thickness. Thicker PCMs are only beneficial in regions with high energy savings and temperatures, where there is enough temperature difference to drive the phase change within the daily cycle.

In cooler climates around 20 °S latitude, 'Brick and Block' with 21 °C and 25 °C PCM consistently showed higher energy savings across all PCM thicknesses, while 'Timber Frame' constructions outperformed 'Brick and Block' between 30 °N and 50 °N. Notably, 'Timber Frame' structures displayed a larger variance in performance between PCM thicknesses due to their lower thermal resistance. This characteristic allows for more complete phase change. However, this also results in quicker energy release back into the environment, potentially diminishing the net energy savings. These observations suggest that 'Timber Frame' constructions may require a lower optimal MT of PCM, enhancing the effectiveness of the 21 °C PCM and diminishing that of the 29 °C PCM, especially when compared to 'Brick and Block' constructions.

These findings underscore the importance of optimising not only the PCM thickness and MT but also the construction type that houses the PCM. This ensures that the PCM is utilised to its full potential by optimising the heat transfer rate between the building's interior and exterior, thereby maximising energy efficiency.

3.4. Environmental and economic analysis

To evaluate the environmental impact of PCM integration, Fig. 11 displays the potential CO_2 savings using the same construction templates that showed the highest energy savings in Fig. 6. The map highlights significant CO_2 saving, 700–1400 kg per year, in regions such as the Caribbean, Central Africa, India, the Malay Archipelago, and remote islands, where substantial cooling energy savings and high carbon intensities from underdeveloped renewable energy infrastructures.

Conversely, in cooler, economically developed regions like Europe, Russia, and Canada CO_2 savings are considerably lower, e.g. lower than 200 kg per year. These areas predominantly require heating rather than cooling, and the carbon intensity of natural gas, the dominant fuel for heating, is relatively low at 0.185 kg/kWh reducing the potential for substantial CO_2 reductions.

To assess the economic impact of PCM integration, Fig. 12(a) illustrates the maximum cumulative net cost savings over a 50-year period using the 'Brick and Block' construction template that resulted in the highest energy saving. Accurate energy pricing data is crucial for this analysis, but such data was not uniformly available across all regions, particularly for natural gas in areas like the

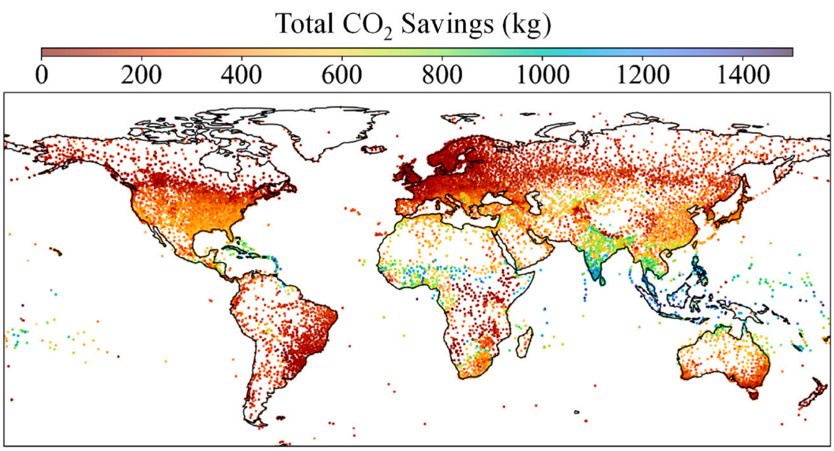
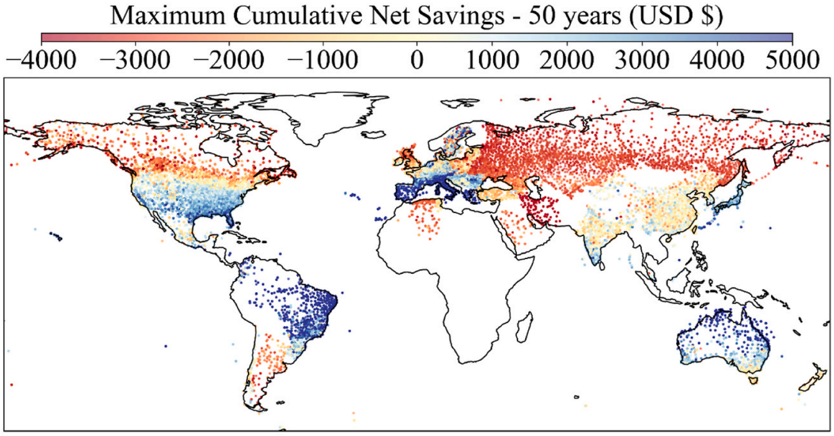
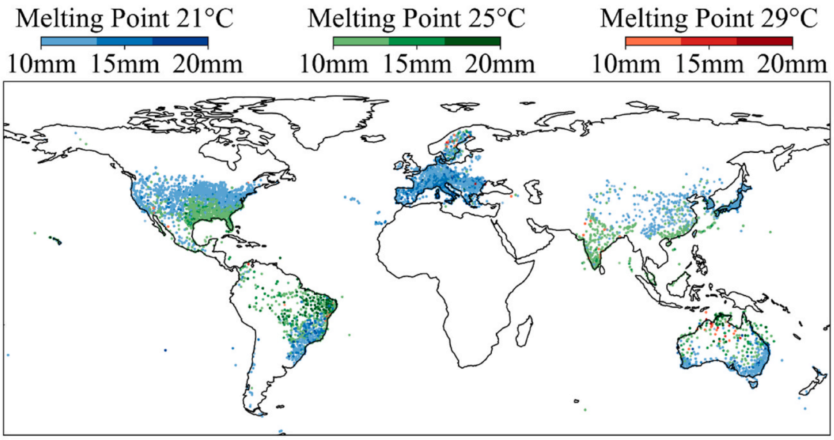


