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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Phase Change Material-Enhanced Insulation for Residential Exterior Wall Retrofits

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Phase Change Material-Enhanced Insulation for Residential Exterior Wall Retrofits is the final report for Contract Number PIR-18-007 conducted by Theresa Pistochini, Aref Aboud, Sarah Outcault, Jingjuan Dove Feng, and Debrudra Mitra. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project assessed two technologies designed to enhance the typical "drill-and-fill" insulation retrofit of residential exterior walls: phase change material (PCM) integration and aerosol sealing of the building envelope. Through modeling validated by laboratory testing, the study evaluated the impact of PCM thickness on heating, ventilation, and air conditioning energy for varying wall insulation levels, envelope sealing, thermal mass, window opening, and nighttime ventilation. Field demonstrations of the retrofit package (insulation, PCM, and sealing) were conducted in three homes in disadvantaged communities located in Vallejo, Sacramento, and Los Angeles, California.

Field results demonstrated the potential for substantial reductions in cooling (10 percent to 41 percent) and heating (-23 percent to 24 percent) energy and reduction of peak demand (3 percent to 81 percent). These widely varying results were attributed to user behavior. The retrofit also enhanced envelope air tightness by up to 58 percent. Occupants noted improved comfort, reduced heating, ventilation, and air conditioning reliance, and decreased noise transmission, post-retrofit.

The study identified challenges to widespread adoption of PCM due to retrofit costs and limited market availability. The PCM studied was estimated to provide a thermal storage energy benefit that was equal or better for increasing standard wall insulation by 20 percent, showing that the addition of PCM on interior wall surfaces is a feasible way to reduce heating and cooling energy consumption in existing homes. However, it was demonstrated that increasing insulation has diminishing returns in terms of energy savings (approximately 200 to 300 kilowatt-hours annually for insulation greater than four-inch wall cavity insulation). The payback period for the entire retrofit ranged from 4.5 to 41 years, depending on climate zone. Results indicated that PCM may be a cost-effective way to achieve high-performing envelopes in new construction. Aerosol sealing of envelopes through the attic and crawlspace was effective, fast, and promises to improve indoor air quality and reduce heating energy in existing homes.

Keywords: Phase change material, building envelope, air leakage, insulation, exterior walls

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Executive Summary

Background

Homes built before 1978, when California introduced its first building energy efficiency standards, were commonly constructed without exterior wall insulation. This resulted in high heating and cooling loads. To reduce energy use in these older homes, a retrofit process typically involved drilling holes into the walls and filling the wall cavities with fiberglass or cellulose insulation. For this project, researchers at the Western Cooling Efficiency Center and TRC Companies, Inc., developed and evaluated an advancement that built on this retrofit process by aerosol sealing the wall cavities and installing phase change material (PCM) to the interior surface of exterior walls to improve insulation.

Project Purpose and Approach

The project demonstrated the effectiveness of aerosol sealing and PCM installation in enhancing typical "drill-and-fill" insulation to retrofit residential exterior walls. The research team conducted energy modeling with EnergyPlus™, laboratory testing to validate the PCM component of the EnergyPlus™ model, and field installations in three homes. This work tested installation procedures and assessed real-world feasibility and performance. The team collected data to measure energy savings, assessed occupant comfort, and evaluated market viability. The project evaluated the effectiveness of these technologies in reducing energy consumption, enhancing occupant comfort, and improving indoor air quality.

Key Results

EnergyPlus™ modeling and laboratory testing of the PCM demonstrated the importance of simulating the hysteresis behavior of the material. A hysteresis means that the freezing and melting curves for the PCM are shifted by a few degrees in temperature so that the material does not change phase (and therefore does not store or release latent heat) when it is inside the hysteresis. The research team could not validate the existing "PCM-hysteresis" model in EnergyPlus™ with laboratory testing, and further investigation revealed critical errors to the EnergyPlus™ development team. The team therefore validated and adopted a custom phase change hysteresis model developed by Feng et al. (2022a). This model is an edited EnergyPlus™ product made for EnergyPlus™ versions 8.9 through 9.3. Simulations demonstrated that PCM integration contributed to reductions of between 3 percent and 26 percent in overall heating, ventilation, and air conditioning energy consumption. The entire retrofit package was modeled to provide energy cost savings of $265 to $2,300 per year, with most of the savings from insulating, sealing, and ventilation. The modeled simple payback time for the retrofit ranged from 4.5 to 41 years, with the fastest payback in California's interior climates and the slowest payback in the state's coastal climates.

R-value is a measure of how well a material insulates and resists conductive heat transfer through the material. Retrofitting an uninsulated home with insulation increases the R-value of the wall assembly from R-1.4 to R-15. The R-value of R-1 is equal to one square foot times one degree Fahrenheit times one hour divided by one British thermal unit ($ft^2 \cdot °F \cdot h/Btu$). Phase change material stores and releases heat, which reduces heat transfer through building walls, yielding similar results to insulation. The project demonstrated that adding a layer of Insolcorp PCM to the interior surface of the exterior walls increased the effective R-value by 20 percent or more (from R-15 to R-18 to R-60), depending on the climate zone. This showed that the addition of PCM on interior wall surfaces is a feasible way to reduce building energy use for heating and cooling. The results are shown as an equivalent R-value to provide a useful metric for comparing PCM with standard insulation in California climates. This equivalence method is useful for considering PCM's adoption into existing codes and standards for both new buildings and major renovations. While this project focused on retrofits, it was noted that new construction builders may be able to achieve superior results by combining an insulated four-inch-deep wall construction with a layer of PCM instead of an insulated six-inch-deep wall construction, additionally reducing overall construction costs. Policy and regulatory adjustments could jumpstart PCM's integration into mainstream construction practices. Policy changes that incorporate PCM into building codes as an option, along with outreach to increase awareness among homeowners and builders, could further drive adoption.

The modeling demonstrated that insulating attics and walls is the most important step in home envelope retrofits, with significant energy savings potential for reducing heating energy consumption (58 percent to 87 percent heating reduction, 45 to 240 therms, with the largest reductions in Climate Zone 1 and Climate Zone 16. In a majority of climate zones, modeling showed that wall insulation beyond R-15 had diminishing returns for energy savings (approximately 200 to 300 kilowatt-hours annually), so it would be difficult to reduce installed product costs enough for consumers to adopt PCM retrofit applications, which are more expensive than new construction. Retrofit aerosol sealing of envelopes through the attic and crawlspace is fast, effective, and promises to both improve indoor air quality and reduce heating energy used in existing homes, in all climate zones. The final application site in Los Angeles, where the method was refined, achieved a measured 58 percent reduction in envelope leakage.

The team also explored nighttime ventilation through modeling to increase the benefits of available PCM storage and reduce the impacts of building sealing on the potential loss of "free cooling" during summer nights (which is lost when infiltration is reduced). Nighttime ventilation was shown to have important benefits on cooling energy use regardless of whether PCM or other sealing measures were applied, so increased nighttime ventilation increased forecasted cooling energy savings from PCM. Interestingly, the occupants of the retrofit home in Los Angeles reduced the use and length of time they ran their whole house fan at night (because the home cooled faster); this correlated with a reduction of median concentration of small particulate matter indoors. Presumably, the reduction of whole house fan use reduced the transfer of outdoor particulate matter (for example, smoke, dust, traffic-related air pollution) to indoors. The interactions of nighttime ventilation with envelope properties, heating, ventilation, air conditioning energy use, and indoor air quality are important areas for future research.

Knowledge Transfer and Next Steps

The project identified challenges to widespread adoption of PCM due to costs, intrusiveness of the installation of the retrofit, and limited market availability. PCM is initially expected to be most cost-effective in new construction. The equivalent R-value approach developed in this project could be used to consider wall constructions with PCM as an approach to meet both existing and future insulation requirements in building codes and standards. PCM incorporated directly into the drywall sheets (a potential future product offering from Insolcorp) would greatly simplify installation, as opposed to the two-step process that was used in the field retrofits for this project (encased PCM panels followed by drywall sheet). While puncture and leakage of PCM was a possible concern of the wall retrofit, this was not a problem in any of the field sites 18 months after installation, and all occupants kept the retrofit at the end of the research period. This project led to follow-on research for sealing envelopes through aerosol injection to attics and crawl spaces, funded by the United States Department of Energy and CalNEXT.

CHAPTER 1: Introduction

Homes built before 1978, when California introduced its first building energy efficiency standards, were commonly constructed without exterior wall insulation. This resulted in high heating and cooling loads. To reduce energy use in these older homes, a retrofit process typically involves drilling holes in the walls and filling the wall cavities with fiberglass or cellulose insulation. For this project, researchers at the Western Cooling Efficiency Center (WCEC) and TRC Companies, Inc., developed and evaluated an improvement that builds on this retrofit process by aerosol sealing and installing phase change material (PCM) to the interior surface of exterior walls to improve insulation.

Aerosol Sealing

Aerosol sealing has been used to seal ductwork for more than 20 years (Carrié et al., 2002). It was recently adapted and commercialized to additionally seal building envelopes. The WCEC developed the envelope aerosol sealing process in 2011 and patented and licensed the technology to Aeroseal. The envelope sealing process injects aerosolized sealant into a home, pressurized with a blower door. As air escapes the home through envelope leaks (for example, between wall and top and bottom plates), it carries sealant particles that impact the leaks and seals them (Figure 1). The technology is currently limited to new construction and major renovations because the home must be empty of contents and finishes — such as flooring, cabinets, and counters — for cost-effective application. This research project modified the sealing process for existing homes by leveraging the wall retrofit process. Because older homes are significantly leakier than newer homes (Chan et al., 2013), addressing leakage in the wall cavities as part of the wall retrofit package was a key goal. The project developed and tested modified ways of sealing existing homes with their contents by injecting the sealant into the wall cavities, attic, and crawlspace.

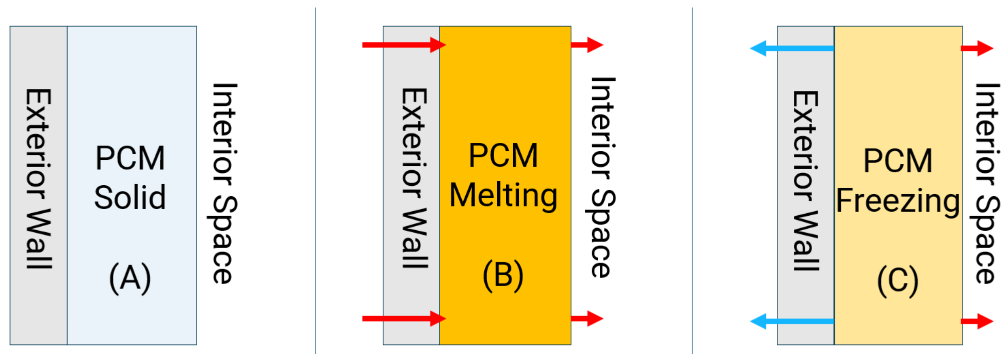
Figure 1: Example of an Unsealed Wall (Left) After Aerosol Sealing (Right)

Source: University of California, Davis

Phase Change Material

PCM is used to achieve thermal storage by changing the phase of a material between solid and liquid at a specific temperature. This process results in a thermal storage capacity per unit weight that is more than 10 times the storage available from typical building materials of the same mass. Initial modeling efforts, combined with a search of available commercial and near-commercial products, indicated that PCM installed on interior wall surfaces had the greatest energy savings potential for home applications. The project focused on installing PCM on interior wall surfaces, using PCM panels to cover the holes drilled for insulation installation. To visualize the design, consider a cold, but sunny, winter morning where one can assume the initial state of the PCM is a solid (Figure 2a). As the sun shines throughout the day, solar radiation creates a heat flux on the exterior wall, traveling through the insulation and slowly melting the PCM, with some of the heat passing into the house (Figure 2b). When the sun goes down, the heat flux on the exterior changes direction. The PCM on the interior surface reduces the heat loss from the house (potentially continuing to heat it) until it runs out of capacity and returns to the solid state (Figure 2c).

Figure 2: Example of How PCM Stabilizes Interior Wall Heat Transfer

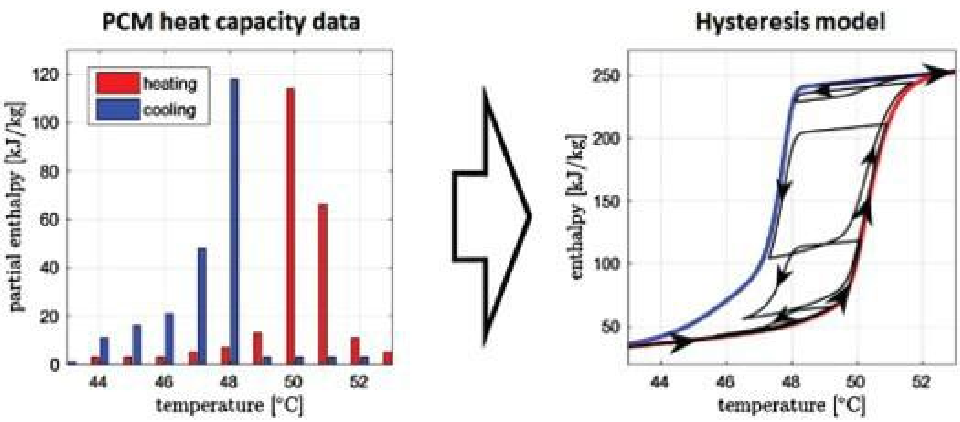


Source: University of California, Davis

To achieve PCM's full potential, it is critical for the phase change temperature to be tuned to typical interior space temperatures to maximize the storage and release of latent heat. This study tested the only commercially available source of PCM identified for building envelopes. The material, manufactured by Insolcorp, is a mineral-based salt hydrate PCM with a latent heat of 86 British thermal units (Btus) per pound. This PCM includes no palm oils or organics and is not flammable (Class A fire rated). Insolcorp can modify the phase change temperature between 65 degrees Fahrenheit (°F) (18 degrees Celsius [°C]) and 84°F (29°C) by altering the mixture of chemicals that go into the PCM during manufacturing. For this study, a PCM with a melting temperature of approximately 70°F (21°C) was used. It is important to note, however, that the phase change does not solely occur at this temperature.

