DISCLAIMER

Sumner County Field Validation: An Assessment of Thermal Energy Storage in Municipal Buildings in Mixed-Humid Climates

Sajith Wijesuriya,[1] Chuck Booten,[1] Barry Dicker,[2] Ravi Anant Kishore,[1] Mario Medina,[3] and Habib Arjmand Mazidi[4]

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NREL is a national laboratory of the U.S. Department of Energy
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Disclaimer of Endorsement

List of Acronyms

AFN	airflow network
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CDD	cooling degree days
CFM	cubic feet per minute
CondFD	conduction finite difference
CVRSME	coefficient of variation of the root-mean-square error
EIA	U.S. Energy Information Administration
FEMP	Federal Energy Management Program
HDD	heating degree days
HVAC	heating, ventilation, and air conditioning
IPMVP	International Performance Measurement and Verification Protocol
PCM	phase change material
PVC	polyvinyl chloride
PMT	peak melting temperature
R-value	thermal resistance
SCFM	standard cubic feet per minute
TES	thermal energy storage

Executive Summary

The aging U.S. building stock requires various retrofit measures to enhance building energy efficiency, and these measures have the potential for energy conservation and the modulation of peak energy demand. With many U.S. counties introducing time-of-use electricity pricing and peak shaving incentives, building retrofits can be aligned to save HVAC energy-related costs. This study considered a cluster of administrative and office buildings located in Wellington, Kansas, to explore the energy benefits achievable through thermal energy storage retrofits.

This report discusses studies conducted in two buildings in the buildings considered. The first part of the study conducts a comprehensive study spanning nearly three years to validate a whole-building model of the City Hall building of the city of Wellington. This study required detailed implementation of sensor and data acquisition systems to measure a number of different parameters necessary for the comparisons of experimental and modeled data. Data were collected in two main stages, pre-retrofit and post-retrofit. The retrofit considered is the application of around 2,000 phase change material (PCM) tiles in the drop ceiling of the occupied zones of the building. The PCM tile later was added between the insulation and the drywall layer of the ceiling envelope. The total data acquisition process took nearly two years.

Parallel to the data acquisition process, a whole-building energy model was built using software tools Rhinoceros and Grasshopper, and then building features were added using OpenStudio™ and EnergyPlus™ platforms. Data collected from the building pre-retrofit identified many building thermal characteristics to calibrate the whole-building model. Specifically, HVAC leakage to the plenum above the ground floor, thermal bridging caused by the unevenly spread insulation, ceiling-opening-related heat flow, and the thermal stratification caused complex thermal behaviors in the building that impacted the comparisons in the temperature and the energy consumption of the building. The calibrated building model showed coefficient of variation of root-mean-square error values within the acceptable criteria defined for this study. Special consideration was given to create a comprehensive geometric model of the model to measure temperatures and energy consumption values from three main occupied zones of the building. Particularly, comparisons of temperature and HVAC energy for the zone 1 of the building are included in this report. The validated building model provided an opportunity to conduct further parametric studies to investigate the energy benefits by tuning PCM application. The current passive PCM implementation showed nearly 12% peak cooling energy reduction.

The second part of the study included duct-integrated experiments after the passive PCM retrofit study in the ceiling to explore further applications for PCMs using a second building from the cluster of the buildings. This study was conducted over two months and the same PCM tiles were repurposed to be integrated within a 2-ft × 2-ft supply register in an unoccupied building. The goal was to demonstrate controlled charge and discharge of the PCM through normal HVAC system operation in a configuration suitable for retrofit scenarios using common hardware such as 2-ft × 2-ft supply registers. Two PCMs were investigated, with 14°C and a 22°C transition temperatures, both focused on cool storage for the cooling season. The experiment highlighted the plausibility of using this approach for integrating PCM into building HVAC systems. The mass of PCM per supply register, ~32 kg, is high but not prohibitive for building structures to mechanically support, and therefore showcased a potential way of effectively using PCMs in building applications.

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1 Introduction

Buildings account for nearly 39% of total energy consumption in the United States, 21% in residential buildings and 18% in commercial buildings (U.S. Energy Information Administration [EIA] 2024). Office buildings are a subset of commercial buildings, and in 2018, U.S. office buildings consumed the most electricity (775 TBtu) of the different building types considered in surveys conducted by the EIA (2022). Energy from electricity consumption amounted to nearly three times that from natural gas consumption of office buildings. Of building types surveyed, office buildings also had the second highest natural gas consumption. In the United States, 74% of commercial buildings were constructed before 1990 and therefore require energy audits to effectively apply efficiency measures (Basuroy, Chuah, and Jha 2013). Excessive energy demand is attributed to faults in buildings, which include heating, ventilation, and air-conditioning (HVAC) system leakages and building envelope-related energy losses (Roth et al. 2004). This energy demand exerts great stress on the energy supply for heating and cooling, which highlights the need to reduce the HVAC energy consumption and peak energy demand of office buildings.

A field investigation of thermal energy storage (TES) deployed in administrative office buildings in climate zone 4A in the United States was carried out in this study. An administrative building (City Hall) located in Wellington, Kansas (Sumner County), was used to conduct energy audits and implement TES retrofit solutions. The overall aim of the project was to conduct a full-scale implementation of TES in an operational (occupied and used for normal operations) administrative building with a special focus on phase change material (PCM) passive implementation in the ceiling envelope. PCM was used to increase the ability of public buildings to shift their peak HVAC energy demand and consumption. The PCM product used in this study was Templok™, produced by Insolcorp Inc. The rights to Templok have been acquired by Armstrong World Industries Inc.

The study was conducted over 3 years in three phases: (1) energy audit (pre-retrofit), (2) ceiling tile installation (PCM retrofit), and (3) energy evaluation (post-retrofit). Temperature and HVAC energy measurements as well as weather data were used for an extensive validation study. In addition to the measurements of the installed TES system, parametric assessments based on whole-building simulations were conducted to further evaluate the annual HVAC energy savings and peak period electricity and load reductions due to the TES that can be realized in cooling-dominant months of the year. Although Sumner County does not have a formal time-of-use rate, it offers a peak shaving program. The average residential rate—approximately 15.03 ¢/kWh—is slightly above the state average of 14.30 ¢/kWh. This provides a motivation to evaluate TES as a retrofit solution for Sumner County, and this approach could also be used in other locations in the same climate zone.

2 Building Information

Wellington is a small city in Sumner County, Kansas, with a population of 7,664 (as of 2021) (U.S. Census Bureau n.d.). According to ASHRAE climate zone categorization (ASHRAE 2021), Wellington is located in zone 4A, mixed and humid climate. Wellington's City Hall, the site of the demonstration, is a one-story building with a total enclosed area of 7,900.7 ft^2 (734 m^2) and median floor-to-ceiling height of 10.0 ft (3.05 m). The building also has a plenum level in addition to the occupied ground floor level, with a height of 9.0 ft (2.74 m). The building was initially built as a department store and was remodeled into an office building in 1980. Figure 1A shows the geographical location of Wellington, and Figure 1B shows the City Hall building, which was used to test the PCMs in the drop ceiling. Figure 1C shows the 3D rendering of the whole-building model constructed using the Rhino software tool. Figure 1D shows the four thermal zones of the building.

The following describes factors related to the thermal conditions of the building, which were used to develop the EnergyPlus thermal model employed in the study. The internal thermal loads in the building include people, lighting, equipment, and plug loads. There are, on average, 18 permanent office workers in the building. In addition, temporary clients or general meeting attendees varied from 1 to over 25 at any point during the work hours of the years monitored. The primary interior lighting system consists of 89 recessed and ceiling-mounted 2-ft × 4-ft (0.6-m × 1.2-m) fluorescent troffers. In terms of plug loads, there are 17 desktop computers, two copy machines, two coffee makers, a vacuum/carpet cleaner, a security camera system, and a small server room. Additionally, several randomly used personal heaters (not surveyed) are also employed in the heating season. The business hours of the building are from 8 a.m. to 5 p.m., Monday through Friday; the building was assumed to be unoccupied on weekends. These aspects are considered in the whole-building energy modeling conducted in this study.

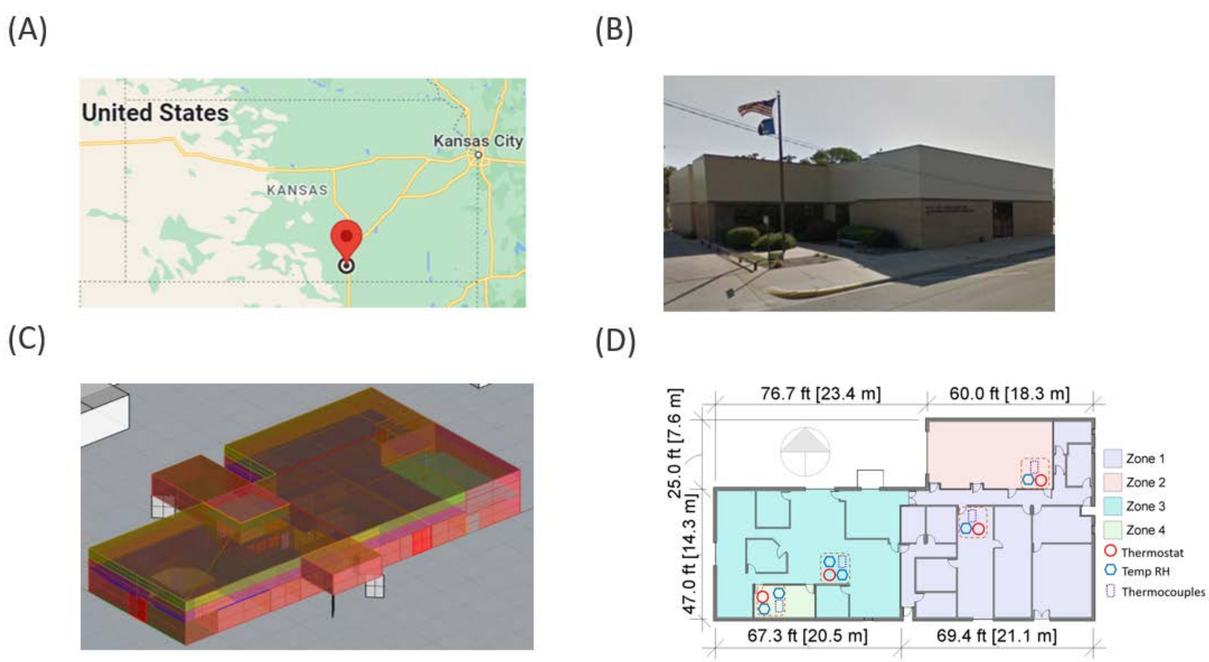

Figure 1. Administration building (City Hall) used for the study located in Wellington, Kansas (Sumner County)

2.1 Weather Characteristics

At a nearby national weather station (Strother Field, Kansas, at 37.2°N, 97.0°W, 351 m), weather data obtained in 2021 (which includes more than 8 years of measurements) indicated a cooling degree day (CDD) measurement of 1036 and a heating degree day (HDD) measurement of 2262 °C-days, which is similar to the CDD and HDD shown in Figure 2. The significant cooling demand, which relies on electricity to run the air conditioning system, highlights the importance of thermal storage in the summer to reduce peak electricity usage, but the even greater heating requirement also shows the potential value of winter thermal storage if there is substantial electric heating employed in buildings.