Fig. 11. Maximum CO_2 savings across 'Brick & Block' construction templates.



(a)



(b)

Fig. 12. (a) Maximum 'Brick & Block' Cumulative Net Saving (50 years) after integrating PCMs; (b) corresponding construction templates that results in maximum positive cumulative net savings.

Caribbean, Africa, Central Asia, and the Malay Archipelago. In regions lacking either gas or electric price data, cumulative savings calculations could not be completed.

Regions showing positive net cost savings represent areas where PCM integration is economically feasible within the lifespan of the building envelope. Notable regions include the USA, Mexico, Brazil, central and southern Europe, India, China, Japan, and Australia, with the highest savings observed in the southeastern USA, southern Europe, Brazil, and northern Australia (>3000 USD$ per year). These findings suggest substantial commercial potential for PCM deployment in these regions. While these calculations use 2022 energy prices and do not account for the time value of money, they provide a valuable baseline for identifying where PCM technology could be economically viable, offering a strategic foundation for investments in energy-efficient building technologies. However, maintenance or replacement costs, which could be significant if any of the encapsulated PCM were to leak, were not considered in this analysis.

Fig. 12(b) displays the specific construction templates that yield the highest positive cumulative net savings. The chosen MTs correlate with those that provide maximum energy savings, as seen in earlier analyses. The most common thickness across various locations is 10 mm, attributing to the corresponding lowest capital cost. Higher thicknesses of 15 mm and 20 mm show greater net savings in certain areas such as eastern Brazil, southern Europe, and northern Australia. This suggests that in these regions, the additional upfront cost of thicker PCM layers is offset by significantly higher energy savings over 50 years, highlighting these areas as prime candidates for initial PCM integration.

Moreover, policy and government incentives offering rebates could increase the adoption of PCM technology. Implementing a CO_2 tax policy could significantly enhance the economic viability of PCM integration by adding CO_2 tax savings to direct energy cost savings, especially in regions with high CO_2 savings potential.

For further insights, figures displaying the maximum cumulative net savings for 87 years, the manufacturer-suggested lifespan of the PCM [35], can be seen in Appendix 3, as well as a set of figures for payback periods in Appendix 4. The payback period was not used as the primary economic metric since it does not account for the entire lifecycle of the PCM.