Insolcorp's PCM, like most PCMs, has a hysteresis, which is a multi-degree sweep with peak melting and freezing temperatures occurring at different points (Figure 3). A hysteresis causes the PCM to be in a state of phase change across a wider temperature range. Hypothetically, this would benefit the envelope application by extending the performance over a wider range of temperatures. However, when temperatures change direction while the PCM is changing phase (that is, from melting to freezing or from freezing to melting), the PCM must shift curves. While shifting curves, the PCM temperature changes without any freezing or melting. This phenomenon is expected to reduce performance in envelope applications because each time the state changes the material must change temperature by several degrees before the phase starts to change again. Consensus on the benefits and drawbacks of PCM hysteresis is mixed and largely application dependent — larger temperature changes are less impacted by hysteresis behavior (Zastawna-Rumin and Nowak, 2021; Barz et al., 2019). This dynamic time- and temperature-dependent performance of PCM makes it extremely difficult to calculate the energy impacts of real-world applications. The goal of this project was to model PCM with whole-building energy simulation software and validate that model by dynamically laboratory testing wall sections. A validated PCM model can then be used to forecast energy impacts and the cost-effectiveness for different applications in a range of climates.

Figure 3: Phase Change Hysteresis Concept for Example PCM



Source: Barz et al., 2019

For building applications, PCM is encapsulated to contain the PCM when it is in liquid form. In this project, it was contained within 0.25-inch-thick sheets with sealed squares of PCM. The panels were designed to be installed with fasteners through the empty channels in between squares. Puncturing the panel can leak PCM in liquid form. As the PCM is non-toxic, leaks can be cleaned up and sealed. Alternatively, a section of the PCM panel can be replaced. Residents in the demonstration homes were advised to use adhesive strips for mounting things to the wall to avoid leaks, and no issues were reported.

Real-World Application

In parallel with modeling and laboratory testing tasks, the research team installed the envelope retrofit (sealing, insulation, PCM) in three existing homes in California, each in a different climate zone, to test the retrofit process and measure the energy impacts of the retrofit itself and the homeowner experience in real-world applications. While the sample size was small, documentation of the complete retrofit process and outcomes was important to translate research from the laboratory to the field.

CHAPTER 2: Project Approach

Modeling

To forecast the energy impacts of the technology, the research team modeled a single-family home in EnergyPlus™ with the following parameters, which were constant for all models.

- Three thermal zones (occupied space, crawl space, and attic)
- 872 square feet (ft^2) of conditioned space
- Windows on 20 percent of the exterior wall surface with single speed split-system air conditioner (3.4 coefficient of performance at 95°F [35°C]) (outdoor air)
- Natural gas furnace (0.78 annual fuel utilization efficiency)
- Thermostat setpoints of 77.9°F (25.5°C) for cooling and 67.1°F (19.5°C) for heating
- Occupied space effective leakage area of 9.92 square inches (in^2)
- Ventilated attic and crawlspace with effective leakage areas of 522 in^2 and 634 in^2, respectively
- R-19 floor insulation and R-38 attic insulation
- Internal gains consisting of three adult occupants and electric and gas appliances operating on a typical household schedule (Table 1)

Table 1: Load Schedules and Intensities

Load Schedule and/or Intensity	Source
Activity	United States Department of Energy (U.S. DOE) Residential Reference Models and Alternative Calculation Method (1)
Baths	Smart Power for Smart Homes (2)
Clothes Washer	Smart Power for Smart Homes (2)
Electric Equipment	DOE Residential Reference Models and Alternative Calculation Method (1)
Gas Equipment	DOE Residential Reference Models and Alternative Calculation Method (1)
Lighting	DOE Residential Reference Models and Alternative Calculation Method (1)
Occupancy	DOE Residential Reference Models and Alternative Calculation Method (1)
Sinks	Smart Power for Smart Homes (2)
Showers	Smart Power for Smart Homes (2)

Sources: (1) U.S. DOE, 2023 and (2) Xia et al., 2015

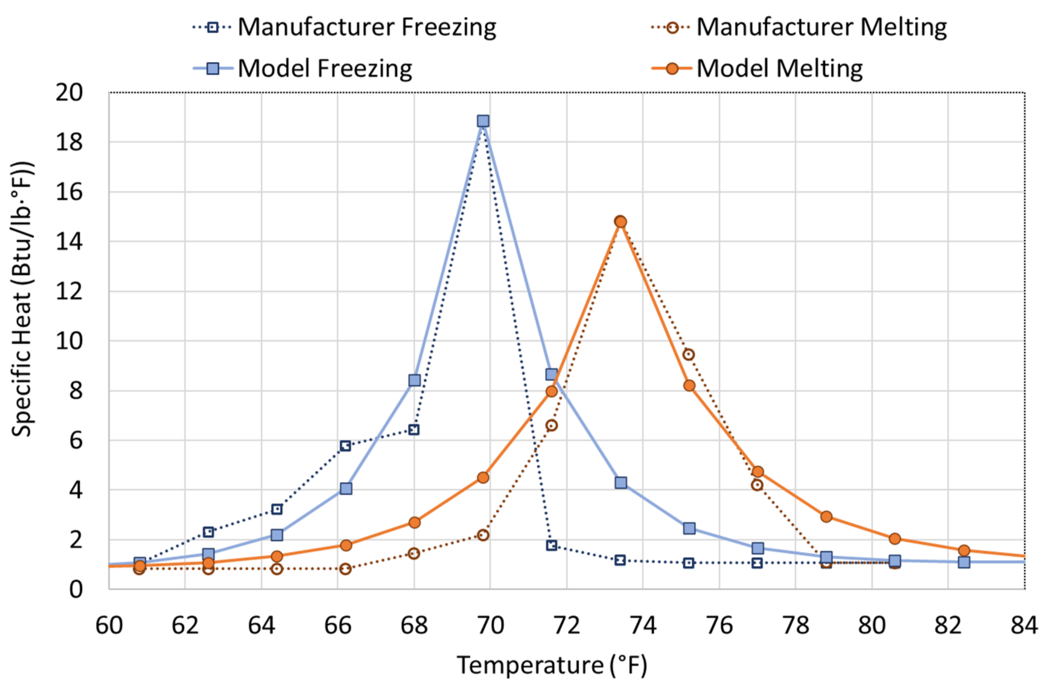
Additionally, the following parameters were varied to understand their interactions with the energy impacts of the technology.

- Internal mass consisting of 157 ft^2 to 1744 ft^2 (twice the floor area) of 0.5-inch-thick plywood
- Window openings up to 65 ft^2 for free cooling

Four different wall geometries were modeled with the following terminologies:

1. **Uninsulated:** Included no insulation in the wall (drywall, wood/air gap, plywood, stucco).
2. **Insulated:** Modified the uninsulated wall to add fiberglass insulation in wall cavities (replaced the air gaps).
3. **+ PCM (t inch, SA ft^2):** Added PCM of thickness "t" to the interior surface of the drywall of the insulated wall model. A layer of 0.14 inch is representative of commercially available Insolcorp tiles (Figure 4). The amount of interior wall surface covered is noted by "SA."
4. **+ Sealed:** Reduced the effective leakage area of the occupied space by 30 percent to 68.8 in^2 to simulate the impact of aerosol sealing the envelope. This could be implemented with any wall configuration.

Figure 4: Material Properties of Insolcorp PCM



Source: University of California, Davis

The research team initially developed the PCM model with EnergyPlus™ version 9.5, using the object "phasechangehysteresis" to model the PCM (Lee and Crossett, 2017). The laboratory testing results did not agree with the model (see Modeling Validation and Laboratory Testing), and further investigation determined that the code incorrectly switched between the PCM melting and freezing curves. To remedy this, the research team adopted a phase change hysteresis model developed by Feng et al. (2022a), which was previously validated by developers with limited laboratory data. This model was not available in the official EnergyPlus™ release; it was downloaded from GitHub (Feng et al., 2022b) and compiled in the compatible version of EnergyPlus™ version 8.9. The laboratory testing results had excellent agreement with this model, and it was used for subsequent analyses.

The research team conducted simulations for the 16 California climate zones for each model variation, using weather data from White Box Technologies CZ2022 weather files (White Box Technologies, 2022). The team compared electricity and natural gas use for each model to understand the energy impacts of insulation, sealing, and PCM applied to interior wall surfaces.

Laboratory Testing

The research team conducted laboratory testing to validate the results of the EnergyPlus™ simulations. Indoor and outdoor exterior wall temperature profiles (temperature versus time) were output from the EnergyPlus™ mode and imposed on a physical wall sample (width: 32 inches, height: 48 inches) constructed to match the modeled exterior wall composition. The team measured the heat-flux on both faces of the wall sample and compared it to the model's output.

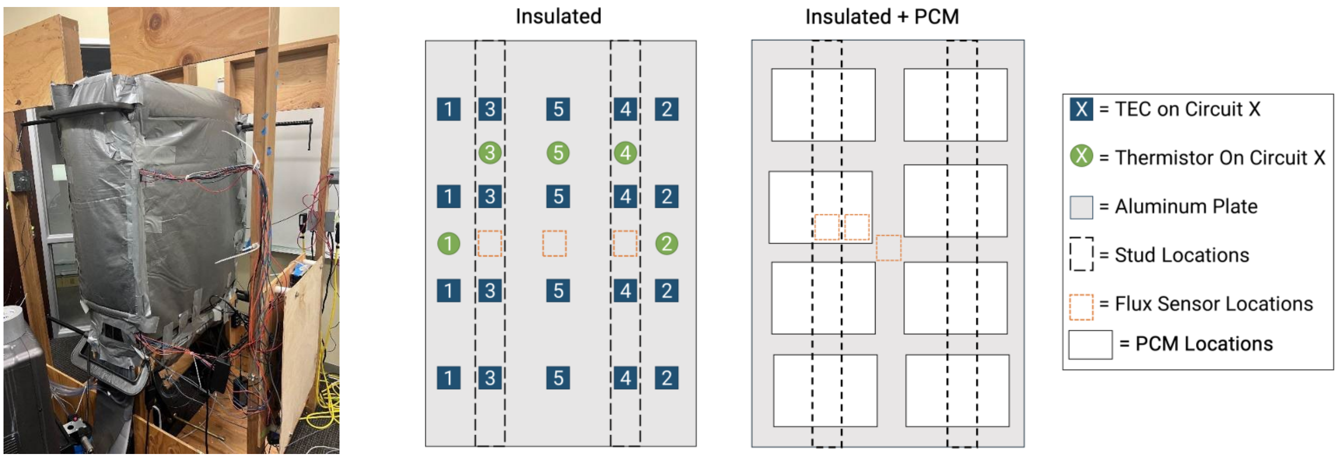
To impose the temperature profiles, engineers constructed an apparatus consisting of two dynamically controlled thermal plates, one for each side of the exterior wall. Each thermal plate consisted of:

- An aluminum heat spreader (width: 32 inches, height: 48 inches, depth: 0.5 inch) to distribute heat and impose a uniform temperature on the wall sample.
- A matrix of water-cooled thermoelectric coolers (TEC) for heating and cooling the heat spreader.
- Thermistors embedded in the heat spreader to measure temperature.
- Controllers to control the output of the TEC, based on both the heat spreader temperature and the current temperature set point.

The water used to chill the TECs was kept at 68°F to 72°F (20°C to 22°C) and was conditioned using a 3,000 Btu per hour chiller (model Active Aqua AACH25HP). The thermal plates were supported using low-conductivity cedar. Engineers sandwiched the wall samples between the thermal plates, clamping the plates together to ensure sufficient conduction. Lastly, the apparatus was wrapped using insulating blankets to reduce environmental heat loss (Figure 5, left).

National Instruments hardware and LabVIEW software were used for apparatus control and data acquisition. Engineers programmed LabVIEW to directly communicate wall temperature setpoints to the TEC controllers. The controllers used their internal proportional-integral-derivative control to adjust TEC output based on the thermistor readings. To improve control, engineers segmented both thermal plates into five vertical control zones consisting of one control thermistor and associated TECs (Figure 5, right). The resulting heat flux was measured with Ultra-09 Fluxteq flux sensors applied between the wall surface and heat spreader with thermal paste.