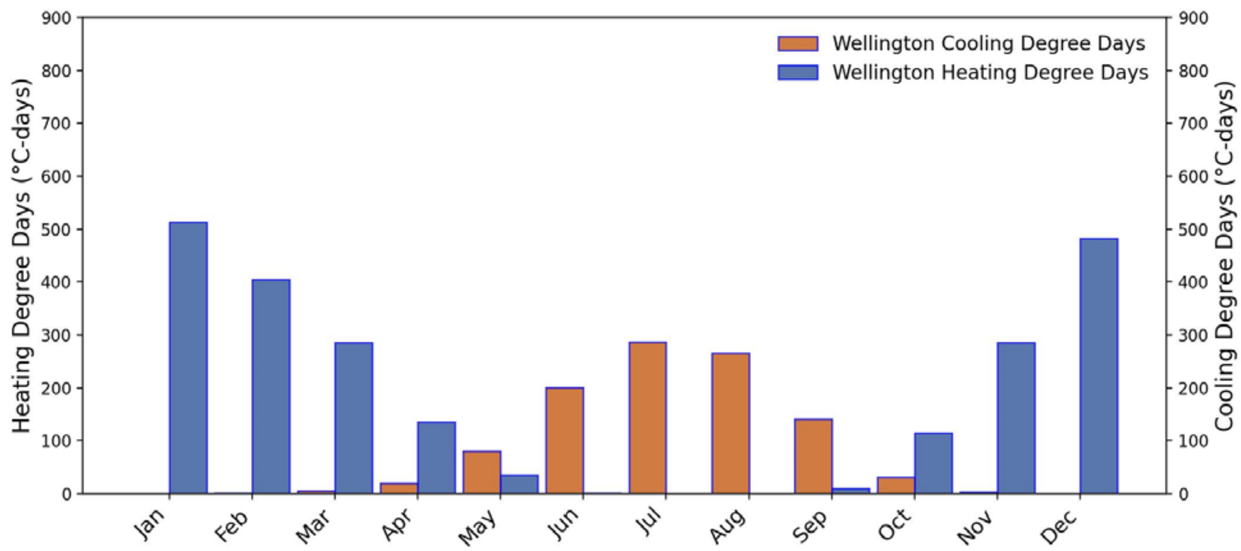

Figure 2. $CDD_{18.3°C}$ and $HDD_{18.3°C}$

2.2 Weather Data

A weather station comprising temperature and relative humidity sensors, an anemometer, and a pyranometer was installed on-site on the roof top of the City Hall building to gather weather data and update the weather files for the building energy simulations. The measurable temperature range was -40°C to +60°C with ±0.2°C accuracy (at 20°C), and the measurable relative humidity range was 0% to 100% with ±2% (0%–90%). An ultrasonic anemometer was also integrated with a horizontal wind speed range of 0–30 m/s with ±0.3 m/s accuracy and ±5% accuracy for the wind direction. A digital thermopile pyranometer was also used for measuring solar radiation with a measurement range of 0–2,000 W/m^2 with ±2% error. The weather station was installed on the city courthouse, a taller building located 807 m from the City Hall building, since the station data were used for five other buildings in the city. The data collected from this weather station were augmented with the EnergyPlus® input weather file for Wichita, Kansas, for the annual simulations.

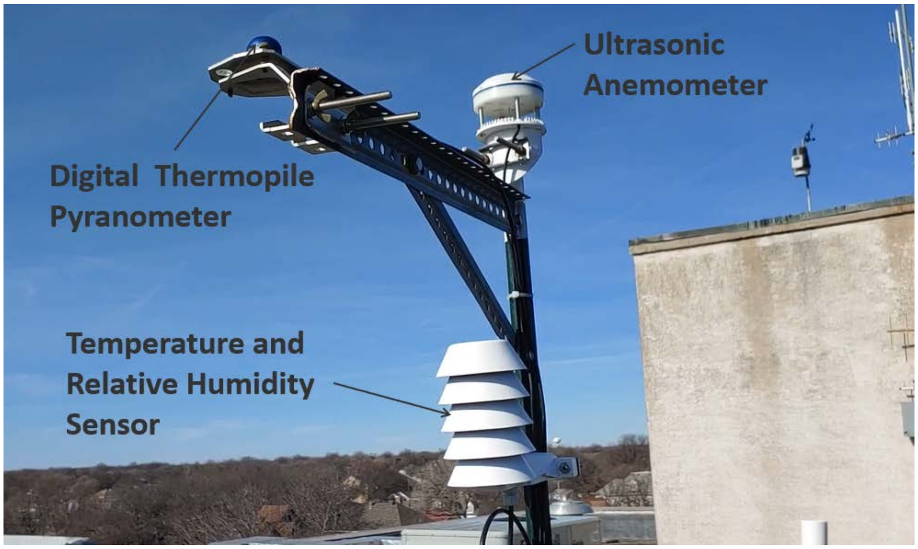

Figure 3. The weather station on the Wellington city courthouse

2.3 PCM Specifications

Insolcorp has manufactured inorganic-based PCM tiles under the Templok brand name in two sizes; 24-in. × 24-in. (61-cm × 61-cm) PCM tiles were utilized in this research. The Insolcorp PCMs were based on calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$), calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$), and gluber's salt ($Na_2SO_4 \cdot 10H_2O$) for 18°C–22°C, 27°C–31°C, and 22°C–26°C transition temperatures, respectively. The PCM tile was shape-stabilized and packed in rigid thermoformable PVC with a density of 1.3–1.45 g/cm^3 and thermal conductivity of about 0.14–0.28 W/m·K. Hence, the PCM tiles have a thermal storage capacity of 1,145 kJ/m^2. The peak transition temperatures of the PCM in the tiles available for use in the current study were 18°C, 22°C, 25°C, and 29°C. The peak transition temperature for the PCM is the temperature corresponding to the peak value of the change in enthalpy with temperature recorded in PCM characterization data when the material is changing phase from solid to liquid. The PCM characterization is usually done using differential scanning calorimetry method, which is a well-known thermal analysis technique used to determine the thermal properties of PCMs. The manufacturer who contributed to this study had products showcasing the four peak transition temperatures listed above.

3 Building Envelope Integrated PCM Experiment

The experiments from this study can be divided into two categories: drop ceiling integration and duct integration. The primary focus was on the drop-ceiling-integrated PCM retrofits; the duct-integrated experiments were incorporated as part of an opportunity that arose during the course of the project. The duct-integrated experiments were carried out for a relatively shorter time period of two months, whereas a year's worth of data was collected after the PCMs were integrated to the drop ceiling. This section discusses the building ceiling-integrated PCM experiment.

Table 1 shows the materials and heat transfer resistances of different envelopes of the building. The exterior wall of the building consists of a brick layer at the exterior that is only present at the occupied zone level. A metal panel encloses the plenum level, which is above the occupied ground level of the building. Six inches of batt insulation and half-inch drywall cover the interior side of the occupied spaces.

Table 1. Building Envelope Materials and the Thermal Resistance (R-value)

Envelope	Material	Thickness cm (in.)	R-value m^2·K/W (ft^2·°F·h/Btu)
Exterior Wall	Brick layer	10.2 (4)	0.11 (0.64)
	Mass wall	30.5 (12)	0.22 (1.24)
	Batt insulation	15.2 (6)	3.31 (18)
	Gypsum board	1.27 (0.5)	0.08 (0.45)
Roof	Build-up roof		0.06 (0.33)
	Rigid foam on wood deck	2.54 (1)	0.88 (5.00)
Ceiling	Batt insulation	30.48 (12)	6.62 (38)
	Acoustic (gypsum) tile 0.61 m × 1.02 m (2 ft × 4 ft)	1.27 (0.5)	0.08 (0.45)

Figure 4A shows the 24-in. × 24-in. (61-cm × 61-cm) inorganic PCM tiles installed in the building above the drop ceiling. Figure 4B shows the material layers of the building envelope in an elevation view of the building. There are two main levels of the building: plenum and occupied zone. The plenum zone wall height is 9 ft (2.8 m), and the occupied zone wall height is 10 ft (3.05 m). The exterior wall has a 12-in. (0.3-m) mass wall that encloses the living space as well as the plenum zone. Figure 4C shows the arrangement of the PCM in the 24-in. × 24-in. tile. The mass of the tile is nearly 3 kg. The ceiling area available to be covered by PCM tiles was nearly 7,910.8 ft^2 (734 m^2). However, there were limitations on the PCM tiles' availability. As a result, we have assumed a reduced area of coverage in the EnergyPlus model, covering thermal zones 1, 2, and 3. The total covered area considered for the model is 5,527 ft^2 (513.4 m^2). The PCM thickness was 0.25 in. (6.35 mm). Hence, the total volume of PCM was 115 ft^3 (3.3 m^3). This amounted to around 4,540 kg of PCMs applied in all thermal zones of the building. This assumes that the area that could be covered from the tiles in the three occupied spaces was covered.