4. Conclusions

This study has comprehensively explored the integration of PCMs in building envelopes across varied climates, emphasising a global perspective on energy efficiency improvements and market viability. Through extensive simulations and AI models, the study evaluated the energy savings and economic benefits of integration of PCMs in buildings in different geographic locations. It examined the impact of various PCM properties, such as melting temperature and thickness, tailored to optimise building energy performance economic viability worldwide. Below are the significant conclusions drawn from the study.

Highest Energy Savings: Significant total annual energy savings, 1250 kWh to 2000 kWh in average, were observed in latitudes between 40 °N and 20 °S by using 'Brick and Block' construction templates. Highest total energy savings occur in equatorial regions (e.g., northeast Brazil, central Africa, Malay Archipelago), ranging from 2500 kWh to 3000 kWh annually.

Key Variables Influencing Savings: Maximum and minimum daily temperatures were identified as the most critical variables affecting energy savings, with extraterrestrial horizontal radiation (ETHR) and global horizontal radiation (GHR) also contributing to energy conservation. The large diurnal temperature difference in regions with substantial direct solar radiation during the day and cooler temperatures at night maximises PCM's phase change efficiency, leading to higher energy savings.

PCM Thickness: The most common effective PCM thickness is 20 mm for maximum energy savings. Thicker PCM applications provided the greater energy savings in warmer climates, particularly for 21 °C and 25 °C melting temperatures. However, the benefits of increasing thickness diminished in cooler regions where daily temperature differences are lower.

PCM Melting Temperature: The 25 °C MT outperformed the 21 °C MT between latitudes 15 °S and 30 °N, particularly in warm climates, delivering 743.2 kWh more in energy savings. The 21 °C MT showed better performance outside this range, with minimal advantages from the 29 °C MT.

Construction Type: 'Brick and Block' constructions performed better in cooler latitudes, while 'Timber Frame' constructions outperformed in the 30 °N to 50 °N range due to their lower thermal resistance. Observations suggest that 'Timber Frame' constructions may require a lower optimal MT of PCM.

CO_2 Savings: Regions like the Caribbean, Central Africa, India, and the Malay Archipelago showed substantial CO_2 savings due to high energy savings and carbon-intensive energy grids. Cooler developed regions had lower CO2 savings due to their reliance on relatively low-carbon natural gas heating.

Economic Viability: PCM integration showed positive net cost savings over 50 years in regions like the USA, Mexico, Brazil, southern Europe, India, China, and Australia, attributing to energy saving and/or relatively high energy price.

These findings provide insights into the regions where PCM integration is most financially viable, suggesting targeted areas for commercial deployment. While the findings highlight key drivers of high energy savings and offer recommendations for optimising PCM integration, they emphasise the necessity of customising PCM solutions to specific climates, building types, and use cases. This tailored approach is essential for maximising energy efficiency and ensuring the successful adoption of PCM technology in global building practices. For the future, the following works are recommended.

- Investigating the causes behind the large negative energy savings observed with the 29 °C melting temperature.
- Conducting a detailed study on the diminishing returns from increased PCM thickness, focusing on why thinner layers can yield better performance.
- Implementing a more granular evaluation of melting temperatures with smaller steps to fine-tune the PCM property.
- Exploring how different construction templates influence the thermal transfer rates to and from the building's interior and exterior, affecting the overall thermal efficiency.
- Further optimise the building designs by considering local construction practices, economic conditions, and occupant comfort, all of which are influenced by regional climate conditions.
- Expanding the economic analysis to include levelised cost of energy and net present value assessments to provide a more detailed financial viability of PCM integration.