Figure 5: Completed Laboratory Test Setup (Left), Diagram Displaying Circuit and Sensor Configuration for Insulation Wall (Middle), and Relocation of Flux Sensors After PCM Installation (Right)

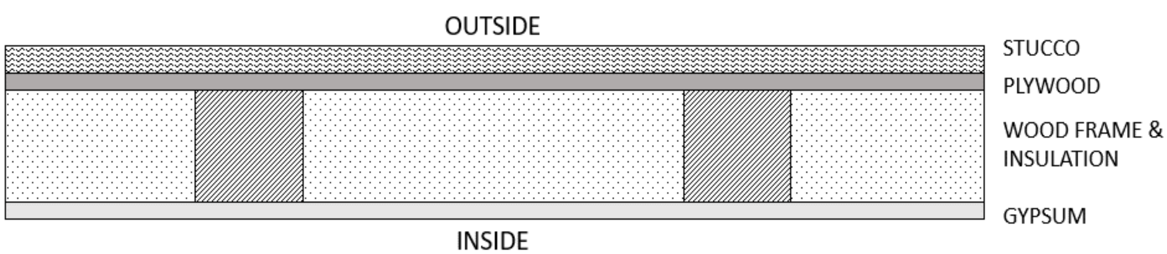


Source: University of California, Davis

Initial testing was performed on an insulated wall sample (Figure 6), which consisted of:

- 0.5-inch gypsum drywall (inside surface).
- 3.5-inch wood (fir) studs and fiberglass insulation or air cavities.
- 0.5-inch plywood.
- 0.875-inch stucco (outside surface).

Figure 6: Construction of the Baseline Wall Sample



Source: University of California, Davis

A typical residential wall is constructed with 1.5-inch by 3.5-inch studs spaced 16 inches on center. Wood framing is added at the top and bottom of the wall and surrounding window and door frames. This results in walls consisting of approximately 20 to 25 percent wood (Enermodal, 2001). To simplify the laboratory testing, the wall sample was built with 3.5-inch by 3.5-inch studs spaced 16 inches on center, which is 22 percent wood. Loose-fill fiberglass insulation with an expected thermal resistance 0.47 Btu/(ft^2·Btu·°F) was installed in the wall cavity. To ensure consistency between tests, the research team completed testing on the insulated wall, then built the "PCM" wall sample using the insulated wall sample. To complete the PCM sample, the research team added two layers on top of the baseline wall.

- 0.25 inch Insolcorp Templok™ PCM panels (on top of existing drywall)
- 0.25 inch gypsum drywall (new inside surface)

The Insolcorp Templok™ panels were not continuous sheets of PCM. They instead consisted of a plastic molded rectangular frame that contains a salt-based PCM. The squares are 12 inches wide by 9 inches tall and have a border for installing the panels on wall studs that are 16 inches on center. This resulted in PCM material covering 56 percent of the wall area (Figure 7).

Figure 7: 3D Model of Wall Sample Showing Insolcorp Templok PCM Geometry

Source: University of California, Davis

Field Installation

The research team implemented home retrofits in three California climate zones to measure the real-world efficacy of sealing and retrofitting single-family homes with blow-in insulation and Insolcorp Templok PCM tiles. All three homes are located in disadvantaged communities (OEHHA, 2020).

The homes retrofitted were in:

- Climate Zone 3 – Vallejo (April 2022).
- Climate Zone 9 – Los Angeles (October 2022).
- Climate Zone 12 – Sacramento (June 2022).

Each retrofit procedure spanned seven days and included five major tasks:

1. Home preparation.
2. Aerosol sealing.
3. Blow-in insulation.
4. PCM installation (select walls).
5. Wall finishing.

Home Preparation (Day 1)

The research team selected walls for PCM installation with maximum solar radiation (unshaded south, west, and east exposures), with maximum wall surface areas (minimal windows and doors). Figure 8 (top left) displays the walls of the Vallejo home, with drilled insulation holes.

Occupants were moved to a hotel for one week to reduce the disruption of the retrofit. The team moved furniture away from the exterior walls and removed all wall-mounted objects. Window trim, baseboards, crown molding, and electrical outlet covers from walls where PCM would be installed were also removed. All materials were saved for reinstallation. The wall surface temperature monitoring sensors were removed, while the cavity sensors were left in place. The insulation contractor then drilled 1.5-inch holes in the exterior wall cavities.

Aerosol Sealant Application (Day 2)

The research team used two different methods for sealing the home. The first method was direct cavity sealing, which pressurized the home to +100 Pascals (Pa) and injected sealant directly into the wall cavity holes drilled by the insulation contractor. As the sealant particles traveled through the cavity leaks, particles impacted the leaks and sealed them over time. Unfortunately, this method proved to be too slow and ineffective when it was attempted in Vallejo and Sacramento. Minimal leak reduction was seen after three hours of sealing time for one wall where the goal was to complete the sealing process within one day.

To improve sealing performance, the team devised and implemented a new method to achieve sealing by injecting sealant into the attic and crawlspace. This method depressurized the home to -100 Pa and injected sealant into the crawlspace (Sacramento and Los Angeles) and attic (Los Angeles only). This allowed for aerosolized sealant to reach all the leaks both between the attic and the home interior and between the crawlspace and the home interior. This sealing process took approximately half a day.

Blow-In Insulation (Day 3)

A contractor insulated the home with the same dense-packed fiberglass insulation used in the laboratory testing. The contractor used the cavity holes to pump insulation into the walls and plugged the holes with Styrofoam.

PCM Installation (Day 4)

The research team installed the PCM tiles directly onto the interior drywall, covering up the holes created by the insulation contractors. Workers installed the PCM in a grid-like pattern across the wall, drilling wood screws through the PCM's plastic framing and into the wood studs. Figure 8 (top right) shows a wall with PCM before drywall installation. Because the PCM tiles cannot be cut (since it would leak out), contractors installed drywall blanks where PCM tiles did not fit to ensure a solid, flat layer for the wall-finishing process. Diagrams were provided to the homeowners showing where the empty plastic channels were located to aid in future installation of wall-mounted items, such as pictures and television mounts. For simplicity, adhesive type mounts were recommended when applicable. It is important that these documents are created and shared with current and future tenants.

Wall Finishing (Days 5 Through 7)

The research team installed an additional layer of 0.25 inch drywall to cover the PCM layer. Drywall screws were installed into the wood studs through the known locations of the plastic channels. The drywall was mudded and sanded according to typical procedures. Trim was then reinstalled, and plastic spacers were installed on outlets and wall switches, so they aligned with the new drywall surface. The Styrofoam™ plugs on walls without PCM were patched with spackle covering. Painting contractors caulked, painted, and returned the walls to the pre-installation condition. The research team reinstalled study instrumentation as close to their original locations as possible. The research team then cleaned the home to remove dust and replaced all relocated furniture. Figure 8 (bottom) displays both the drywall installation and the walls returned to normal cosmetic conditions.

Figure 8: Home Retrofit Stages Across Different Installations Including Home Preparation (Top Left), PCM Installation (Top Right), Finishing (Bottom Left) and Completion (Bottom Right)

Source: University of California, Davis

Field Assessment

The project team applied generally accepted measurement and verification methods for evaluating heating, ventilation, and air conditioning (HVAC) energy use, envelope performance, thermal comfort, and indoor air quality. These methods rely on industry standards, including the International Performance Measurement and Verification Protocol, the

Residential Energy Services Network's Standards, and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standards 55-2020 and 62.1-2019.

HVAC Energy Use

The PCM-enhanced insulation solution was expected to save energy, reduce peak energy use, and potentially shift the time of peak HVAC energy use. The research team used International Performance Measurement and Verification Protocol Option B (retrofit isolation with all parameter measurement) to quantify normalized annual and peak-hour HVAC energy savings.

Annual energy savings were calculated using daily energy-use data before and after the retrofit. The daily energy use data was input into a change-point regression model with the time-of-week-and-temperature regression method for each site. The research team chose this model to accommodate variations in energy use as heating and cooling systems were engaged. For the daily regression analysis, this method also generated cooling-degree day and heating-degree day variables. These variables improved the daily regression model by providing additional context beyond the average daily temperature. The developed models were subsequently applied to typical meteorological-year weather files, normalizing the measured energy use to consistent weather conditions. The normalized energy use and resulting savings were then computed for the entire year (as well as separately) for the summer and winter seasons.

To calculate reductions in peak energy use,[1] the team developed hourly models using only data from peak hours. The research team investigated the effectiveness of the PCM at reducing peak loads by comparing HVAC energy use during the winter and summer seasons, during peak hours only.

The research team confirmed that HVAC equipment efficiency for the pre- and post-retrofit periods was unchanged at the Vallejo and Sacramento sites for both cooling and heating, and at the Los Angeles site for heating. This indicated that any changes in HVAC energy use were not the result of a change in equipment efficiency such that they could then be attributed to changes in the envelope performance and/or user behavior. The cooling efficiency in Los Angeles was difficult to verify because the envelope improvements greatly reduced the length of the cooling cycles, so the supply temperature rarely reached steady state. However, results indicated that cooling efficiency may have degraded by about 15 percent by the end of the study due to a change in the HVAC equipment (for example, refrigerant leak), meaning that the energy savings attributed to the envelope retrofit in Los Angeles are conservative.

Envelope Performance

The research team used blower-door tests to determine the air tightness of a home's envelope before and after the retrofit. The blower door testing followed standard industry practices and involved closing all the windows and doors, pressurizing the house with a special fan

[1] Peak hours in this report were defined as 4:00 p.m. to 9:00 p.m. in the summer season (June through August) and 4:00 a.m. to 9:00 a.m. in the winter season (December through February). Peak hours are intended to represent peak utility rate hours in residential homes.

(positioned in an exterior door), and measuring the leakage rate in cubic feet per minute at 50 Pa pressure difference, designated "CFM50." The leakage rate was divided by the volume of the home to calculate the air changes per hour (ACH) at 50 Pa, designated "ACH50."

To characterize the envelope's thermal properties, indoor and outdoor surface temperatures were measured and logged for one year. The retrofit was expected to increase thermal resistance and stabilize indoor temperatures, resulting in a larger difference between indoor and outdoor surface temperatures.

Thermal Comfort

Pre- and post-retrofit thermal comfort conditions at each site were evaluated by comparing measured data with thermal comfort standard ASHRAE 55-2020. The variables affecting thermal comfort include air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and metabolic rate. The research team collected three physical variables (air temperature, air humidity and wall-surface temperature (used for mean radiant temperature), and assumed reasonable values for air velocity, clothing, and metabolic rate. Thermal comfort metrics were evaluated on the predicted mean vote index. This index combines all six thermal comfort variables into a single prediction of how an average person will vote on a scale of -3 (cold) to 3 (hot). A predicted mean vote between -0.5 and 0.5 is estimated to satisfy 80 percent of people. This approach does not account for occupants' thermal comfort preferences, their ability to change their thermal environment (for example, window operation) or behavior to adapt to the thermal environment (for example, wearing a jacket).

Indoor Air Quality

Measurements of indoor air quality included carbon dioxide (CO_2) concentration and particulate matter less than 2.5 microns (PM2.5). These measurements evaluated whether reduced envelope leakage impacted air quality. CO_2 concentration was used as a proxy for ventilation rates. The research team compared the measured CO_2 concentrations to levels generally expected from previous work. PM2.5 was measured using low-cost particle counting sensors and the sensors' proprietary algorithm to convert particle counts to an estimated mass density of PM2.5. These results were only useful for comparing the pre- and post- retrofit data and cannot be compared with any reference standard.

Data Processing and Adjustment

The research team reviewed the provided pre- and post-retrofit metered data for missing or inaccurate data. Portions of the data set were removed or corrected where required.

Occupant Experience

The research team gathered occupants' attitudes and experiences with their retrofits through pre- and post-installation surveys. The surveys collected information about occupants' comfort, HVAC use, perceptions of air quality, noise transmission, and energy bills (in summer and winter) at baseline and after the retrofit. One of the post-retrofit surveys also queried occupants about their experiences with the installation process.

To minimize the burden on participants, most questions were closed-ended, while a handful of open-ended questions were included to gather more exploratory information. The survey instruments and implementation protocol were submitted to the University of California, Davis Institutional Review Board to protect participants and their data. The surveys were programmed in Qualtrics, an online survey software platform.

Researchers conducted the survey in both English and Spanish by reading the survey questions aloud to participants over the phone and typing their responses into the Qualtrics survey, where it was stored on servers in real-time. Surveys were completed with the adult members of each participating household and lasted 12 to 20 minutes. Researchers analyzed survey data using both quantitative and qualitative methods.

Market Characterization and Commercialization Assessment

The team employed several research methods when conducting market characterizations and commercialization assessments. For the former, the research team used a combination of a literature review, an analysis of databases with estimates for energy savings and costs, and interviews with 13 market actors: three blown-in insulation manufacturers, one injection foam insulation manufacturer, one aerosol sealing manufacturer, one PCM manufacturer, three drill-and-fill insulation contractors, one aerosol sealing contractor, two utility program managers, and one consultant. To develop cost estimates for retrofit insulation, the team compared costs reported by both interviewees and RSMeans (software for residential and commercial construction estimates).

The commercialization assessment summarized information from both academic and non-traditional grey literature on the potential of and need for the technologies, as well as the known and perceived market barriers to adoption. Information on competitive products was gathered from manufacturers' websites. Researchers analyzed secondary data on the number and characteristics of California housing stock and regional climate and air-quality conditions. This information was used to qualitatively (and roughly quantitatively) estimate the technology's market potential.

To inform the commercialization assessment, interviews were also conducted with representatives of the two firms (PCM company Insolcorp and the aerosol-sealing company AeroBarrier), whose technologies were evaluated in this project. A third interview was conducted with representatives of an advanced materials company (EnKoat) that uses PCM and was peripherally involved in the project (but whose product was not installed in the homes). The interviews provided insights into the companies' product development plans as well as the foreseen market barriers and opportunities. Engineers from the field demonstration team completed two technology assessments to create a profile of the non-energy impacts and technology characteristics of each of the technologies.