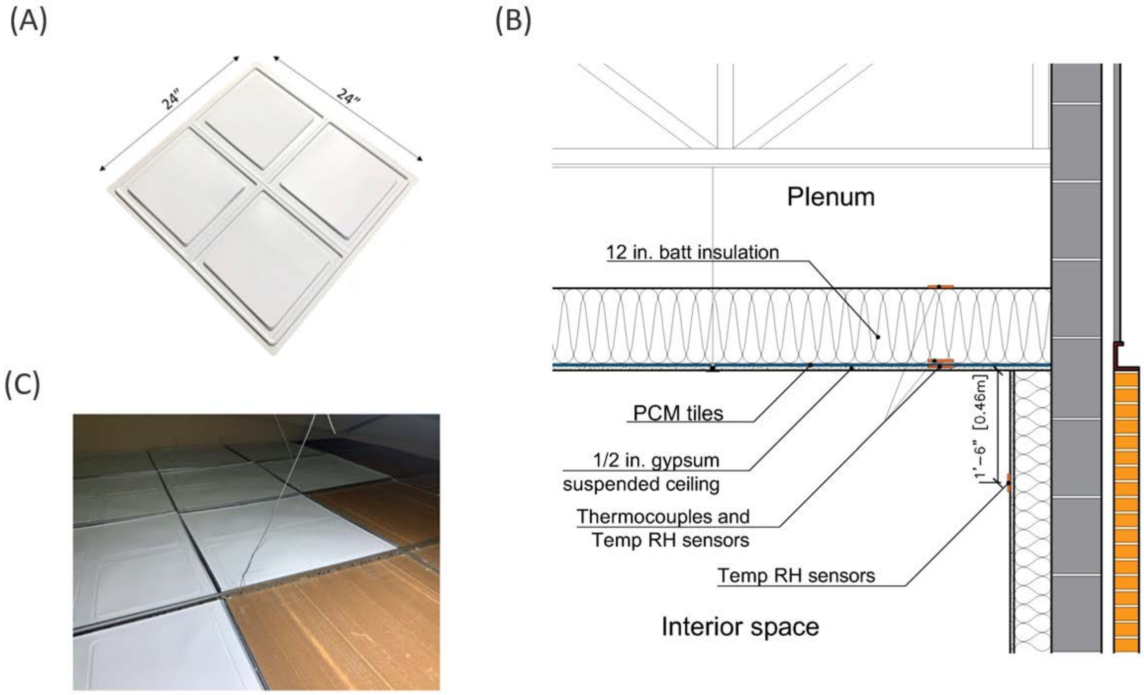

Figure 4. (A) 24-in. × 24-in. PCM tile used in the study. (B) PCM tiles applied between the 12-in. batt insulation layer, PCM ceiling tile layer, and the gypsum suspended ceiling. Temperature sensors are placed above the insulation layer (plenum), under the insulation layer and above the PCM tile layer, and under the ceiling (conditioned space). (C) Application of the PCM tiles above the existing acoustic tiles, which can be easily removed.

3.1 Experimental Setup and Data Acquisition

Figure 5 shows the sensors employed in the occupied zones. Figure 5A shows the sensors above the drop ceiling and under the batt insulation. Figure 5B and C shows the sensors in the occupied zones of the building. Two systems of sensors were deployed in the building, HOBO and ezeio mkII, with associated controller and sensors that measured temperature and relative humidity (thermostat, thermocouples, HOBO temperature/relative humidity sensor, and ZCGj temperature/relative humidity sensor). As a redundant data collecting system, HOBO data loggers were also installed in target locations in the building, where the more comprehensive data collection was needed for the validation study. All data were collected every 5 seconds, and the system had the ability to average the measurements at 1 minute, 10 minutes, and 1 hour intervals. This minimized the signal errors caused by variations in wind speed, passing clouds, and indoor temperature changes due to HVAC on-off cycles. Pulse-output gas meters (1.5 in.) and Continental Control Systems WattNode Modules (integrated into the ezeio system) were installed in the two mechanical rooms to measure natural gas and HVAC electricity consumption in the building, respectively.

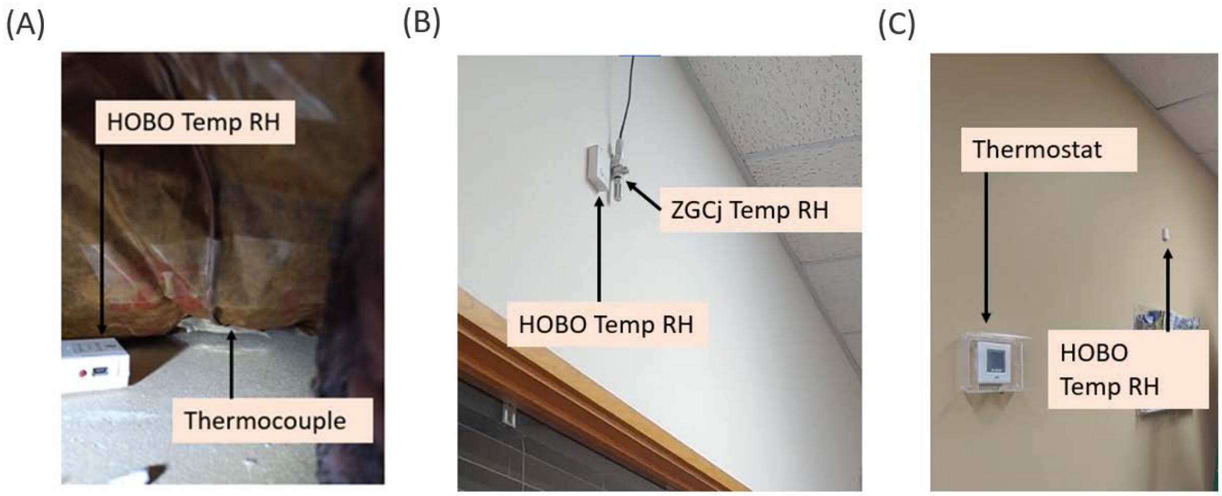

Figure 5. Sensors installed (A) above the drop ceiling and (B,C) in the interior occupied zones

The retrofit plan of the ceiling-integrated study comprised three phases: energy audit (pre-retrofit), ceiling tile implementation (PCM retrofit), and energy evaluation (post-retrofit).

- In Phase I, sensors and data-collecting systems were deployed, including temperature/humidity sensors, a heat flux sensor, thermocouples, a weather station, and gas and electricity meters. In addition, the utility data history was obtained and compared to other measurements. This phase aimed to create a baseline energy model and develop and calibrate a state-of-the-art EnergyPlus model for the whole building. Furthermore, the complex thermal behaviors of the building—like the HVAC leakage to the plenum zone, thermal stratification, heat transfer through ceiling openings and spaces without ceiling insulation—were also uncovered in Phase I of the study. Phase I temperature measurements were also used to select the optimal peak melting temperature of the PCM to implement.
- In Phase II, PCM tiles were added above the ceiling tile. The thermophysical properties of the PCMs, including density, specific heat, and melting temperature, were obtained from the manufacturer's specifications and their laboratory tests.
- In Phase III, the two EnergyPlus scenarios, without PCM tiles and with PCM tiles, were compared and validated using experimental data.

The next section discusses the EnergyPlus whole-building model that was constructed at the end of Phase I and that was modified during Phases II and III.

4 Duct-Integrated PCM Experiment

The duct-integrated experiment was carried out after the passive PCM retrofit study in the ceiling to explore further applications for PCMs. The PCM tiles shown in Figure 4 were repurposed to be integrated within a 2-ft × 2-ft supply register in an unoccupied building. The goal was to demonstrate controlled charge and discharge of the PCM through normal HVAC system operation in a configuration suitable for retrofit scenarios using common hardware such as 2-ft × 2-ft supply registers. Charge and discharge were inferred from entering and leaving air temperatures in the modified register. The PCM heat exchanger was in-line with the supply duct; there was no bypass damper or other mechanism to isolate the PCM from airflow through the duct. Two PCMs were investigated, with 14°C and a 22°C transition temperatures, both focused on cool storage for the cooling season. There were three modes of operation:

1. Charging: The air conditioner was operating, thus freezing the PCM or maintaining the frozen state.
2. Discharging: The air conditioner was off, but the air handler was operating in fan mode, thus blowing return air from the room over the PCM and discharging/melting it.
3. Off: No air was flowing over the PCM. There was slow discharging via natural convection.

Figure 6 shows the experimental heat exchanger with PCM mated to a 2-ft × 2-ft supply register. The air flows downward across the heat exchanger to charge or discharge the PCM. This was installed in one 2-ft x 2-ft supply register in an unoccupied 1970s vintage, approximately 2,000 ft^2 municipal office building, which is different than the City Hall building that was used to install the ceiling PCMs. The room considered was 400 ft^2 (37.2 m^2) and was chosen for this experiment because it had the largest airflow of any supply register on the system. The HVAC system of the building was not configured properly, resulting in much lower supply airflow rates than appropriate for the nominal capacity of the system. Due to a limited project budget, the HVAC system could not be repaired or replaced for the experiment. This imposed limitations on the experiment by having lower-than-anticipated airflow through the supply register: 23 cubic feet per minute (CFM) with the heat exchanger and diffuser installed as measured with a hood flow balometer. This in turn limited the performance characterization of the PCM. The inlet to the heat exchanger is shown in Figure 7. The construction was rather basic, as this was meant to be a proof of concept; full characterization of the performance of a well-designed heat exchanger was beyond the scope of the project. PCM tiles were spaced 1/4-inch apart, and the sides were blocked to increase airflow across the tiles to improve the charge/discharge rates. Sixteen tiles were installed with a total thermal storage capacity of 4,736 kJ with a nominal transition temperature of 14°C ± 2.5°C. A total of 10 thermocouples were installed, five on the outlet and five on the inlet; all were taped to the PCM tiles as shown in Figure 8.

Figure 6. (Left) Insulated heat exchanger box with PCM. (Right) Landscape fabric attached to the outlet was used as a diffuser to distribute flow.

Figure 7. Heat exchanger inlet with PCM tile fins. The area is smaller than the diffuser size to increase airflow velocity across the PCM.

Figure 8. Thermocouple placements at the inlet and outlet of the heat exchanger

5 EnergyPlus Model and Calibration With PCM Retrofits in the Ceiling

EnergyPlus whole-building energy simulations were used to analyze the performance of the PCM in the ceiling tiles that were passively integrated in the building envelope. To construct a whole-building model for the analysis, the shell of the building was constructed using the Rhinoceros tool and Grasshopper platform (Ericson 2017). The shell of the building was added with envelope components using the Ladybug Tools package. The plenum space above the conditioned zones, which is a single continuous space in the building, was modeled as a single thermal zone above the occupied zone. Information about the building envelope's structure was collected from visual investigations of the building's architectural drawing set created for the 1980 remodel. Thermophysical properties of the materials were obtained from the above plans, ASHRAE Handbook of Fundamentals (ASHRAE 2021), and the Honeybee Energy (Honeybee Energy n.d.) and Climate Studio (Solemna n.d.) libraries. More information on the validation process can be found in another publication by the authors (Arjmand Mazidi, et al., 2025).