CRediT authorship contribution statement

Andrew James Mettrick: Writing – original draft, Software, Methodology, Formal analysis. **Zhiwei Ma:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

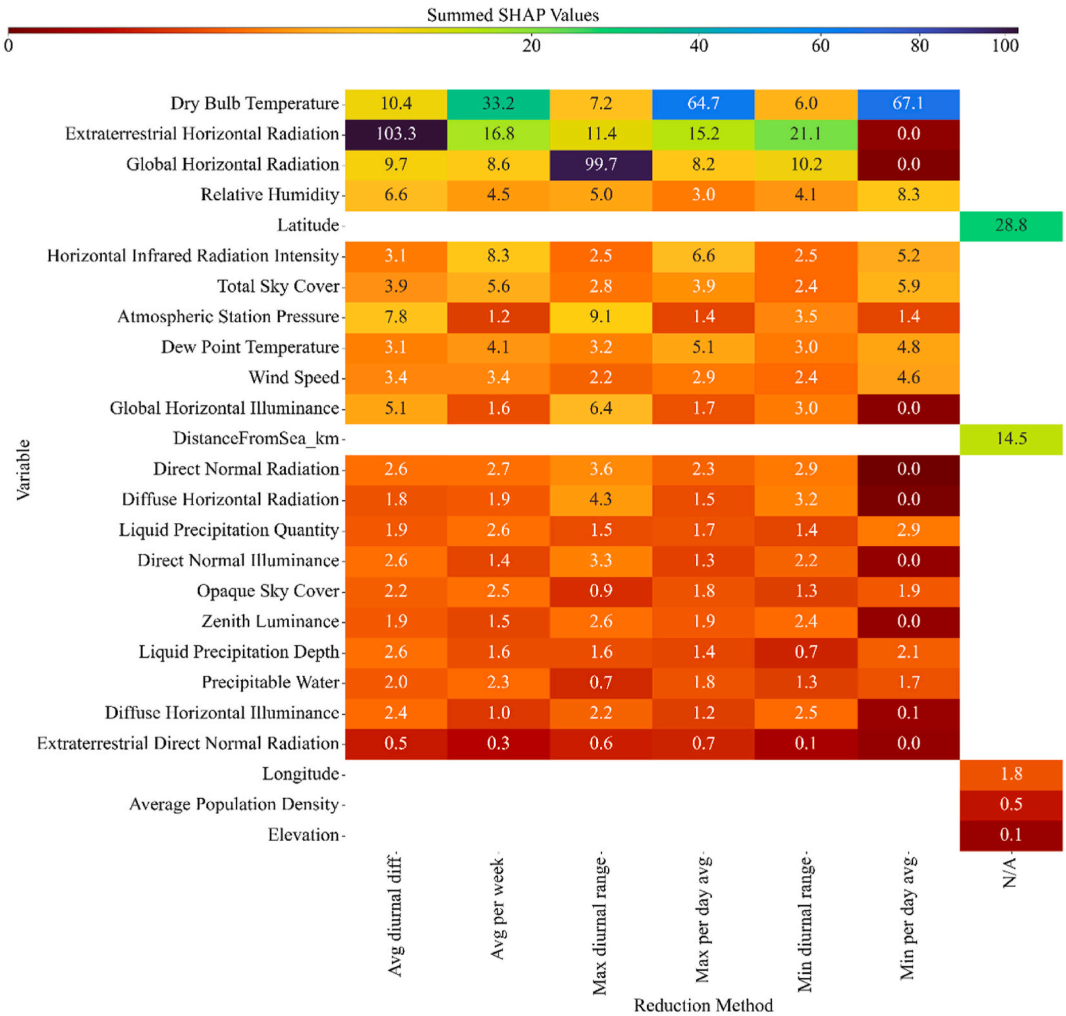
The authors gratefully acknowledge the support from the Solar S&HP project (EPSRC, EP/T023090/1) funded by the UK Engineering and Physical Sciences Research Council. Data supporting this publication is openly available through Durham Research Online

DATAsets Archive (DRO-DATA)