CHAPTER 3: Results

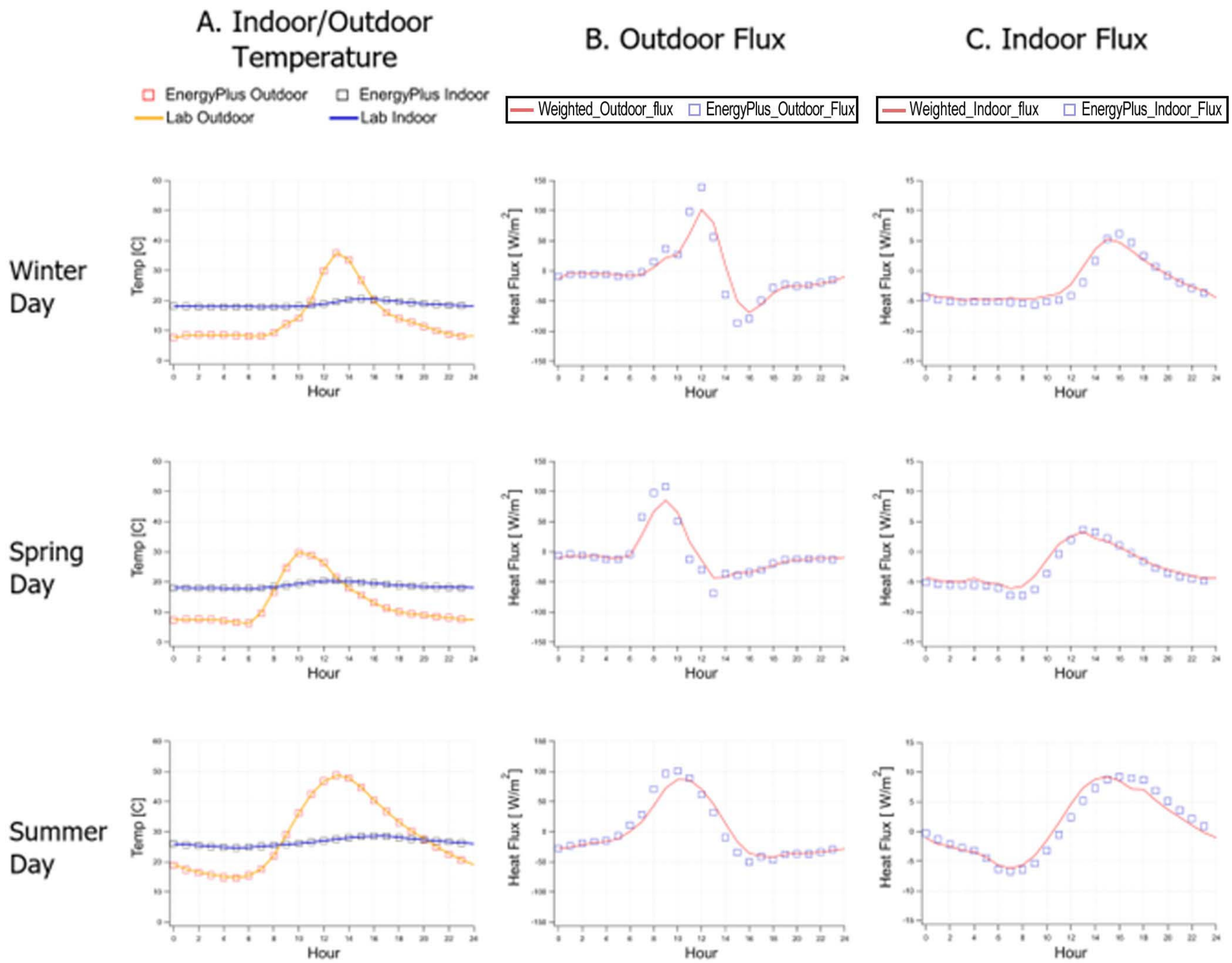
Modeling Validation and Laboratory Testing

The research team conducted insulated wall experiments (Figure 9) using 24-hour profiles representing sample days from the winter, spring, and summer seasons. Each test ran the temperature profiles for four consecutive 24-hour days to reduce the influence of starting boundary conditions. For all tests, data from days two to four were similar; Day 4 is presented in the results. The left column in Figure 9 compares the hourly EnergyPlus™ wall temperature outputs to the temperatures recorded by the laboratory test apparatus. Accurately achieving the desired temperature profiles was required for a valid comparison of the modeled and measured heat-flux results. The agreement between the modeled and measured temperature profiles was excellent for these tests (Figure 9, Column A). The outdoor temperature had an average error of 1.2 percent, and the indoor temperature had an average error of 0.12 percent. The larger error associated with the outdoor profile was attributed to the wider range of temperature control for the outside wall.

The middle and right columns compare the average outdoor flux (Figure 9, Column B) and average indoor flux results (Figure 9, Column C) for both the laboratory test and the model. The research team used 3-dimensional (3D) finite modeling to determine how best to weight the heat flux measured both over the stud and the center of the wall. For the insulated wall, the indoor surface weight was 28 percent stud and 72 percent center, and the outdoor surface weight was 24 percent stud and 76 percent center. A positive flux represents heat moving from outside to inside the house. The agreement was excellent, meaning that the EnergyPlus™ insulated wall modeling assumptions accurately reflected the constructed wall geometry evaluated in the laboratory.

Once insulated wall testing was complete, PCM was added to the insulated wall sample (Figure 7). A challenge of PCM testing was that the PCM can have multiple states at one temperature, making it difficult to control initial test conditions. Therefore, the team started the testing using a modeled day where the PCM was known to be frozen (January 7, 65°F [18°C] inside wall temperature), then ran the laboratory test apparatus for up to two weeks to allow the PCM to change state multiple times. The indoor flux sensors were weighted based on the wall surface area percentages represented by their locations (38 percent no PCM, 40 percent PCM, 22 percent stud).

Figure 9: Baseline Wall Results for a Three-Day Profile Including Indoor and Outdoor Temperatures, Outdoor Wall Flux, and Indoor Wall Flux

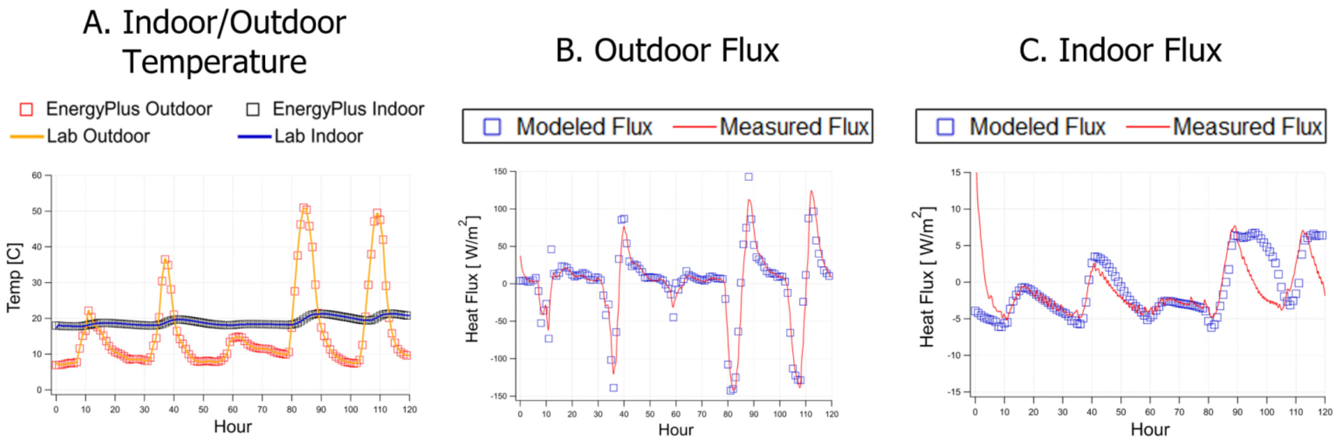


Baseline wall results for outdoor wall flux (column B) and indoor wall flux (Column C) are in watts per square meter (W/m^2).

Source: University of California, Davis

The research team initially conducted laboratory tests using simulated results from the EnergyPlus™ version 9.5 "MaterialProperty:PhaseChangeHysteresis" object. The temperature profile match was excellent, with an average error of 1.5 percent for the outdoor temperature and 0.5 percent of the indoor temperature. Unfortunately, when the PCM reached phase change temperatures, the measured flux differed from the simulation on the indoor surface, and the experiment was stopped after five days due to poor agreement (Figure 10).

Figure 10: PCM Wall Results for a Five-Day Profile Including Indoor and Outdoor Temperatures, Outdoor Wall Flux, and Indoor Wall Flux

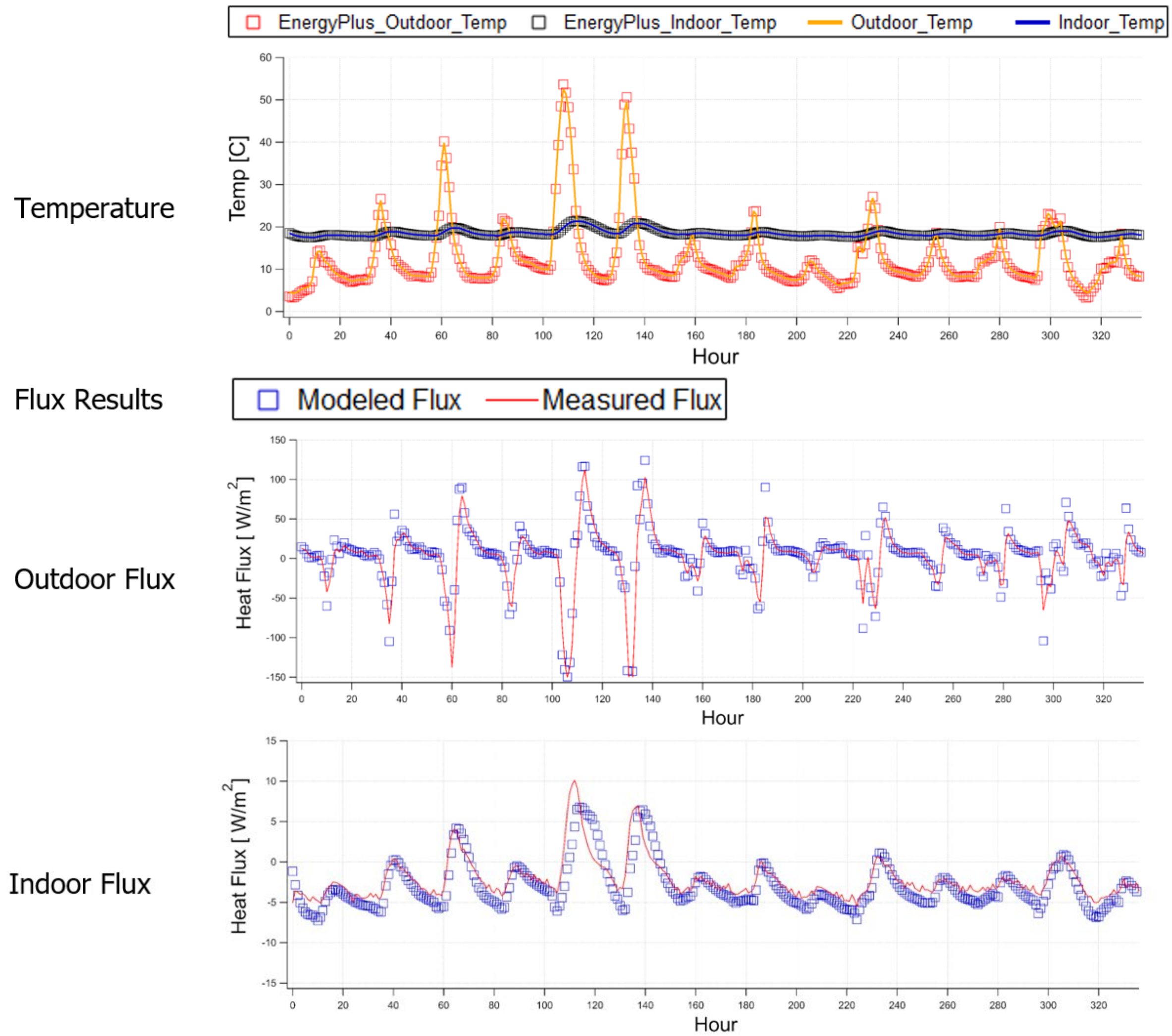


Results modeled using EnergyPlus™ version 9.5, "MaterialProperty:PhaseChangeHysteresis" object.

Source: University of California, Davis

The team then repeated the experiments for the Feng et al. (2022a) PCM model. The agreement between the modeled and measured temperature profiles was excellent for the test (Figure 11), with an average error of 1.1 percent for the outdoor temperature and 0.08 percent of the indoor temperature. Agreement between the simulated and measured indoor and outdoor flux values was also excellent, even during periods where substantial phase change occurred between 100 to 140 hours. The research team attributed minor differences in flux measurement throughout the test to the simplification of the temperature-enthalpy curve of the PCM model used in EnergyPlus™ (as well as the flux weighting to calculate an average result). Despite these minor differences, these results validated the EnergyPlus™ capability to accurately model heat transfer through PCM phase change, using the Feng et al. (2022a) model.