The HVAC system in the building, the airflow modeling EnergyPlus module (the Air Flow Network [AFN]), and the simulation parameters were integrated into the building using Honeybee Energy built-in libraries. The generated OpenStudio file was then used to populate the final HVAC system loops based on the manufacturer and surveyed information. The final detailed calibrations were all accomplished in EnergyPlus IDF Editor, and the simulations were run using the EP-Launch tool.

The EnergyPlus model was calibrated to incorporate the intricate thermal behavior and characteristics observed in the temperature measurements. This level of calibration requires careful comparisons and adjustments to obtain a reasonable match between experimental and model data. The process is time-consuming and highlights the difficulty of accurately modeling the thermal behavior of PCMs vs. traditional insulation or objects with high thermal mass. Following are some of the considerations used in the current study.

- To address the ceiling's thermal conditions, the ceiling insulation was derated by 15%, and an airflow rate was added to the AFN to account for leaks through cracks in the ceiling. A flow rate of 0.032 kg/s per m^2 of ceiling area, at 20°C and 101 kPa, was applied between the plenum zone and conditioned spaces in the AFN components.
- HVAC leakage in the plenum space through the ducting system resulted in a portion of the heating and cooling energy being supplied to the plenum space. Additionally, the complexity was compounded by two uncontrolled venting systems on the roof of the plenum space. The ducting leakage ratios of 0.35, 0.45, 0.43, and 0.35 for zones 1, 2, 3, and 4 as well as an average U-factor of 0.95 $W/m^2{\cdot}K$ for duct walls were integrated into the AFN distribution system based on the HVAC supply and return air pressure test and observation of the ducting system.
- The building featured two back doors with direct access to the outside for facility and delivery purposes, along with one drive-through window with no fixed schedule, leading to air and heat exchange at various times during the day. The surveyed and observed door schedules were created for each door and distributed over the workday to prevent EnergyPlus divergence.

These considerations and assumptions supported the monthly and hourly measured energy consumption data presented in the results of this study.

6 Envelope PCM Modeling in EnergyPlus

EnergyPlus uses the conduction finite difference (CondFD) method and fully implicit approach for numerical formulation and the Gauss-Seidel iterative method to calculate heat transfer across the building envelope. Additionally, the enthalpy method is used with CondFD method to model and integrate the heat transfer characteristics of the PCM using the "MaterialProperty: PhaseChange" and "MaterialProperty: PhaseChangeHysteresis" modules available in EnergyPlus. In this study, the specific enthalpy-temperature curve is used, which is generated based on data supplied by the manufacturer and implemented in EnergyPlus version 23.1. This curve is shown in Figure 9. The thermophysical data used to populate "MaterialProperty: PhaseChangeHysteresis" module is shown in Table 2. The high temperature of the melting curve and the low temperature of the melting curve refer to the entries to the "MaterialProperty: PhaseChangeHysteresis" module.

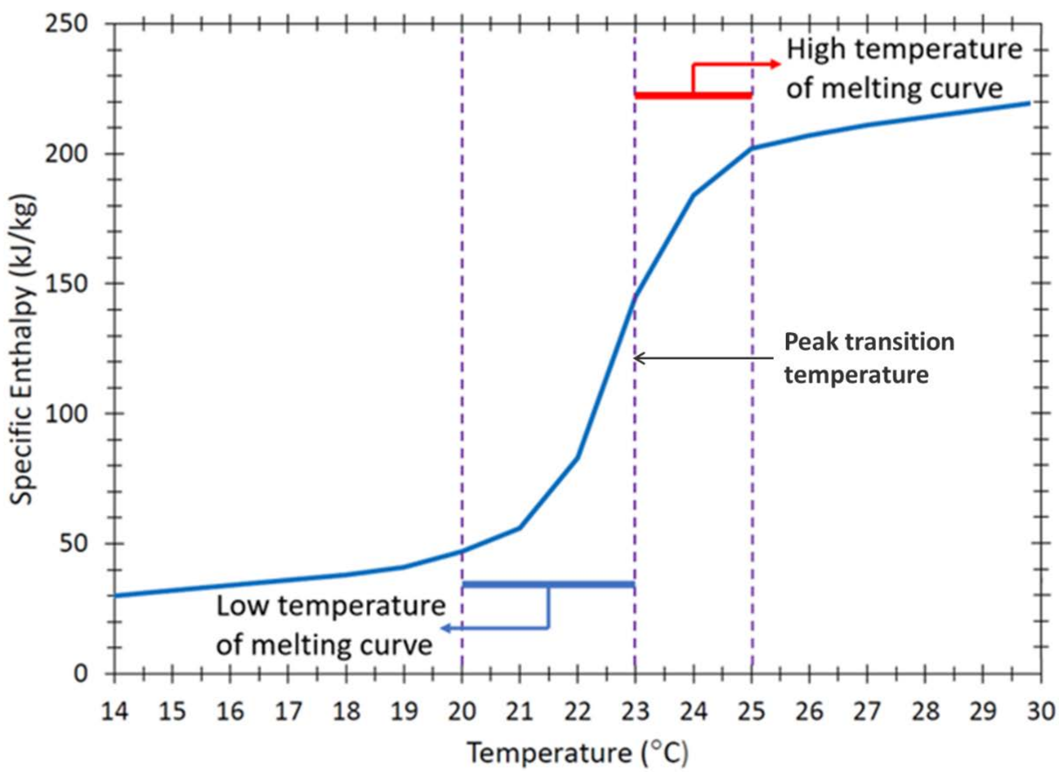

Figure 9. Temperature-enthalpy data of the PCMs used above the ceiling tiles

Table 2. PCM Properties Input to the EnergyPlus PCM Modeling Module

Thermophysical Properties	Value
Latent heat during entire phase change process (J/kg)	147,000
Liquid state thermal conductivity (W/m·K)	0.54
Liquid state density (±3%) (kg/m^3)	1,550
Liquid state specific heat (J/kg·K)	2,300
High temperature difference of melting curve (delta °C)	2
Peak melting temperature (°C)	23
Low temperature difference of melting curve (°C)	3
Solid state thermal conductivity (W/m·K)	1.09
Solid state density (± 3%) (kg/m^3)	1,630
Solid state specific heat (J/kg·K)	2,500

7 Results

The results of this study are presented in three sections.

- The first section discusses the calibration and validation of the whole-building energy model created in EnergyPlus for the City Hall administrative building used in the study. The validation is carried out pre- and post-retrofit of the PCMs in the ceiling.
- The second section discusses a parametric assessment that investigates the HVAC energy and demand savings for variations of PCM properties and activation methods used to enhance the PCM contributions with the focus on PCM implementation in the ceiling envelope.
- The third section discusses a duct-integrated PCM study that targeted further utilization of PCMs using the HVAC system of another building in the buildings cluster considered for the study.

7.1 Validation of Energy Consumption

The performance of the calibrated EnergyPlus model is evaluated using the coefficient of variation of root-mean-square error (CVRMSE), a standardized statistical index.

$$\text{CVRMSE (\%)} = \frac{\sqrt{\left(\sum_{i=1}^{N_p}(m_i - s_i)^2 / N_p\right)}}{\bar{m}} \quad (1)$$

Where:

- m_i and s_i = the measured and simulated data at instance i
- N_p = the number of data points at interval p (e.g., $N_{monthly}$=12, N_{hourly}= 8,760).
- m is the average
- $\bar{m}$ = the average of the measured data points.

Table 3 shows the acceptance criteria of CVRMSE for the calibration of building energy performance standards models, the International Performance Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Program (FEMP). A daily criterion is not defined in ASHRAE Guideline 14. However, an acceptance criterion of CVRMSE percentage of 30% for the energy predictions was used for the daily comparisons for this study. This selection was based on the ASHRAE Guideline 14. The PCM data obtained both pre- and post-retrofit were considered for the validation. The daily and monthly data were used for the comparisons.

Table 3. Acceptance Criteria of CVRMSE Percentage Values

Standard/Guideline	CVRMSE		
	Monthly Criteria (%)	Daily Criteria (%)	Hourly Criteria (%)
ASHRAE Guideline 14	15	-	30
International Performance Measurement and Verification Protocol	-	-	20
Federal Energy Management Program	15	-	30
Current study acceptance criteria	15	30	30

Figure 10 shows the data pre-retrofit. In the absence of a control case, sets of 3-day data were selected in pre- and post-retrofit scenarios based on similarity of the outdoor temperature variation. The difference in exterior temperature during the days selected were within 1% for the hourly data. Data for summer 2022 pre-retrofit for zone 1, location 1 are shown. Figure 10B shows the cooling electricity. This includes direct expansion and chiller electricity consumption, and fans associated with cooling systems electricity. The values are averaged over each hour for zone 1. The temperature data shown in the figure is also hourly averaged. The simulated data are obtained from the calibrated model. For the cooling season (summer 2022), the simulated temperatures at the ceiling tile and insulation interface closely agreed with the measured data in all three zones.

Duct leakage in the plenum, air mixing between the plenum and the conditioned space from ceiling cracks, and thermal stratification through the ceiling were identified as likely reasons for the difference in the measured and simulated plenum temperatures. Addressing these issues in the building was beyond the scope of this work; in addition, these factors are not easily simulated in EnergyPlus. The result is that these differences could not be fully eliminated via further model calibration. Similar to the pre-retrofit data, the measured summertime plenum temperatures (summer 2022) were typically lower than the simulated data. The PCM tile-insulation interface and ceiling tile-conditioned space interface temperatures differed by a maximum of around 0.2°C, showing the high conductivity of the PCM layer. In winter 2023, the average measured plenum temperatures were higher, which showed that the cause identified in the pre-retrofit data still existed. Based on the pre-retrofit measured surface temperatures during the cooling season for zone 1, there is a consistent alignment between the measured and simulated temperatures for the ceiling tile-conditioned space interface and ceiling tile-insulation interface points. However, there is an average temperature difference of 2°C observed in the above-ceiling (plenum space) temperatures.