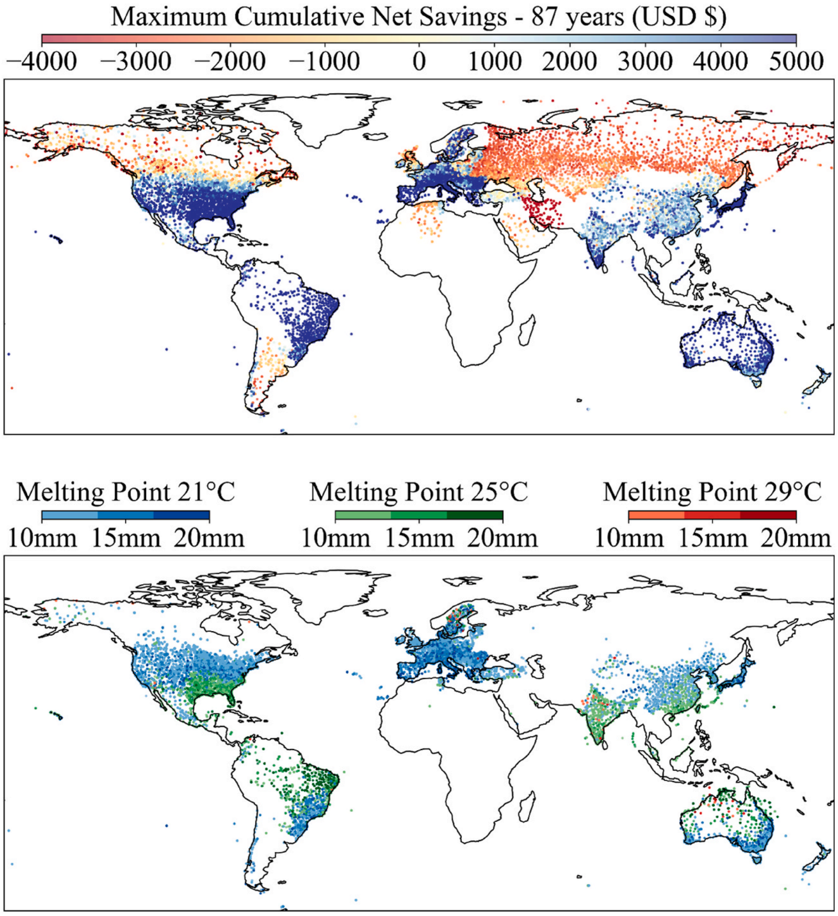
Appendix 1. Detailed construction templates

					External Walls					Flat Roof	Pitched Roof (occupied)	Pitched Roof (unoccupided)	Internal Partitions	Semi-Exposed Walls	Semi-Exposed Ceiling			Semi-Exposed Floor	Ground Floor	External Floor	Internal Floor
Construction Template ID	PCM vs No PCM	Construction Type	Thickness (mm)	PCM Melting Point (c)	Layer 1 (Outa)	Layer 2	Layer 3	Layer 4	Layer 5 (inner)						Layer 1 (Outa)	Layer 2	Layer 3				
0	0	Brick and Block	N/A	N/A	Brickwork (100mm)		Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls		Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
1	0	Timber Frame	N/A	N/A	Lightweight Metallic Cladding (6mm)		Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls		XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
2	1	Brick and Block	10	21	Brickwork (100mm)	InfiniteRPCM21C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
3	1	Brick and Block	10	25	Brickwork (100mm)	InfiniteRPCM25C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
4	1	Brick and Block	10	29	Brickwork (100mm)	InfiniteRPCM29C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (10mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
5	1	Brick and Block	15	21	Brickwork (100mm)	InfiniteRPCM21C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
6	1	Brick and Block	15	25	Brickwork (100mm)	InfiniteRPCM25C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
7	1	Brick and Block	15	29	Brickwork (100mm)	InfiniteRPCM29C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (15mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
8	1	Brick and Block	20	21	Brickwork (100mm)	InfiniteRPCM21C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
9	1	Brick and Block	20	25	Brickwork (100mm)	InfiniteRPCM25C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
10	1	Brick and Block	20	29	Brickwork (100mm)	InfiniteRPCM29C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Aerated Concrete (100mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (20mm)	Glass Fiber/wool - fiber slab (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
11	1	Timber Frame	10	21	Lightweight Metallic Cladding (6mm)	InfiniteRPCM21C (10mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (10mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
12	1	Timber Frame	10	25	Lightweight Metallic Cladding (6mm)	InfiniteRPCM25C (10mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (10mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
13	1	Timber Frame	10	29	Lightweight Metallic Cladding (6mm)	InfiniteRPCM29C (10mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (10mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
14	1	Timber Frame	15	21	Lightweight Metallic Cladding (6mm)	InfiniteRPCM21C (15mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (15mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
15	1	Timber Frame	15	25	Lightweight Metallic Cladding (6mm)	InfiniteRPCM25C (15mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (15mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
16	1	Timber Frame	15	29	Lightweight Metallic Cladding (6mm)	InfiniteRPCM29C (15mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (15mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
17	1	Timber Frame	20	21	Lightweight Metallic Cladding (6mm)	InfiniteRPCM21C (20mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM21C (20mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
18	1	Timber Frame	20	25	Lightweight Metallic Cladding (6mm)	InfiniteRPCM25C (20mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM25C (20mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab
19	1	Timber Frame	20	29	Lightweight Metallic Cladding (6mm)	InfiniteRPCM29C (20mm)	Glass Fiber/wool - fiber slab (80mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	Flat Roof	Clay Tiles	Clay Tiles	Lightweight 2 x 25mm gypsum plasterboard	Same as External Walls	InfiniteRPCM29C (20mm)	XPS Extruded Polystyrene (80mm)	Plaster Board (15mm)	External Floor - Heavyweight	Ground Floor Slab - Heavyweight	External Floor - Heavyweight	300mm Concrete Slab