Figure 11: PCM Wall Results for a Two-Week Profile Including Indoor and Outdoor Temperatures, Outdoor Wall Flux, and Indoor Wall Flux



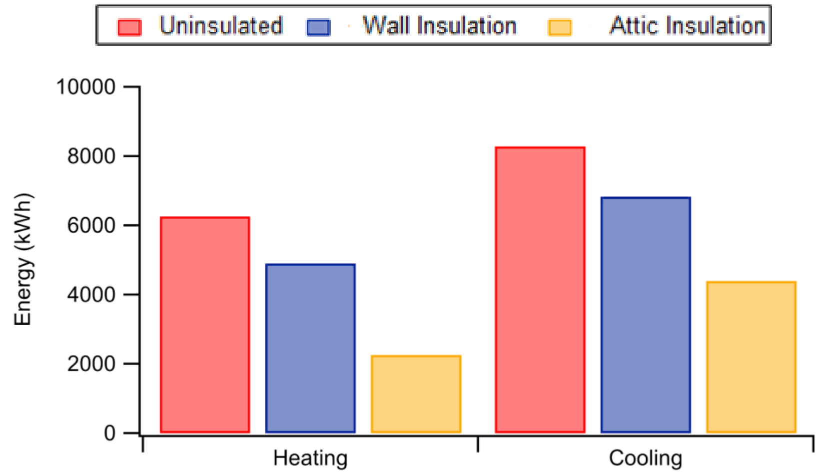
Results modeled using the Feng et al. (2022a) model.

Source: University of California, Davis

Modeling Energy Evaluation

Before evaluating the advanced technologies studied in this project, it is important to illustrate the importance of attic and wall insulation (which are state-of-the-art retrofit measures) on HVAC energy use. Consider results for the simulation of the modeled home in Climate Zone 12 (Figure 12). Note that the heating energy consumed by the natural gas furnace was converted from therms to kilowatt-hours (kWh) for all results. Compared with an uninsulated home, R-38 attic insulation reduced cooling energy and heating energy by 47 and 73 percent, respectively. Compared with an uninsulated home, R-15 wall insulation reduced cooling energy and heating energy by 18 and 40 percent, respectively. This illustrates that attic insulation is the highest priority envelope retrofit measure, followed by wall insulation. All further simulations were, therefore, completed assuming the attic is insulated to R-38 standards.

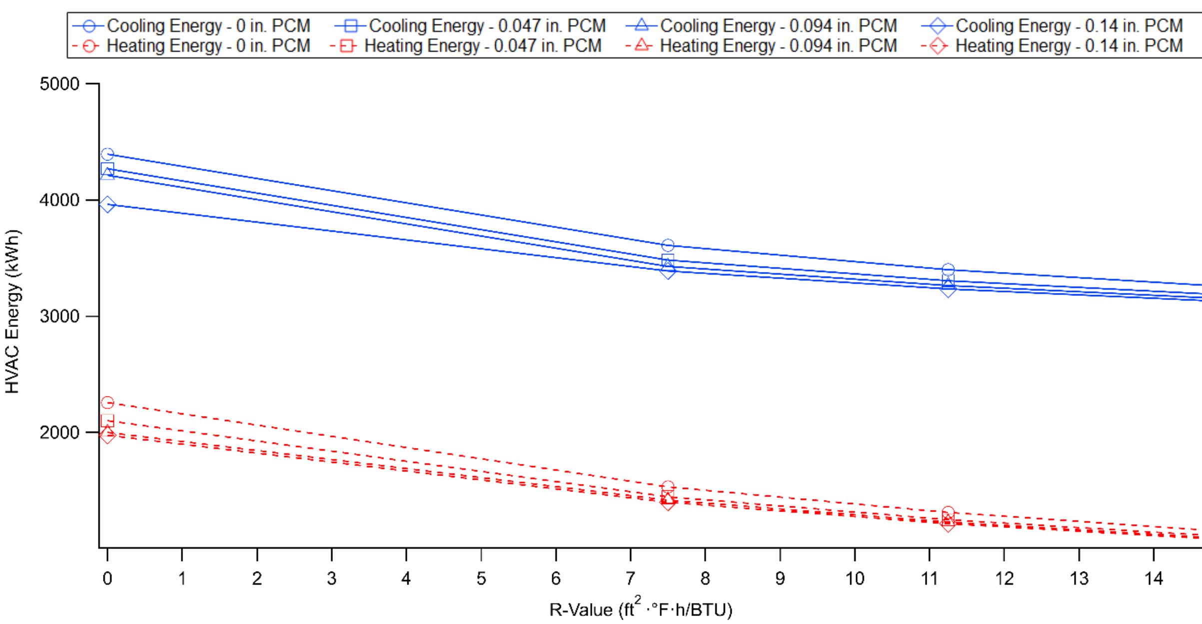
Figure 12: Impact of Adding Wall Insulation Only (R-15) or Ceiling Insulation Only (R-22) to Uninsulated Home in Climate Zone 12



Source: University of California, Davis

Because wall insulation reduces heat transfer through the wall that reaches the PCM, the team characterized the impacts of varying both wall insulation levels and PCM thicknesses on HVAC energy consumption (Figure 13). PCM has the greater impact with reduced wall insulation; however, the data show that installing R-15 insulation in existing wall cavities is the highest priority, with PCM providing an incremental benefit. Therefore, all further simulations were completed assuming the attic was insulated to R-38 standards, and the walls were insulated to R-15 standards.

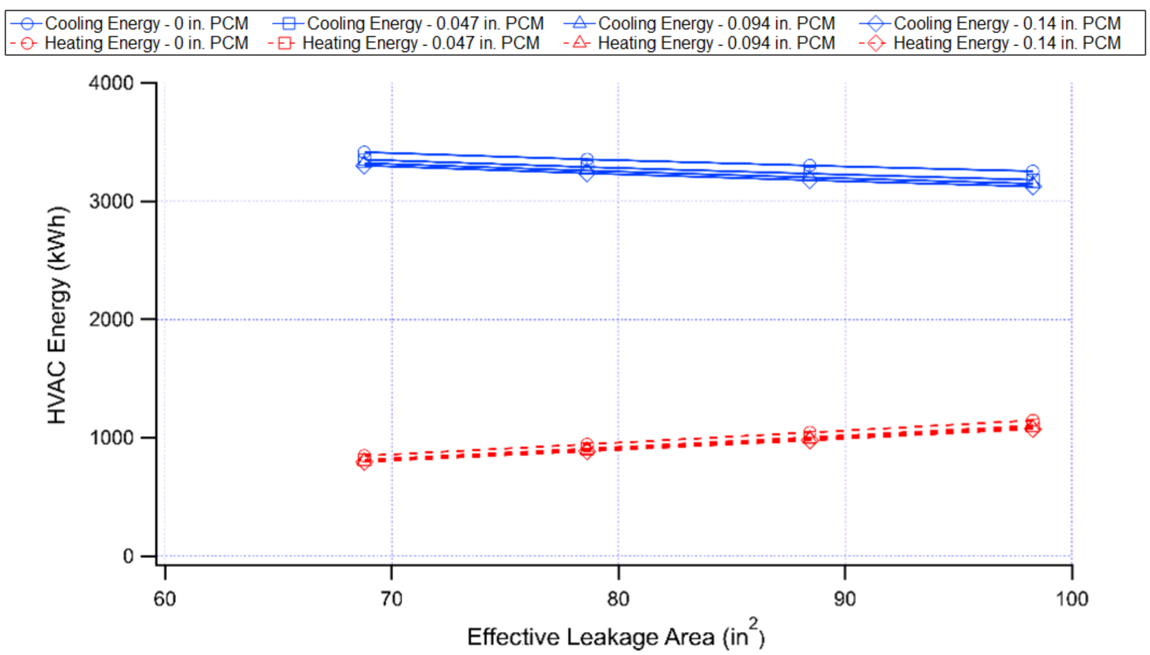
Figure 13: Impact of Varying Wall Insulation and PCM Thickness in Climate Zone 12



Source: University of California, Davis

The team then assessed the impact of envelope sealing and PCM thickness on HVAC energy. Reducing envelope leakage linearly increased cooling energy (due to loss of free nighttime cooling) and decreased heating energy, as expected. The performance of the PCM was unaffected by the sealing of the home over the range evaluated, meaning that the difference in savings from adding additional PCM was approximately the same regardless of the effective leakage area (Figure 14). Therefore, all further simulations were completed assuming the home was sealed to an effective leakage area of 68 in^2, which is representative of the sealing retrofit demonstrated in this project.

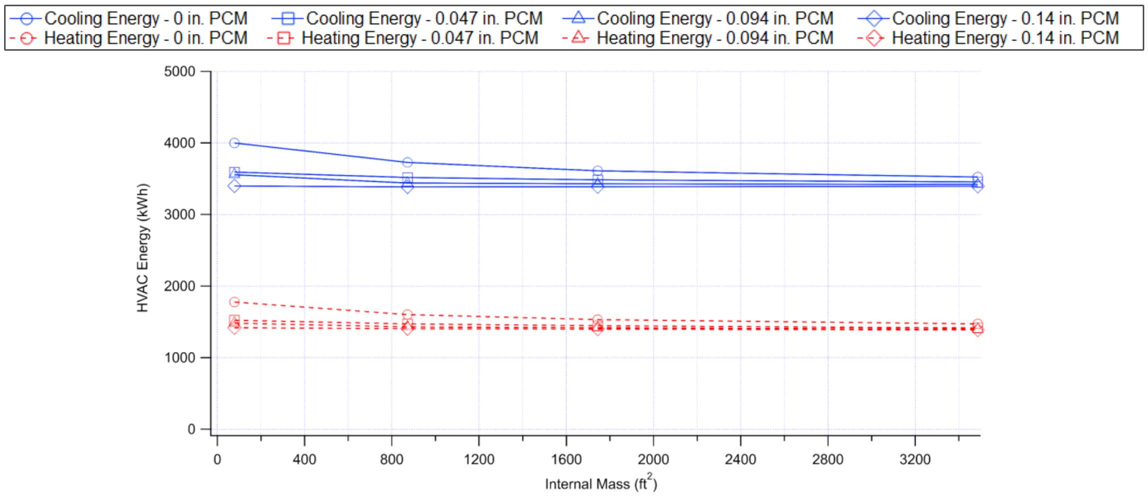
Figure 14: Impact of Effectiveness Leakage Area and PCM Thickness in Climate Zone 12



Source: University of California, Davis

Since the thermal mass of home contents affects thermal storage, the team evaluated the impact of the thermal mass of home contents and PCM thicknesses on HVAC energy. With more thermal mass, the home temperature is more stable, so reduced temperature fluctuations also reduced opportunities for PCM impacts. Thermal mass for contents added to the home (in terms of ft^2 of plywood) varied from 0.09 to twice the surface area of the occupied space, for a range of 79 ft^2 to 1,744 ft^2. The impact of the PCM had an inverse relationship to the internal mass: as internal mass decreased, PCM energy savings increased (Figure 15). The amount of thermal mass in existing homes does not appear to be addressed in the literature but is nonetheless an interesting area to consider for further research. All further simulations conservatively assumed the contents had a thermal mass of twice the floor area, which is the default value in the U.S. DOE residential building prototype models (U.S. DOE., 2023).

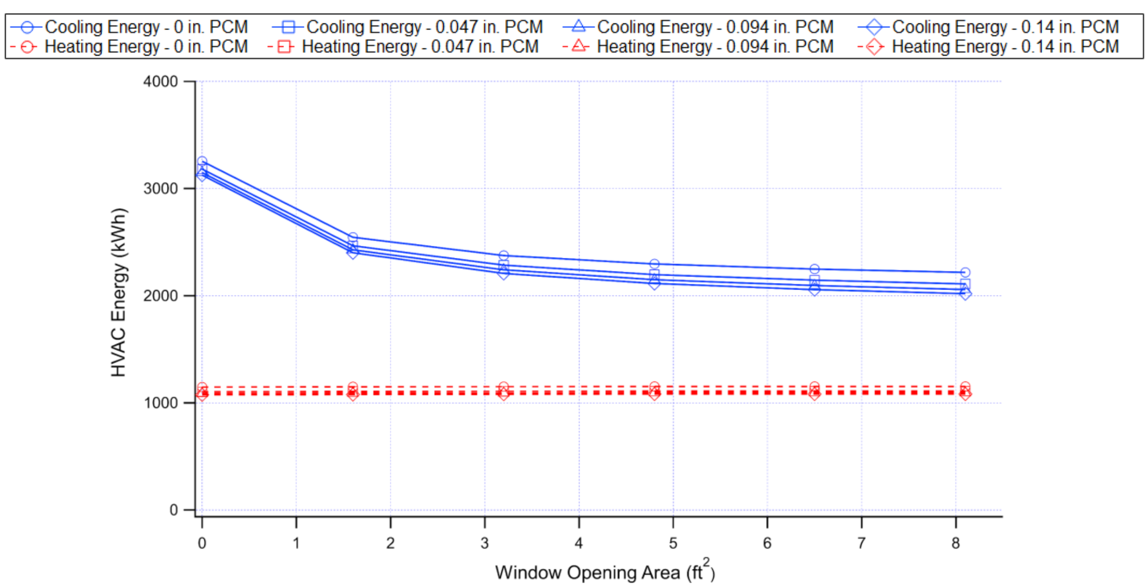
Figure 15: Impact of Varying Thermal Mass and PCM Thickness in Climate Zone 12



Source: University of California, Davis

Finally, the team evaluated the impact of nighttime window opening and PCM thickness on HVAC energy. The research team hypothesized that the nighttime free cooling would leverage cool night air to freeze PCM. The ventilation was varied by simulation window opening between 0 ft^2 to 8 ft^2 when advantageous for cooling. The simulations showed that nighttime ventilation, regardless of PCM thickness, could achieve a large amount of cooling savings (Figure 16). This illustrates the importance of nighttime ventilation in the summer to reduce cooling energy in residential homes; technologies and strategies to increase methods for nighttime ventilation are therefore potential areas of future research. In addition, incremental cooling savings from the PCM increased as window opening increased. Therefore, all further simulations were conducted with nighttime window openings of 50 percent.