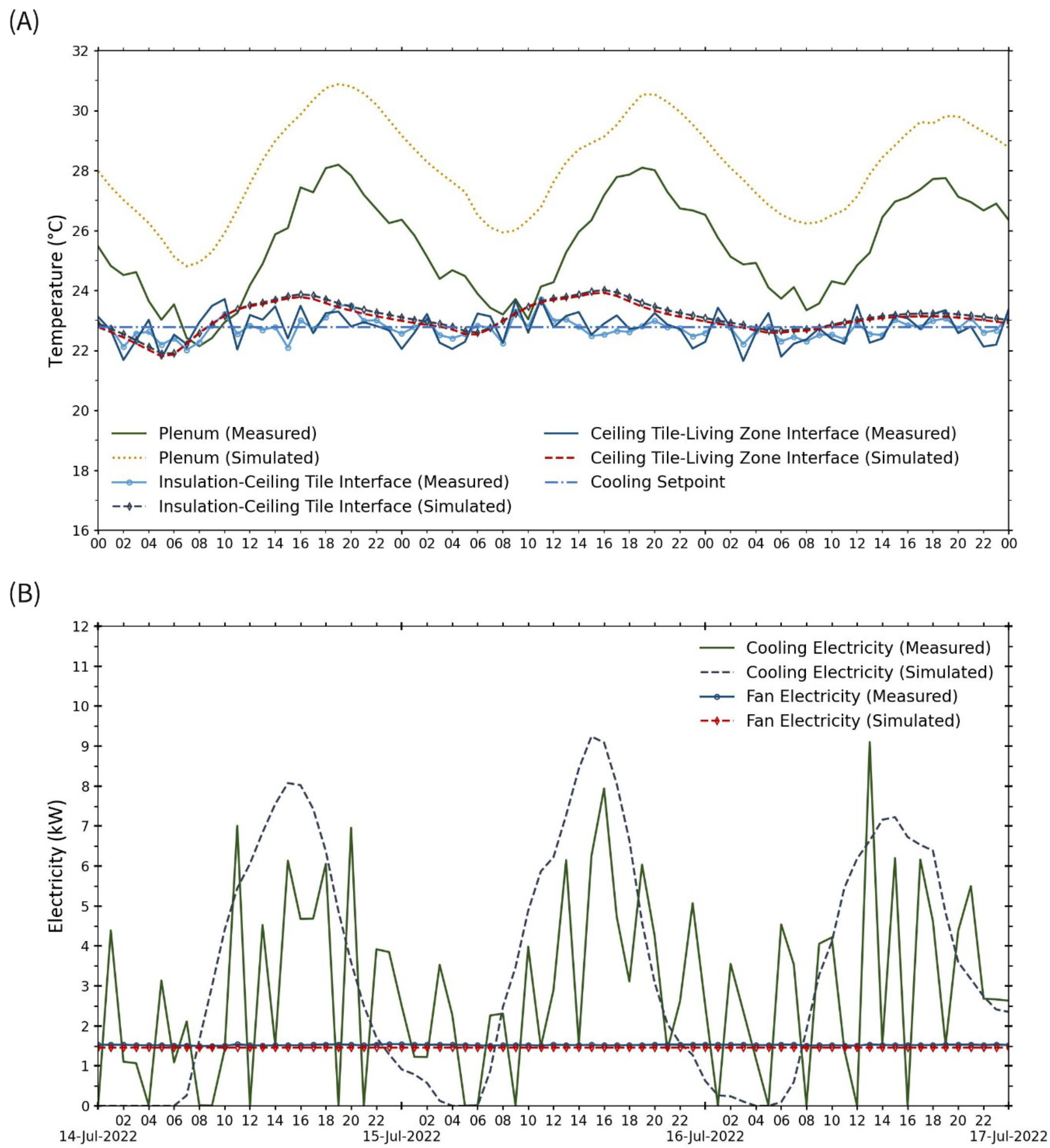

Figure 10. *Pre-retrofit* comparison between measured and simulation data for cooling operation: (A) Zone 1, location 1 temperature and (B) zone 1 electrical power, measured and simulated values

Figure 11 shows the post-retrofit measured and simulated data for zone 1. The living zone indicates the occupied space during the work hours. PCM tile-insulation interface temperatures exhibit a flat curve, closely mirroring each other and aligning with the PCM melting temperature. However, the measured temperatures at the interface of the ceiling tiles and conditioned space show more fluctuation than the simulations. This discrepancy may arise from the sensor's location (≈47 cm under the ceiling), exposed to HVAC supply air. The post-retrofit data emphasize a similar difference in plenum measured and simulated temperatures, indicating a potential for increased air mixing between the conditioned space and plenum space, or duct leakage into the plenum compared to the simulated inputs.

The hourly cooling electricity demand shows a matching pattern between measured and simulated data for both pre- and post-retrofit scenarios. The CVRMSE values for the hourly cooling electricity values, both pre- and post-retrofit, were 28.4% and 24.6%, respectively. The calculated CVRMSE values for hourly natural gas were 28.1% and 25.1% for pre- and post-retrofit, respectively. It is important to note that due to missing continuous natural gas measured data for Mechanical Room 2 from January to March 2023, the error was calculated for Mechanical Room 1 only. While the hourly errors fall within accepted criteria, these relatively higher errors can be attributed, in part, to the intermittent nature of real-world HVAC system operation. EnergyPlus estimates average heating and cooling loads, which can lead to discrepancies in magnitude at each hour, further impacting the errors. Additionally, uncertainties due to schedule overrides, which were not accurately incorporated into the model due to insufficient data, further contributed to these discrepancies.

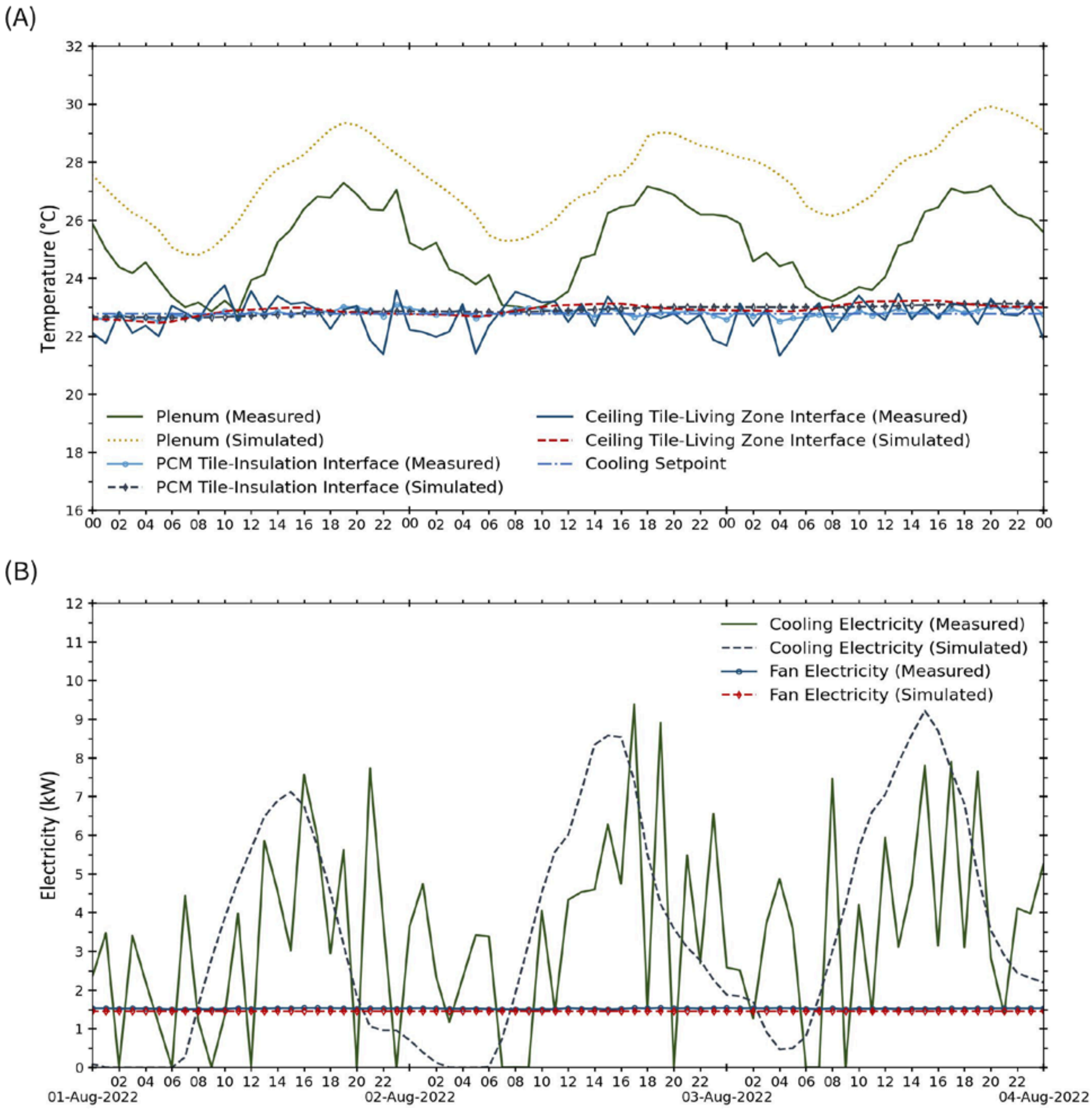

Figure 11. *Post-retrofit* comparison between measured and simulation data for cooling operation: (A) Zone 1, location 1 temperature and (B) zone 1 electricity measured and simulated values

Figure 12A shows pre-retrofit daily natural gas data from Jan. 13 to Feb. 6, 2022, and Figure 12B shows daily total building HVAC cooling electricity consumption from June 21 to July 21, 2022. Daily sums of the measures were used due to the high frequency observed in the hourly data for clear visual representation. Daily energy consumption shows close visual agreement between measured and simulated data. Error calculation for daily natural gas data shows a CVRMSE value of 27.9 %, while daily HVAC electricity data show a CVRMSE value of 18.0%, which falls within the accepted range.