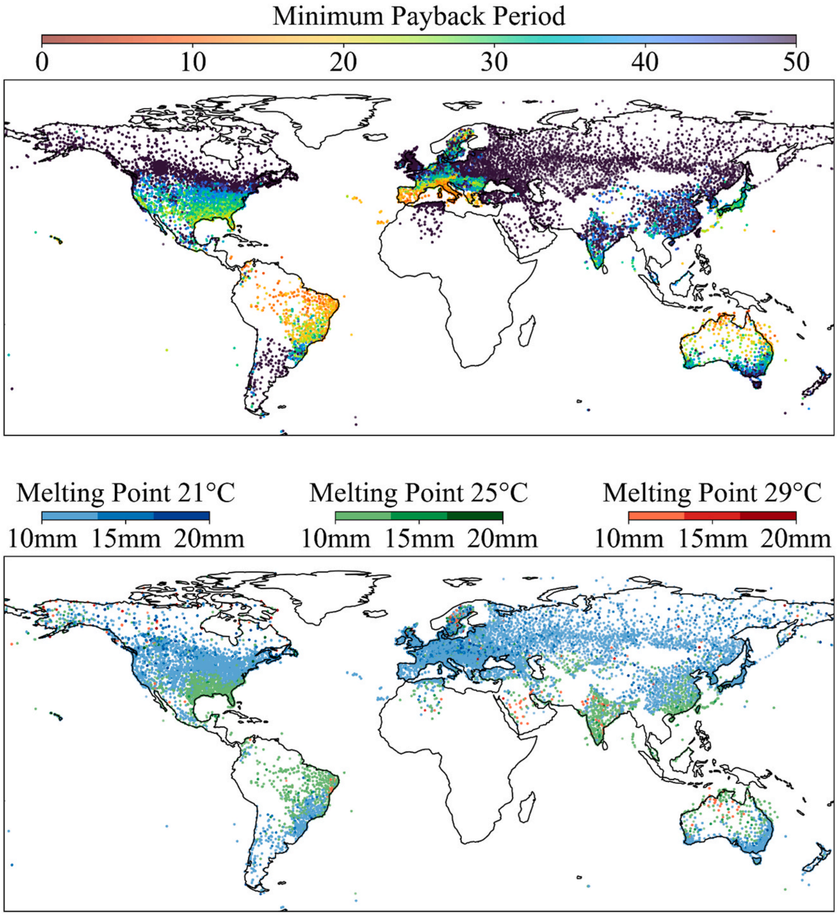
Appendix 2. Complete SHAP values with all variables



Appendix 3. Maximum 'Brick & Block' Cumulative Net Saving (87 years) after integrating PCMs and the corresponding construction templates that results in positive savings



Appendix 4. Minimum 'Brick and Block' Payback Period after integrating PCM and the corresponding construction templates



Data availability

Data will be made available on request.

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