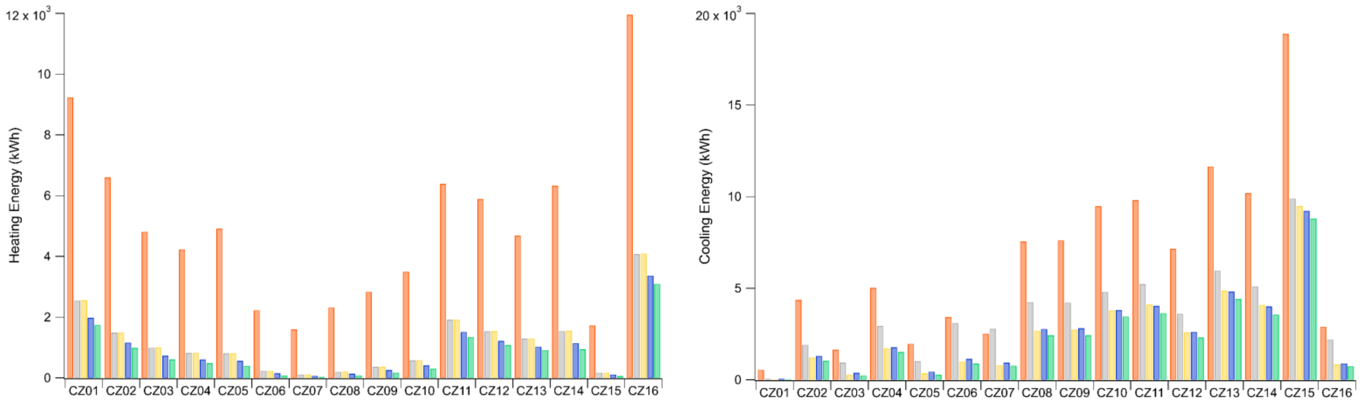
Figure 16: Impact of Varying Window Opening and PCM Thickness in Climate Zone 12



Source: University of California, Davis

While Climate Zone 12 was used to illustrate impacts of the variables evaluated, the trends and relationships are expected to be similar across climate zones. For the limited final set of variables, the impact of each step of the wall retrofit is shown in Figure 17. After wall insulation, the additive measures of window opening (that is, nighttime ventilation), sealing, and PCM are considered in that order as this sequence is expected to represent lowest to highest retrofit cost.

Figure 17: Impact Wall Retrofit Steps by Climate Zone (Measures Are Additive)

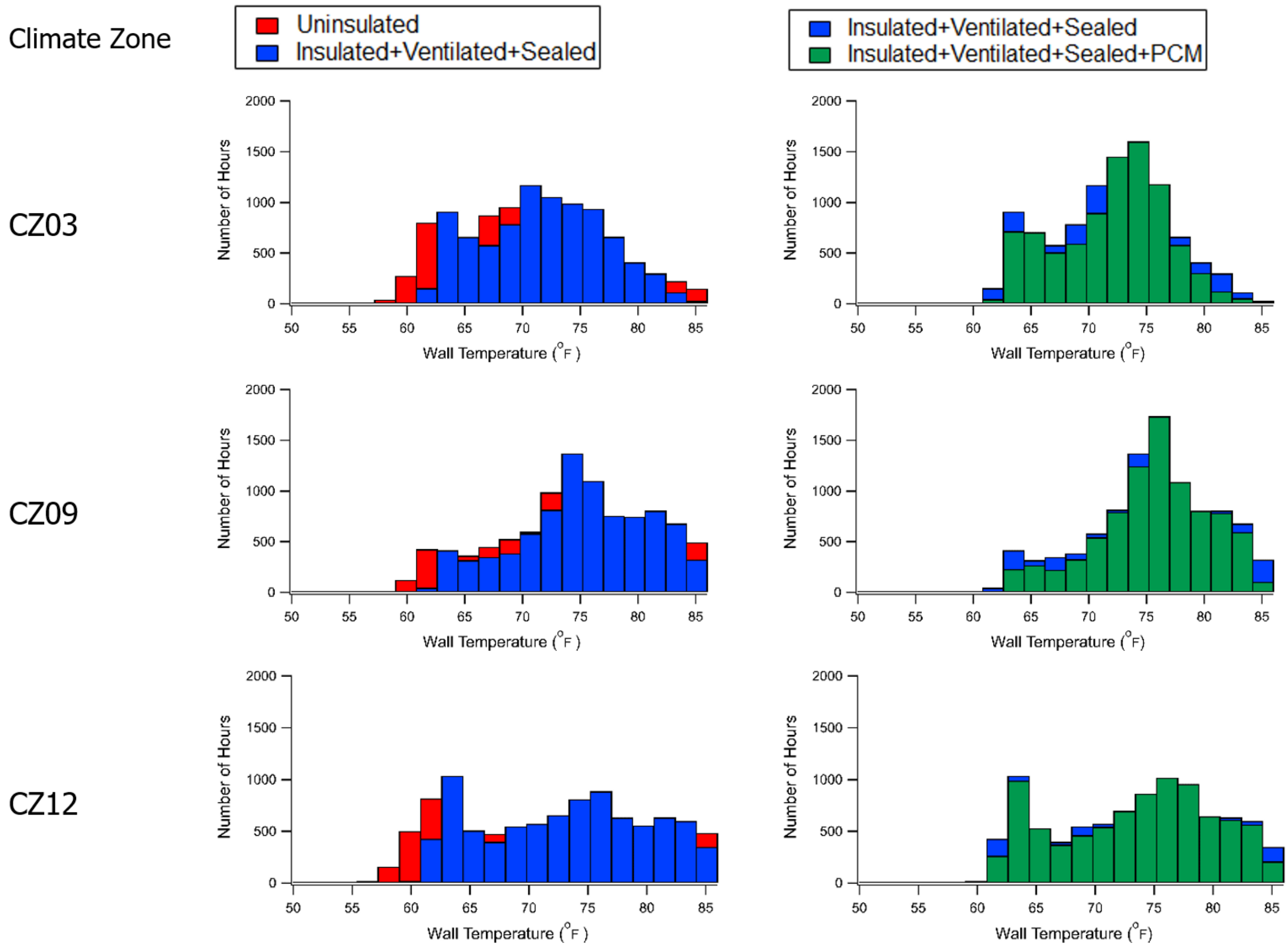


Source: University of California, Davis

For buildings with wall and attic insulation and nighttime ventilation (in the cooling season), incremental savings from completing envelope sealing were predicted to be -145 to 263 kWh (average -27 kWh) for cooling and 48.8 to 729 kWh (average 271 kWh) for heating. For buildings with wall and attic insulation, nighttime ventilation in cooling season, and a sealed envelope, the additional incremental savings from PCM were predicted to be 39 to 437 kWh (average 277.7 kWh) for cooling and 37 to 270 kWh (average 131 kWh) for heating.

In addition to energy savings, inclusion of PCM in the retrofit decreased the range of the interior wall temperature (Figure 18).

Figure 18: Impact of Sealing and 0.14-Inch PCM on Wall Temperature Stability



Source: University of California, Davis

When discussing PCM applications with stakeholders, there was consensus that calculation of an equivalent R-value for PCM would be helpful for the industry. Since this changes with climate for PCM (unlike insulation), this calculation was done for each California climate zone (Table 2), where an equivalent R-value was calculated for a wall with R-15 and a 0.14-inch layer of PCM. The equivalent R-value is the insulation only envelope that has the same forecasted annual HVAC energy use as the envelope with R-15 insulation and PCM. The equivalent R-value varied widely by climate zone but increased the R-15 insulation up to R-18 to R-60. This illustrates that PCM is a useful technology for achieving the highest performance envelope possible. Interestingly, simulations for Climate Zones 6 and 7 did not show a clear energy benefit from increased insulation above R-15, so the metric could not be calculated in that case. However, PCM still had a savings benefit in these climates.

Table 2: Equivalent R-Value Calculation for an Uninsulated Wall Retrofitted with R-15 Insulation and PCM

Climate Zone	HVAC Energy, R-15 Wall (kWh)	HVAC Energy - R-15 wall + PCM (kWh)	HVAC Energy Savings from PCM (kWh) (percent)	Equivalent R-value
CZ01	1443	1306	138 (10 percent)	18
CZ02	1944	1703	242 (12 percent)	28
CZ03	825	677	148 (18 percent)	35
CZ04	1964	1747	217 (11 percent)	32
CZ05	730	539	190 (26 percent)	56
CZ06	1107	903	204 (18 percent)	NA
CZ07	925	781	143 (15 percent)	NA
CZ08	2550	2315	235 (9 percent)	60
CZ09	2650	2357	294 (11 percent)	53
CZ10	3665	3408	258 (7 percent)	30
CZ11	4619	4298	320 (7 percent)	21
CZ12	3184	2939	245 (8 percent)	23
CZ13	4963	4679	284 (6 percent)	20
CZ14	4294	3923	371 (9 percent)	24
CZ15	8259	8022	237 (3 percent)	18
CZ16	3359	3111	248 (7 percent)	19

Source: University of California, Davis

To estimate the simple payback, the price per-square-foot was calculated for each step of the retrofit process (Table 3). Calculations were based on the Los Angeles field site using contractor quotes and local area estimates (DIR, 2023). All costs included material and labor costs. PCM installation labor was estimated using the California prevailing wage rate of a drywall installer. The cost of drywall installation was included with the cost of the PCM because the current product requires an additional layer of drywall for aesthetics. The amount of sealant material and PCM panels were known from the retrofit process. Using the estimated installation costs in conjunction with Pacific Gas and Electric Company (PG&E) reported values for electricity (PG&E, 2024a) and gas (PG&E, 2024b), the estimated yearly cost savings and the estimated simple payback were determined (Figure 19).

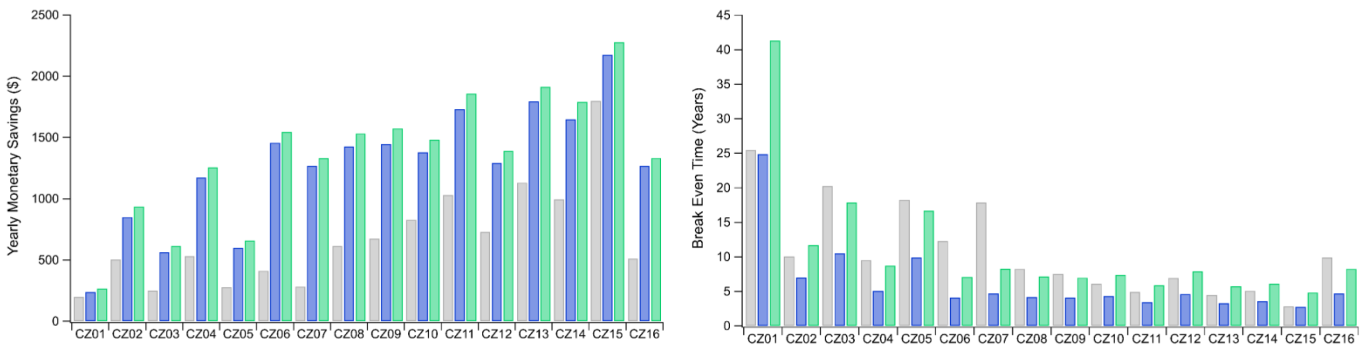
Insulating and sealing the home provided most of the cost savings from the retrofit. The model predicted that the retrofit provided an energy cost savings of $265 to $2,300 per year. The addition of PCM only contributed $25 to $142 of the savings. PCM, while still providing a cost benefit, increased the simple payback time for all climate zones on the scale of two to three years (excluding Climate Zone 1). On a large scale, the complete retrofit package has an estimated simple payback time ranging from 4.5 to 41 years. The retrofit is forecast to be particularly cost effective in Climate Zones 2, 4, and 6 through 16, where the simple payback was 10 years or fewer.

Table 3: Cost Estimates to Retrofit a Home in California

Retrofit Step	Cost ($/ft^2)	Cost for 874 ft^2 House Model ($)
Blown In Insulation	2.25	1,970
Sealing	0.99	866
PCM + Drywall	2.88	2,522
Wall Finishing and Painting	3.54	3,091

Source: University of California, Davis

Figure 19: Cost Impact from Retrofit (Measures Are Additive)



Source: University of California, Davis

Field Installation

A summary of the field installation results is shown in Table 4. One notable finding was that the Vallejo home was already partially insulated during the retrofit. Therefore, insulation was added only to the uninstalled walls (approximately 40 percent of the wall surface area). Additionally, attempts to seal the envelope through dispersal of sealant into the wall cavities were unsuccessful in Sacramento and Vallejo. To improve sealing results, the aerosol sealing process was adapted from wall cavity injections applied in Vallejo and Sacramento to a crawl space injection (Sacramento) and a crawlspace and attic injection (Los Angeles). Crawlspace and attic sealing was effective at both sites where it was applied. The amount of PCM varied depending on the size of the house and the amount of exterior wall available. PCM was installed on south-, west-, and east-facing exterior walls that were expected to receive the most solar radiation. Each PCM panel installed was 24 inches wide by 24 inches tall, with PCM comprising about 56 percent of the surface area.