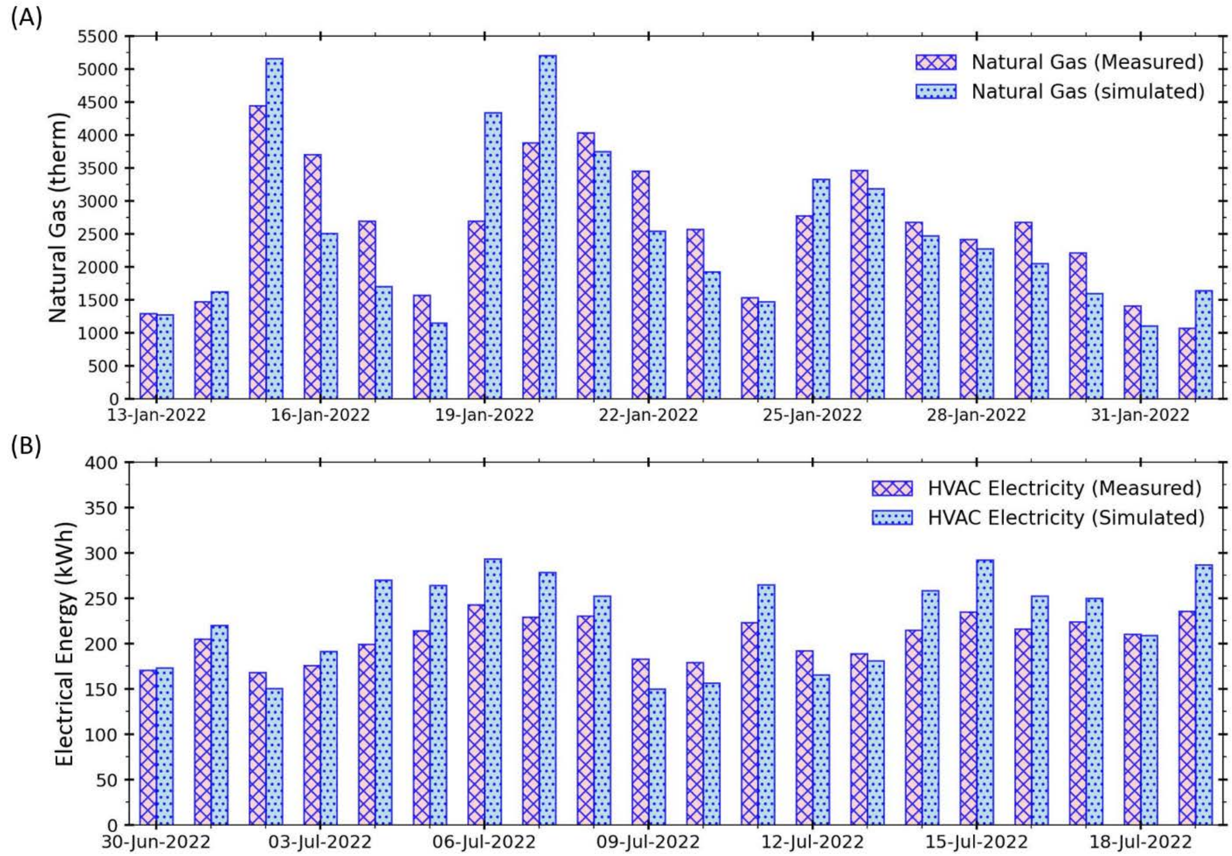

Figure 12. Pre-retrofit daily measured and simulated energy consumption data for City Hall: (A) natural gas consumption for the heating season and (B) electricity consumption for the cooling season. Error calculation (CVRMSE) shows values well within acceptable range for the daily comparisons during the evaluated time period.

Figure 13A shows pre-retrofit daily natural gas data from Jan. 13 to Feb. 6, 2022, and Figure 13B shows daily total building HVAC cooling electricity consumption from June 21 to July 21, 2022. Daily sums of the measures were used due to the high frequency observed in the hourly data. Daily energy consumption shows close agreement between measured and simulated data. The calibrated model for daily natural gas data shows a CVRMSE value of 30.8%, which is higher than that of the pre-retrofit model, while daily HVAC electricity data show a CVRMSE value of 12.4%, which is relatively lower than the pre-retrofit model.

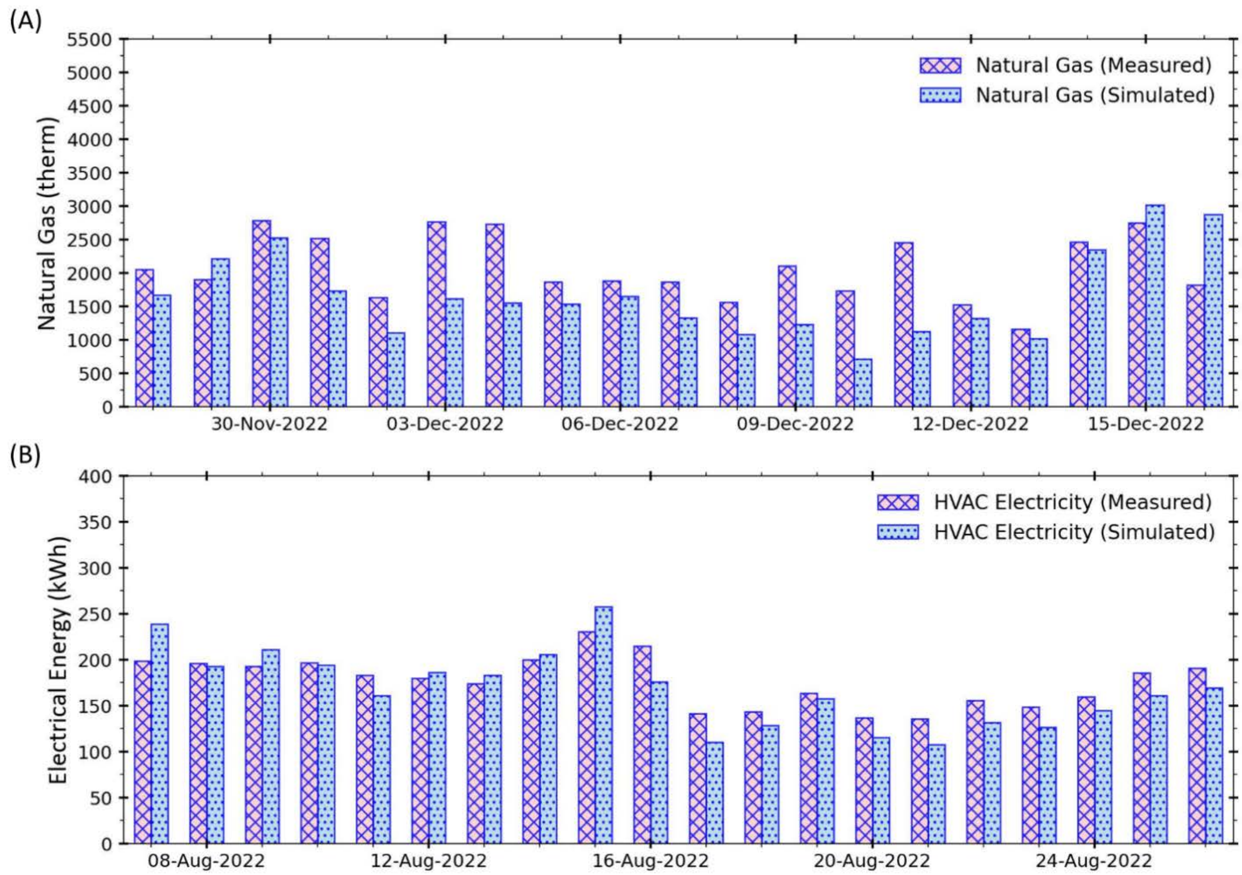

Figure 13. Post-retrofit daily measured and simulated energy consumption data for City Hall: (A) natural gas consumption for the heating season, and (B) electricity consumption for the cooling season. Error calculation (CVRMSE) shows values well within acceptable range for the daily comparisons during the evaluated time period.

7.2 Parametric Assessment for PCM Integrated in the Ceiling With Different Activation Methods

This section presents model data considering changes to various parameters for the PCM integration in the ceiling tiles, and presents simulated data only. Figure 14A and 14B show the annual cooling electricity savings and annual natural gas savings due to PCM peak melting temperature and PCM latent heat, respectively. Figure 14C and 14D show the cooling electrical energy savings and reduction in peak power due to variations in the peak melting temperature and latent heat, respectively, during the cooling months. The peak melting temperature (PMT) of the PCM is varied for the simulations by changing the input values to the whole-building energy model. A heat transfer coefficient of 1.5 $W/m^2{\cdot}K$ is applied to the interior side of the ceiling envelope in the model. Annual cooling electricity savings increase as the PMT is increased from 19°C to 23°C and decrease after 23°C with the other parameters kept the same. Annual energy savings percentage values relative to the baseline case are plotted. A maximum annual total cooling electricity savings of 3.5% is observed. Annual natural gas savings show a maximum of 1.9% at a PMT of 21°C. Cooling electricity savings during the peak period also increase as the PMT is increased from 19°C to 23°C and decrease after 23°C. The maximum electricity savings is 11.5%, and the maximum peak load reduction is 7.5% at a PMT of 23°C. Therefore, reductions in both annual energy and peak power are observed with PCMs applied in the ceiling, which supports the passive use of PCMs. The highest heating natural gas savings are observed at a lower PMT of 21°C since the lower PMT ensures that the PCM melts more readily during the heating season, resulting in higher quantities of energy stored and released each day. The highest cooling savings are observed at a PMT of 23°C, indicating that relatively high PMT performs better during the cooling months. This result shows that the selection of the optimal PCM temperature is highly important for the savings. Because this parametric study focuses on maximizing the cooling electricity and demand savings during the peak period, a PMT of 23°C is selected for the next stage of the analysis. More details regarding the retrofit strategies can be found in another publication by authors (Wijesuriya, Arjmand Mazidi, Kishore, & Booten, 2025).

Figure 14B and Figure 14D showcase the savings as the PCM latent heat is varied from 50 kJ/kg to 250 kJ/kg. The annual HVAC energy savings increase with the latent heat, and diminishing returns are observed after 150 kJ/kg. This result shows that adding PCM with the latent heat above 150 kJ/kg would not yield significant gains. Natural gas savings remain below 2% for the range of latent heat investigated, showing minimal impact on heating energy savings. The reduced heating energy savings can be related to the PMT being chosen to maximize the cooling savings. The annual cooling electricity saving increased from ~2% to 3.5%. The cooling electricity savings during the peak period increased from 7.4% to 12.5%, and the demand savings increased from 4.6% to 8.6% within the range. The reason for diminishing returns is underutilization of the latent storage, which is influenced by the lack of diurnal temperature swing in the occupied zone. The lack of variation is due to the constant thermostat set point of 22.8°C. A latent heat of 150 kJ/kg is used for the next steps of the study based on the diminishing returns. It is evident that to yield higher savings, passive use of PCM in the ceiling alone is not adequate.