Table 4: Retrofit Activity Installation Report

Site	Activity	Installer Report
Vallejo (April 2022)	Direct Cavity Aeroseal Sealing	Unsuccessful due to inability to deliver enough sealant through the wall cavities in a reasonable amount of time
Vallejo (April 2022)	Blow-in Insulation	House was found to be partially insulated. Installed insulation within remaining 40 percent of wall cavities

Site	Activity	Installer Report
Vallejo (April 2022)	PCM Installation	Approximately 113 PCM panels installed on a selection of exterior walls (living room east wall, bedroom south wall, and bedroom west wall)
Sacramento (June 2022)	Crawlspace Aeroseal Sealing	Aeroseal sealing was implemented within the crawlspace of the home with a small benefit seen.
Sacramento (June 2022)	Blow-in Insulation	Blown-in insulation was installed without any complications.
Sacramento (June 2022)	PCM Installation	Approximately 75 PCM panels were installed on a selection of exterior walls (kitchen and living room south wall, bedroom west wall, and bedroom east wall).
Los Angeles (October 2022)	Attic and Crawlspace Aeroseal Sealing	Aeroseal sealing was successfully implemented within the attic and crawlspace.
Los Angeles (October 2022)	Blow-in Insulation	Blown-in insulation was installed without any complications.
Los Angeles (October 2022)	PCM Installation	Approximately 64 PCM panels were installed on a selection of exterior walls (living room south and west walls, bedroom west wall, and bedroom east wall). The living room wall presented a challenge for PCM because the plaster crown molding could not be removed. Instead, the team installed PCM in two large, framed squares.

Source: University of California, Davis

Field Assessment

HVAC Energy Use

The retrofit solution resulted in HVAC cooling and heating energy use reductions in all instances except for heating in Sacramento (Table 5 and Table 6). The research team observed an annual electrical savings of 10 percent and natural gas savings of 11 percent at the Vallejo site, an annual electricity savings of 23 percent and an increase in natural gas use of 23 percent at the Sacramento site, and annual electricity savings of 41 percent and natural gas savings of 24 percent at the Los Angeles site. The field sites presented challenges that are commonly found in residential homes since resident behavior, such as use of portable devices and adjustments to thermostats, can be dominant factors impacting changes in home HVAC energy use.

At the Sacramento site, the homeowner frequently used electric space heaters to maintain space comfort prior to the retrofit. After the retrofit, the homeowners reported that they no longer used the space heaters. This is the likely reason for the increase in winter HVAC energy use. The research team was unaware of the space heater use, resulting in an oversight in monitoring their energy impact. This underscores the importance of surveying homeowners about portable heaters and monitoring their use in future HVAC studies.

Table 5: Normalized Annual Electricity Use and Savings of Central HVAC

Site	Normalized Energy Use – Pre	Normalized Energy Use – Post	Savings
Vallejo	552 kWh	497 kWh	55 kWh (10 percent)
Sacramento	1,385 kWh	1,068 kWh	317 kWh (23 percent)
Los Angeles	4,343 kWh	2,564 kWh	1,779 kWh (41.0 percent)

Source: TRC Engineers

Table 6: Normalized Annual Natural Gas Use and Savings of Central HVAC

Site	Normalized Energy Use – Pre	Normalized Energy Use – Post	Savings
Vallejo	474 Therms	420 Therms	54 Therms (11 percent)
Sacramento	155 Therms	190 Therms	-35 Therms (-23 percent)
Los Angeles	197 Therms	149 Therms	48 Therms (24.4 percent)

Source: TRC Engineers

The Los Angeles site had the greatest savings for both heating and cooling. The envelope sealing was very successful in Los Angeles (as described in a subsequent section), which was likely a major contributor to the energy saving results. In addition, the Los Angeles occupants had a whole house fan that they used daily during cooling season. The occupants reported that the house cooled down quickly after the retrofit, which reduced the daily run times of their whole house fan, saving fan energy that was included in the result (average use dropping from 0.7 hours per day pre-retrofit to 0.15 hours per day post-retrofit). Additionally, the whole house fan operation likely increased the cooling stored by the PCM. It is notable that these savings were achieved even though the occupant lowered the central HVAC temperature cooling setpoint by an average of 0.4°F (-17.5°C) post retrofit. Combining PCM with optimizing nighttime ventilation to achieve the most efficient cooling is a promising area for future research that was outside the scope of this study.

Peak Energy Use

The PCM retrofit shifted electricity use for the Sacramento and Los Angeles homes, with an estimated summer peak-hour reduction of 28 percent in Sacramento and 87 percent in Los Angeles (Table 7). The reduction in energy use during the hottest hours of the day indicates the retrofit's success in reducing demand for cooling during summer peak hours.

Winter peak-hour electricity use remained about the same for both the Sacramento and Los Angeles homes, with an average reduction of 3 percent for Sacramento and 12 percent for Los Angeles (Table 7). The heating setpoints during the winter are similar pre- and post-retrofit, although post-retrofit the Los Angeles home decreased their heating setpoint by an average of 0.2°F (-17.67°C). This could explain part of the decrease in winter peak loads.

Changes in energy use during peak hours at the Vallejo home were attributed to changes in thermostat settings by the homeowner — not to the retrofit. Therefore, the results were omitted. The limitation of small-sized samples in field research is that occupant behavior can confound results.

Table 7: Normalized Electricity Use and Savings During Summer and Winter Peaks

Site	Period	Normalized Energy Use During Peak Hours – Pre	Normalized Energy Use During Peak Hours – Post	Savings
Sacramento	Summer	633 kWh	454 kWh	179 kWh (28 percent)
Sacramento	Winter	34 kWh	33 kWh	1 kWh (3 percent)
Los Angeles	Summer	1,324 kWh	170 kWh	1,154 kWh (87.1 percent)
Los Angeles	Winter	248 kWh	218 kWh	30 kWh (12.1 percent)

Source: TRC Engineers

Envelope Performance

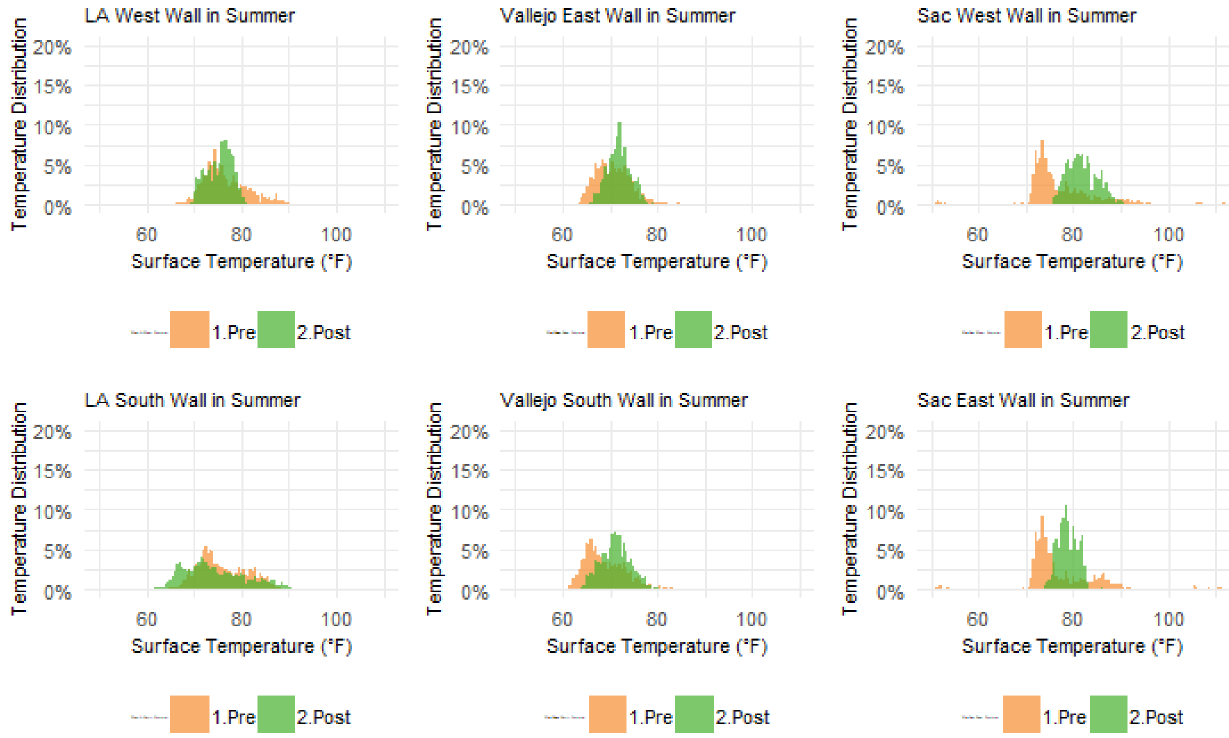
Building airtight envelopes increased at sites where the research team successfully implemented aerosol sealing. After failure of the installation in Vallejo, the team modified the sealing process in Sacramento, which led to partial sealing of the crawlspace. The process was refined before the final installation in the attic and crawlspace in Los Angeles, where it was very successful. The retrofit increased the airtightness of the envelope by 5 percent at the Sacramento site and by 58 percent at the Los Angeles site, as shown in Table 8. Results are reported in terms of air changes per hour (ACH) of the building, pressurized to 50 Pa.

Table 8: Summary of Blower Door Test Results

Site	Pre-Retrofit (ACH at 50 Pa)	Post-Retrofit (ACH at 50 Pa)
Vallejo	16.1	15.0
Sacramento	12.1	11.5
Los Angeles	16.0	6.7

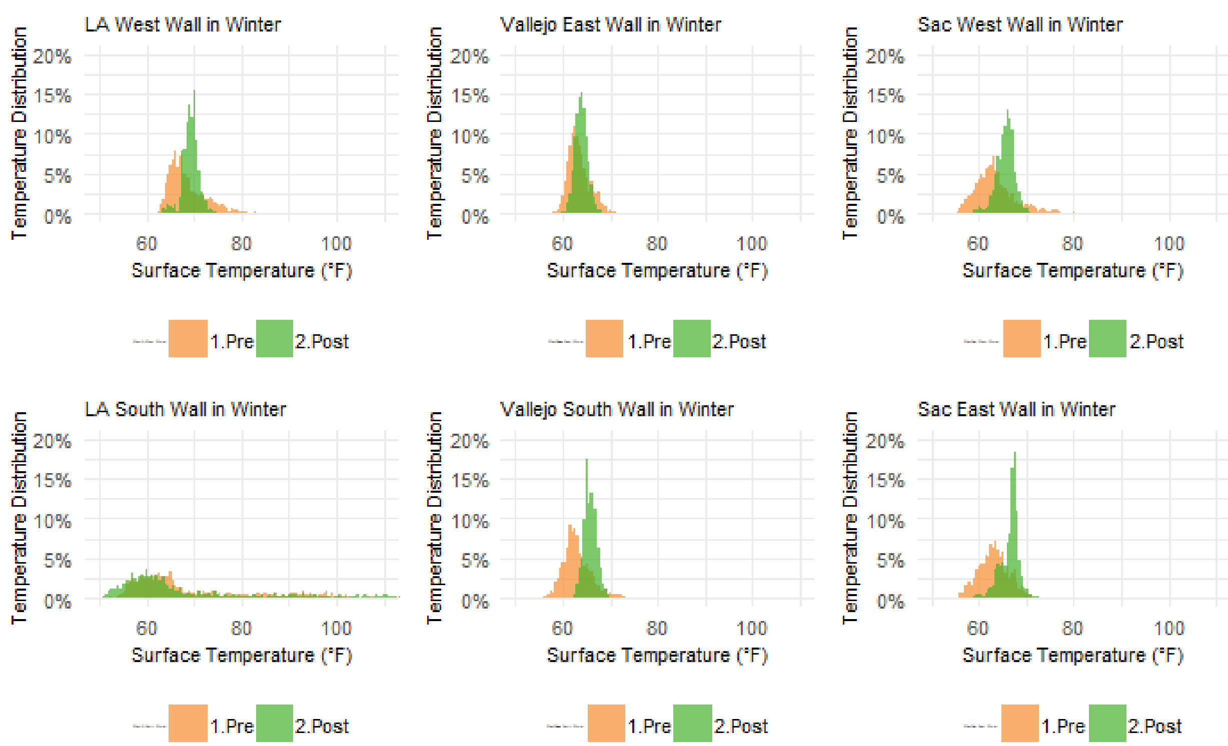
Analysis of the surface wall temperature indicated that the retrofit improved the stability of the interior wall surface temperature in most cases. Interior wall surface temperatures often improved to be closer to the desired room temperature as a result of the retrofit, as shown for summer in Figure 20 and winter in Figure 21. The results for post-retrofit measurements indicate benefits from PCM in Vallejo (both walls, both seasons), Sacramento (both walls, winter only), and Los Angeles (west wall, both seasons). The PCM is a semi-solid in the range of 66°F to 76°F (19°C to 24°C) and will store more thermal energy when the wall temperature is within this range. In Sacramento, in the summer, the interior surface temperatures generally exceeded the PCM melt temperature. In Los Angeles, the south wall temperature sensor did not show a benefit from the retrofit and no explanation was found for this anomaly.