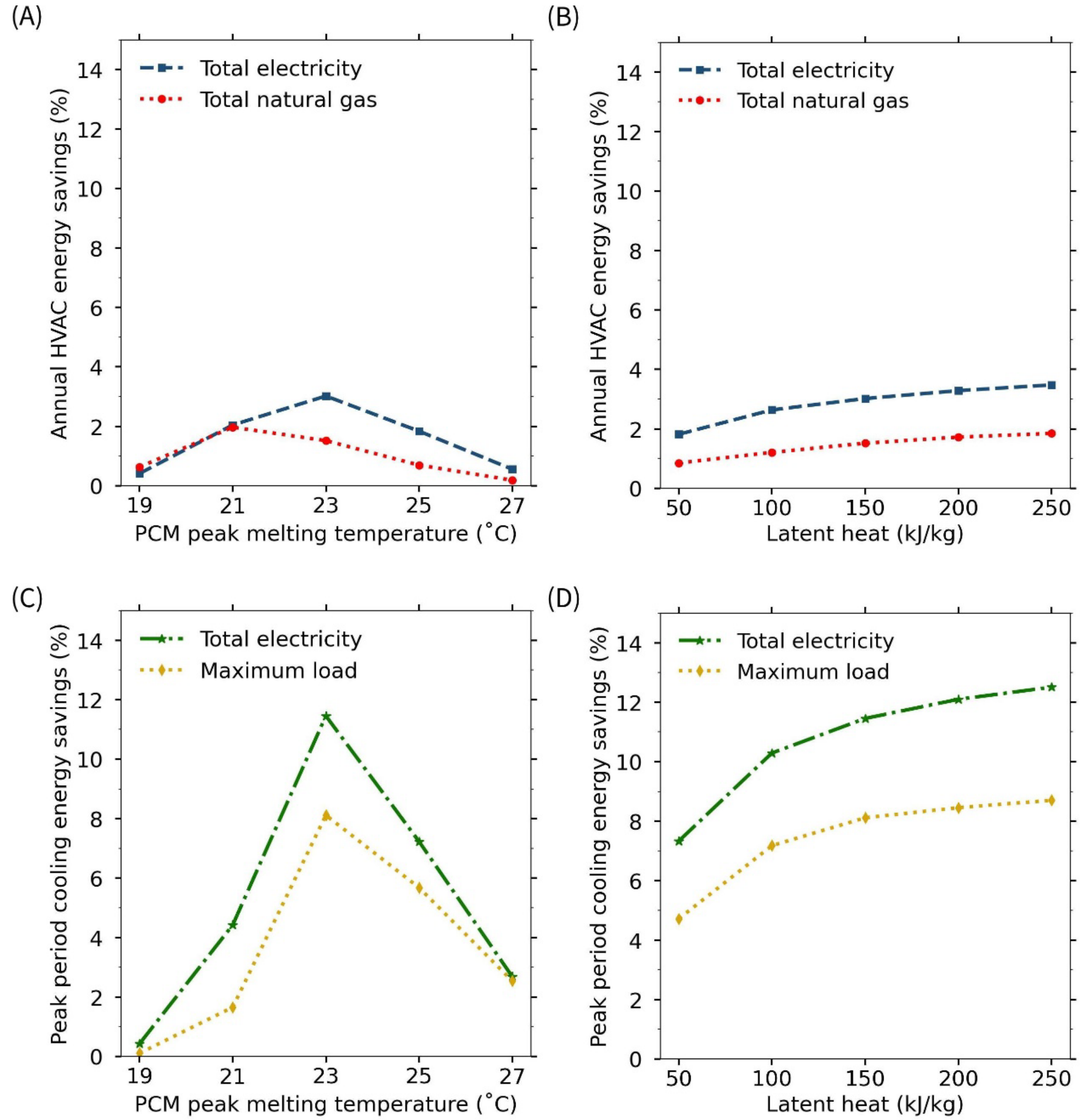

Figure 14. Model results for annual energy savings and peak period energy savings due to PCM property parameters: Variation of (A) Annual HVAC energy savings with peak melting temperature, (B) Annual HVAC energy savings with latent heat, (C) Peak period cooling electricity savings and reduction in maximum electricity demand with peak melting temperature, (D) Peak period cooling electricity savings and reduction in maximum electricity demand with latent heat.

Figure 15 shows the PCM melted fraction over 24 hours (Aug. 1) for different PCM activation methods. The baseline case shows only around 10% change in melt fraction within the day, indicating that only a small fraction of the thermal storage capacity is effectively used. Figure 15A shows that precooling the envelope (for 8 hours, from 6 a.m. to 2 p.m.) causes the PCM to freeze during the precooling period and melts a higher fraction as the precooling temperature increases. It should be noted that a higher cooling load is required during the precooling, so the overall energy consumption from this strategy may deteriorate even though the storage capacity utilization increases. Figure 15B shows the melted fraction variation as the convection heat transfer coefficient is varied near the interior surface of the ceiling envelope (which might be achieved by employing a ceiling fan). While the higher convection coefficient values improve the freezing of the PCM slightly, the impact is inadequate to fully freeze the PCM (down to a melted fraction of 0). Figure 15C shows the melted fraction as the setback temperature is varied from 2 to 6 p.m. As the setback temperature increases, the melted fraction increases further by around 10% at the 2°C setback. None of the methods implemented could fully freeze the PCM before the peak time or fully melt the PCM during the peak time, showcasing the lack of utilization even with the active control applied. This suggests that a significantly lower volume of PCM could be used to achieve the same benefits. It could help make the implementation more cost-effective, although this requires acknowledging the limited potential.

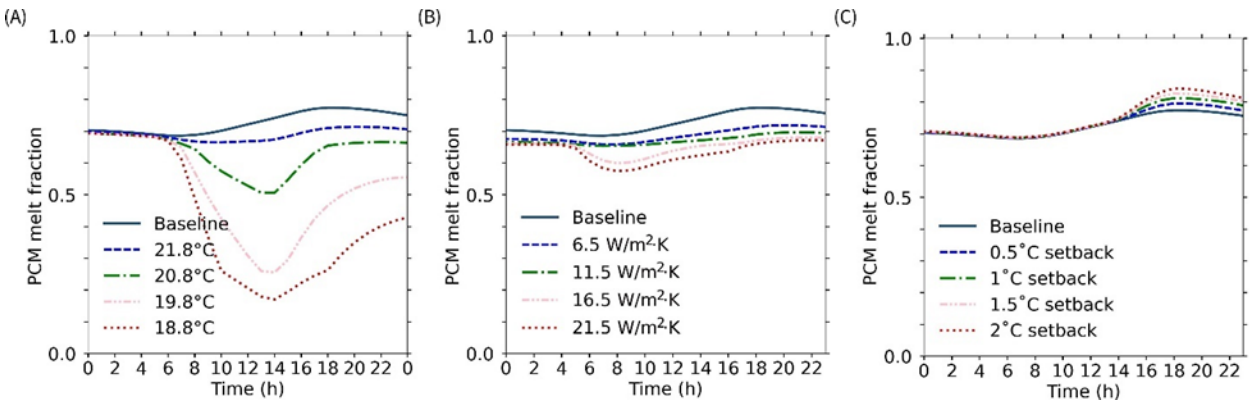

Figure 15. Different activation methods to improve PCM utilization during the cooling season: (i) reducing the temperature in which the zone is precooled, (ii) increasing convection heat transfer coefficient value near the interior side, and (iii) applying the setback by relaxing the setpoint during the peak time.

Table 4 shows the HVAC energy consumption data for the no-PCM baseline and the PCM cases from the whole-building energy model validated above. Annual HVAC energy savings are 3% with the PCMs implemented in the ceiling. However, the heating HVAC energy savings are negligible.

Table 4 also shows savings values for precooling for 8 hours at 18.8°C. The overall cooling energy consumption increases due to precooling. However, cooling energy during peak period savings increases from 9.2% to 35.6% due to precooling. Furthermore, if the precooling is applied while increasing the convection heat transfer coefficient next to the ceiling, the cooling energy during peak period savings increases to 54.6%. Peak cooling demand during the peak period is also reduced by 23.3% with precooling and increased heat transfer coefficient.

Table 4. HVAC Energy Measurements for Different Scenarios, Compared to the Baseline Condition (no precooling or setback, with h= xx W/m²-K)

Scenario	Parameter	Baseline	With PCM	Savings
No Precooling h = 1.5 W/m²·K	Annual cooling energy	13,557 kWh	13,145 kWh	3.01%
	Annual heating natural gas	3,150 therms	3,130 therms	0.63%
	Cooling energy during peak period	3,629 kWh	3,296 kWh	9.16%
	Peak cooling demand	18.37 kW	17.29 kW	5.84%
Precooling at 18.8°C | 8 hrs.	Annual cooling energy		20,560 kWh	-51.65%
	Cooling energy during peak period		2,338 kWh	35.58%
	Peak cooling demand		15.4 kW	16.01%
h = 6.5 W/m²·K, Precooling at 18.8°C | 8 hrs.	Annual cooling energy		20,789 kWh	-53.34%
	Cooling energy during peak period		1,649 kWh	54.55%
	Peak cooling demand		14.0 kW	23.29%

Figure 16 shows the annual HVAC cooling energy savings and the peak period cooling energy savings under different activation methods and value ranges. All cases consider 8 hours of precooling at 18.8°C from 6 a.m. to 2 p.m. The main objective of this section is to explore the combinations of activation methods to maximize the reductions in HVAC cooling electricity consumption and the cooling load/demand savings during the peak period. Savings with PCMs are higher than the respective no-PCM cases for the peak period, cooling energy savings. Therefore, there is a clear contribution from PCM application. With a 2°C thermostat setback from 2 p.m. to 6 p.m. and with a heat transfer coefficient of 6.5 $W/m^2 \cdot K$, total cooling electricity and maximum cooling load/demand can be 99.8% shifted from the peak period. This is a key outcome for this study.

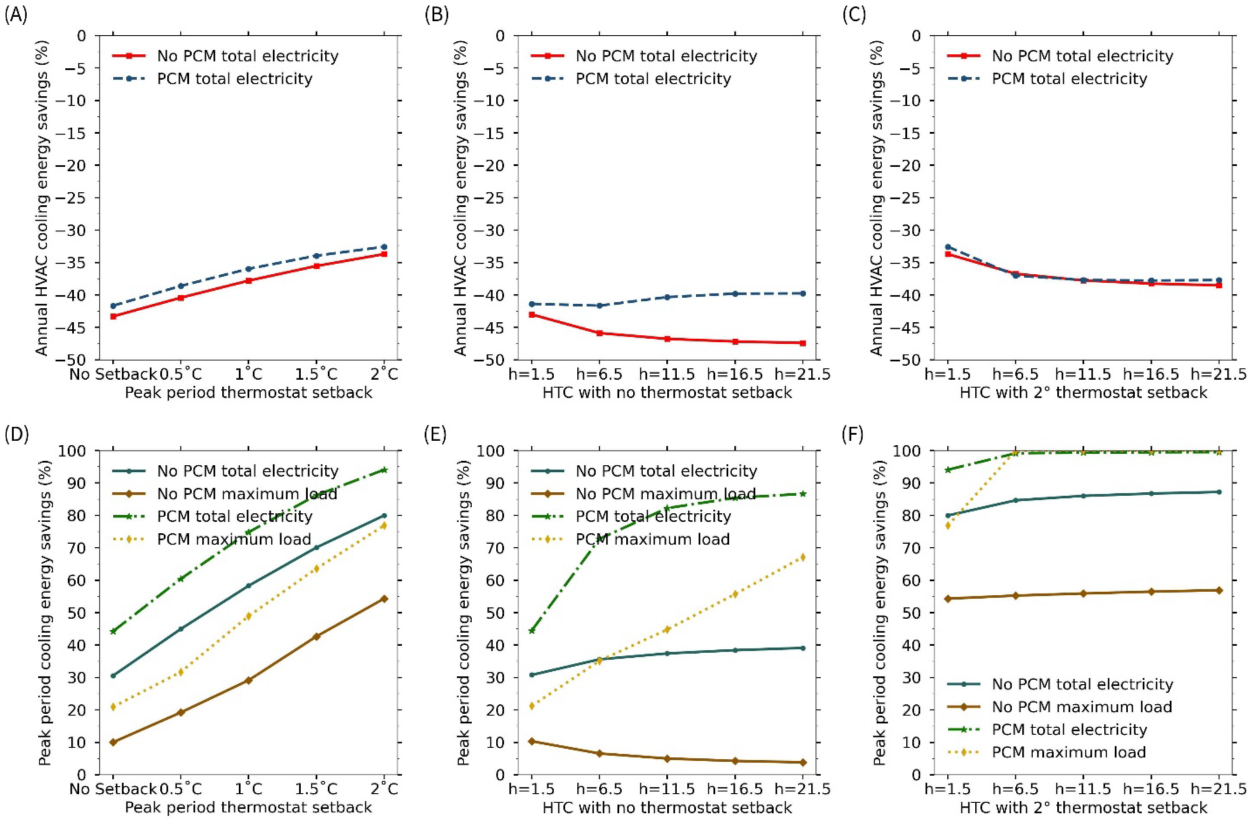

Figure 16. (A–C) Annual cooling electricity savings and (D–F) peak period cooling electricity and demand savings under different PCM activation methods. Scenarios with and without PCMs are compared here to assess the impact of PCMs on the savings.

7.3 Duct-Integrated PCM

Figure 17 shows the measured inlet and outlet average PCM temperatures during the cooling season for a single discharge/charge cycle. These data are representative of results over the two-week experiment. The stored energy in the PCM in a single heat exchanger was insufficient to maintain room temperature for such a large room; the focus was on whether the HVAC system was capable of charging and discharging the stored energy using basic controls such as thermostat setpoint and the use of fan-only mode.

The HVAC system was set to fan-only mode for the first 11 hours, allowing the PCM to discharge. The inlet temperature during the discharge cycle has a sharp drop around 2.5 hours. This is due to the sunset and consequent drop in plenum temperature that otherwise increases the supply temperature. At 11 hours, the charge cycle starts. The air temperature was not measured directly, thus preventing an accurate energy balance; rather, thermocouples were attached to the surface of the PCM in the airstream thus providing a somewhat blended measurement of PCM and local air temperature. This is discussed in Section 5. Point measurements are not intended for full energy balances, as the average temperature is difficult to predict without well-mixed flow. In addition, the enthalpy curve of the PCM was not fully characterized because the cycles were not long enough to guarantee complete phase change, thus also preventing accurate enthalpy calculations. If the phase change was largely complete, approximately 4,736 kJ over 10 hours would have transferred to/from the PCM. When 23 CFM is corrected for local conditions, it averaged 21.4 SCFM (Standard Cubic Feet per Minute). This is a total of 437 kg of air passing through the heat exchanger over 10 hours. The heat capacity of air is 1.005 kJ/kg·K. The inlet and outlet PCM temperatures closely match each other at the beginning of the discharge cycle. The air conditioning had been providing constant operation for 12 hours. Given the rate of charge and discharge exhibited early in either the charge or discharge cycle, this suggests the system was near thermal equilibrium and therefore near fully charged at the beginning of the discharge cycle. Similarly, at the end of the discharge cycle the inlet and outlet temperatures were approaching the same temperature near 25°C, well outside the two-phase region suggesting relatively little heat transfer to the air as it flowed across the PCM heat exchanger. Thus, a near-complete phase change is plausible, but not certain to have occurred.

This experiment does highlight the plausibility of using this approach for integrating PCM into building HVAC systems. The mass of PCM per supply register, ~32 kg, is high but not prohibitive for building structures to mechanically support. It would also not be difficult to retrofit into buildings. At more normal flow rates from 2-ft × 2-ft supply registers (~10x measured here) the PCM could provide approximately one hour of conditioning without compressor operation. In addition, supply registers are ubiquitous in office buildings and generally more accessible than many other locations like walls, which is attractive for retrofitting PCM into buildings using duct-integration into supply registers.

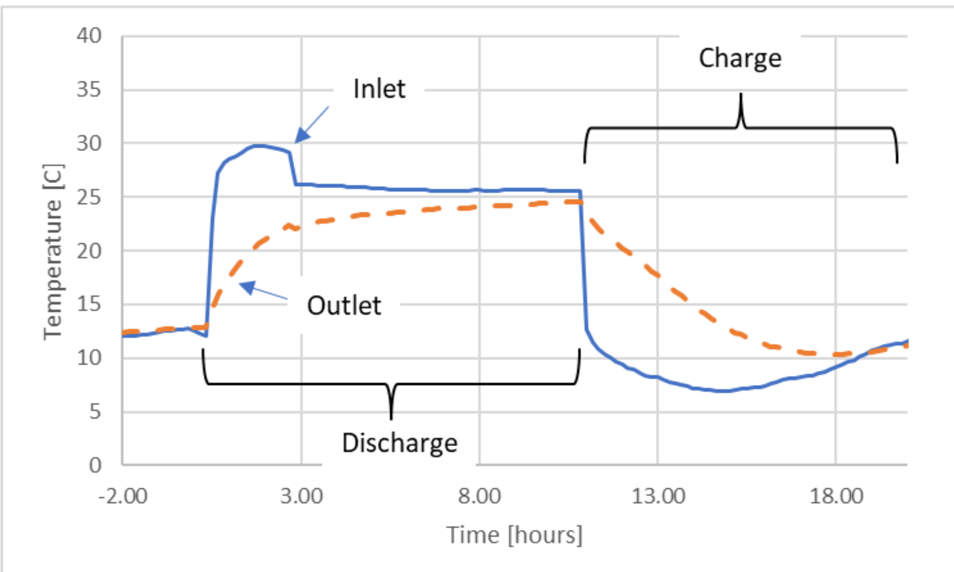

Figure 17. Inlet and outlet temperatures measured at the PCM surface during a charge and discharge cycle for duct-integrated PCM during cooling season. This behavior was typical over the two-week duration of this experiment.

8 Conclusions

This study investigated the use of PCM ceiling tiles as a retrofit solution to reduce the HVAC energy demand of existing municipal buildings in the city of Wellington, Kansas, in ASHRAE climate zone 4A. A whole-building energy model was created using the EnergyPlus simulation engine to approximate temperature variations of key locations and HVAC energy use of the occupied zones of the building. The complex thermal behaviors of the occupied building were considered in the calibration of the model to create a whole-building energy model that represents the observed operational characteristics of the building under investigation.

This report discussed the calibration and validation of the whole-building energy model to approximate the hourly, daily, and monthly cooling electricity and heating natural gas measurements. This is an advanced level of calibration beyond what is typically needed, but for the purposes of evaluating time-sensitive thermal storage systems, this level of calibration was critical. It was concluded that the EnergyPlus whole-building energy model is calibrated and validated against the actual building. Secondly, this report presented a parametric assessment conducted to evaluate the HVAC energy benefits achieved by varying PCM properties and different PCM activation methods.

The following key observations and conclusions were made:

- The cross-validated CVRMSE for the hourly cooling electricity, both pre- and post-retrofit, were 28.4% and 24.6%, respectively. Hourly natural gas error values were 28.1% and 25.1% for pre- and post-retrofit, respectively. These values were well within the acceptance criteria of this study for hourly use.
- The cross-validated CVRMSE for the daily cooling electricity consumption showed a value of 20.8%, and heating natural gas consumption showed a CVRMSE value of 28.6%. A comparison of the billing cycle electricity consumption showed a CVRMSE value of 6.7%, and the natural gas consumption showed a CVRMSE value of 14.3%. Therefore, the calibrated model showed very good agreement with the actual building while capturing the complex thermal behaviors.
- Parametric assessment showed that the selection of PCM peak melting temperature is highly important to increase the HVAC energy savings. A PCM melting temperature of 23°C yielded the highest cooling electricity savings during the peak period (11.5%) and highest cooling demand savings (7.5%). Increasing the PCM latent heat from 50 kJ/kg to 250 kJ/kg increased the HVAC cooling savings with diminishing returns after 150 kJ/kg.
- Parametric assessment also showed that employing precooling for 8 hours at 18.8°C from 6 a.m. to 2 p.m., with a 2°C thermostat setback (to 20°C) from 2 p.m. to 6 p.m. and heat transfer coefficient to the surface of the ceiling tiles of 6.5 $W/m^2 \cdot K$, total cooling electricity and maximum cooling load/demand can be shifted by 99.8% from the peak time period.
- PCM integration with the duct system highlighted the plausibility of the approach used by the researchers. It was concluded that with normal flow rates from 2-ft × 2-ft supply registers, the PCM could provide approximately one hour of conditioning without compressor operation.

The establishment of a detailed and carefully calibrated whole-building EnergyPlus model supported key investigations of the contributions from PCM properties and activation methods to increase the energy demand benefits of a complex administrative building already in use. The results of this study showed agreement with the results from previous modeling-based whole-building assessments. This whole-building energy model could therefore be used to conduct further energy efficiency measures for future publications.

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