Figure 20: Histograms of Measured Interior Surface Temperatures During Summer



Source: TRC Engineers

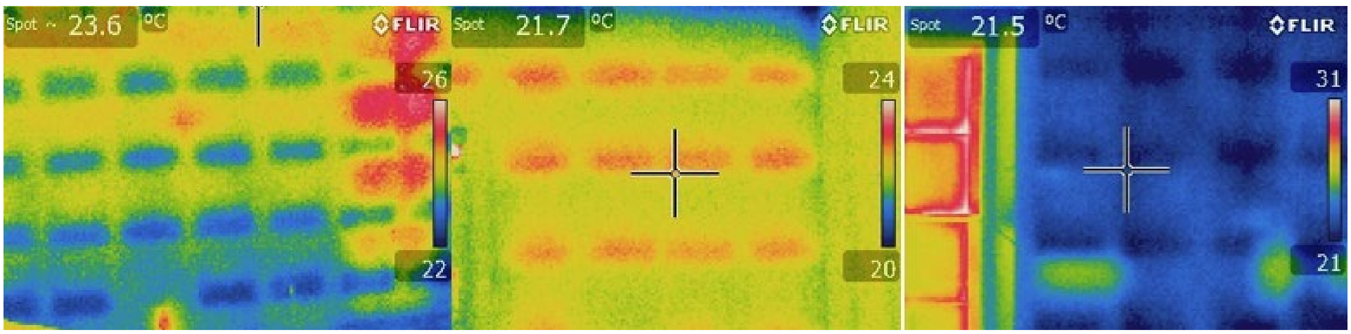
Figure 21: Histograms of Measured Interior Surface Temperatures During Winter



Source: TRC Engineers

The PCM insulation panels had a vertical temperature distribution within each individual panel, which can be seen in Figure 22. Thermal imaging of the PCM after a year in service showed the material accumulated in the bottom half of the panel. This resulted in a 1°F to 3°F (-17°C to -16°C) difference between the top half and the bottom half of the individual panels. Additionally, the PCM material did not cover the entire wall surface, and there were air gaps in the channels surrounding the PCM squares, as seen in the images. Therefore, the wall temperature sensor reading does not necessarily represent the average wall temperature, though the reading should be within 1°F to 3°F (-17°C to -16°C) of the average.

Figure 22: Thermal Imaging of PCM One Year Post-Install at the Vallejo, Sacramento, and Los Angeles Sites (Left to Right)



Source: TRC Engineers

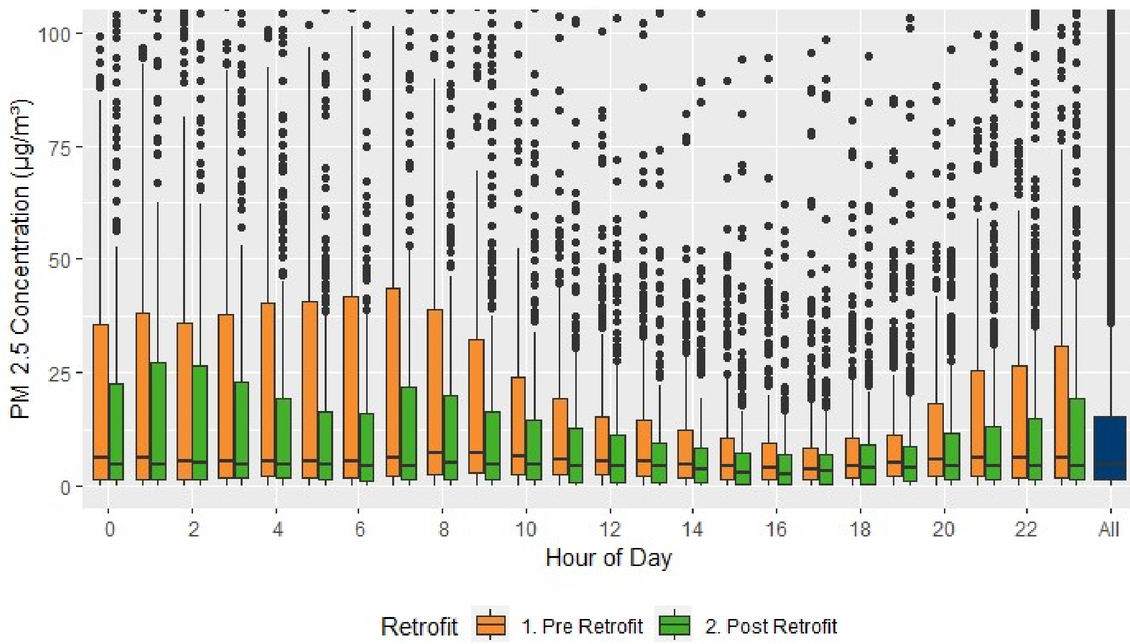
Thermal Comfort

Monitored data showed thermal comfort remained similar during pre-retrofit and post-retrofit periods, with slight decreases or increases at times. Changes in occupant behavior make it difficult to isolate impacts of the retrofit on thermal comfort, however, and no substantial changes in thermal comfort were observed in the data analysis. The occupants' report of their thermal comfort is included in the section on Occupant Experience.

Indoor Air Quality

The field site retrofits had little impact on overall indoor air quality. The Vallejo and Sacramento homes did not experience substantial changes in CO_2 concentration levels (consistent with the low impact of Aeroseal sealing at these sites). The Los Angeles home had the most noticeable change in airtightness due to the retrofit, as seen in Table 8. The large increase in airtightness had minimal impact on CO_2 concentration levels. PM2.5 concentration levels were measured at the Los Angeles site, in addition to CO_2. The range of PM2.5 readings was broad due to variations in occupant behavior (for example, activities such as cleaning, cooking). Median value of the annual PM2.5 readings, however, decreased by 21 percent in the living room (Figure 23). The most likely explanation for this reduction in PM2.5 exposure was the reduction of whole-house fan use during the summer, which reduced the amount of unfiltered outdoor air delivered to the space.

Figure 23: Living Room PM2.5 Concentration Hourly Profile in Los Angeles



Source: TRC Engineers

Occupant Experience

Participants reported that the PCM-enhanced insulation had a neutral-to-positive effect on their thermal comfort. In general, comfort was improved more in the winter than in the summer, in part because two out of the three households use little or no air conditioning. Occupants of the Los Angeles home, who routinely use air conditioning, noticed an increase in comfort after the retrofit, with one member of the household stating, "Generally, it feels a little cooler without having to turn on the AC as much. There is a significant difference in the walls, they feel so much cooler." They also reported less use of their whole house fan, using it for a reduced amount of time to cool the house at night. In addition to greater comfort, the insulation enabled less air conditioning use, including discontinued use of an auxiliary air conditioning unit. Among all three participating households, some participants reported that more conservative thermostat setpoints became comfortable after insulation, while others reported no change.

Non-energy benefits from the retrofit were also examined. Several participants reported reductions in noise transmission. Occupants of the Los Angeles home, whose home envelope was sealed, reported a notable improvement in the envelope tightness.

Despite the research team's efforts to minimize disruption caused by the installation process, some participants still found it inconvenient. They were required to vacate their homes for one week, and several complained of construction dust. To determine overall satisfaction, participants were asked at the conclusion of the project whether the benefits of the retrofits were worth the hassle, whether they would recommend the project to a friend, and, all things considered, whether they would participate in the project again if given the opportunity. All six adult respondents across the three participating households answered "yes" to all three questions suggesting overall satisfaction with the retrofit.

Dissemination and Knowledge Transfer

The project findings will be featured in Western Cooling Efficiency Center's (WCEC's) monthly newsletter and "2024 Research Highlights" — a publication that is sent to both WCEC affiliates and WCEC's 1,611-member newsletter distribution list, which is distributed at industry conferences and available on the WCEC website. The research team implemented and validated a PCM hysteresis object for EnergyPlus™, which was submitted to the EnergyPlus™ development team as a recommended revision to the current PCM hysteresis object, which contains numerous errors (Aboud, 2024). The results of the simulations conducted in this project are useful for the CEC's building codes and standards team to consider adoption of PCM as an insulation method to meet insulation requirements for new buildings.

WCEC engineers worked with AeroBarrier to develop and implement a modified application of their aerosolized building envelope sealing for retrofit applications. As a follow-up to this project, additional funding was obtained for further research on the application of AeroBarrier. Initial efforts were performed as part of a Building America project. CalNEXT is funding continued investigation, and the U.S. DOE Energy Building Energy Efficiency Frontiers & Innovation Technologies is also funding a project for further evaluation. Finally, interviews were conducted with more than a dozen members of industry to explore the market opportunities for PCM-enhanced insulation and aerosolized building envelope sealing.

Market Characterization and Commercialization Assessment

PCM-Enhanced Insulation

Roughly half of pre-1975 single-family homes in California are uninsulated, but only about 0.4 percent of those add wall insulation each year. Slow adoption of traditional "drill-and-fill" insulation retrofit techniques is variously blamed on the cost, obtrusive nature of the work, and the challenges of coordinating various trades. PCM-enhanced retrofit insulation solutions unfortunately face similar barriers.

Results from the field demonstration suggest that PCM-enhanced wall panels have the technical potential to save energy and improve occupant comfort in their residences. In the current form of plastic-encased wall panels, the panels require significant effort to retrofit existing walls, which limits their overall appeal. Similarly, if applied to new construction in their current form, PCM panels would impose added effort and cost, which is likely to be unappealing for developers. By contrast, Insolcorp's proposed PCM-impregnated wallboards offer similar advantages of the PCM panels but require only minimal additional effort when compared with regular drywall (to deal with the extra weight and limitations on cut locations). Nevertheless, PCM wallboards would initially struggle to overcome high upfront costs, low return on investment, and low market availability. Addressing these challenges and making PCM wallboards market-ready would require additional development, testing, and scaling up of production, which would require significant investment. Manufacturers would likely need support to bridge the gap before a market opportunity emerges. The high price of PCM wall boards compared to conventional drywall suggests that subsidies or rebates may be needed to establish a market for the product. Significant outreach to customers, both homeowners and homebuilders, would also be required to raise awareness.

Specifying PCM wallboards in the California building code is another potential mechanism for driving adoption. There is, however, an inherent chicken-and-egg problem with this approach, as the product would need to be widely available at a cost-effective price to be codified in the regulatory framework. Significant support and coordination would likely be required to establish PCM wallboards as a cost-effective and cost-competitive product to help contractors meet energy-efficiency requirements.

Aerosol Sealing

Aerosol sealing building envelopes in the attics and crawl spaces of existing homes has great technical potential to save energy, improve occupant comfort, and deliver other non-energy benefits. More research is needed to identify and document best-use cases that would yield the highest returns and greatest benefits. Larger scale field demonstrations are needed to generate robust findings. Once the best application criteria are known, a strategy to identify those homes will be needed, along with a marketing and messaging plan to target customer priorities (for example, savings, comfort, air quality). Convincing customers of the value of a service that is currently both unfamiliar and not required in building codes will be challenging. Clear presentation of verified performance and explanation of how the technology works (including compelling visuals) is needed to improve occupant understanding of aerosol building envelope sealing.

The path to market option that the manufacturer (AeroBarrier) has identified — expanding the services offered by existing AeroBarrier providers and licensing certain types of contractors (for example, insulation, remediation, weatherization) that offer the service — has several advantages. Leveraging service providers' existing practices, skills, and customer bases would lower customer acquisition and service costs. In theory, some of those savings would be passed through to customers, ensuring lower upfront costs and a better return on their investments.

CHAPTER 4: Conclusion

The research team evaluated PCM-enhanced insulation for retrofitting uninsulated homes, yielding insights into both energy efficiency and thermal comfort. Traditional retrofitting methods for standard attic and wall insulation were shown to be the most impactful methods for reducing energy use in existing uninsulated homes.

The need to simulate the hysteresis behavior of the PCM to ensure accurate estimates complicated simulations of PCM using EnergyPlus™. The research team could not validate the existing "PCM-hysteresis" model in EnergyPlus™ with laboratory testing, and further investigation revealed critical errors that will be reported to the EnergyPlus™ development team. The team, therefore, adopted a phase change hysteresis model developed by Feng et al. (2022a), which was compiled and validated in a compatible version of EnergyPlus™. Simulations demonstrated that PCM integration on exterior walls contributed to a noteworthy reduction (3 percent to 26 percent) in overall HVAC energy consumption. The model predicted that the complete retrofit provided an energy cost savings of $265 to $2,300 per year, with the vast majority of those savings from the insulating, sealing, and ventilation of the home. The forecasted simple payback time for the retrofit ranged from 4.5 to 41 years depending on climate zone but was particularly cost effective in Climate Zones 2, 4, and 6 through 16, where the simple payback time was 10 or fewer years.

Retrofitting an uninsulated home with insulation increases the R-value from R-1.4 to R-15. The project demonstrated that adding a layer of Insolcorp PCM to the interior surface of the exterior walls increased the R-value from R-18 to R-60 (depending on climate zone). This shows that the addition of PCM on interior wall surfaces is a feasible way to increase insulation. The team converted the results to an equivalent R-value to provide a useful metric that compared PCM with standard insulation in California climates, which can support its future adoption in existing codes and standards for new buildings. In many climates, builders could achieve superior results by combining an insulated four-inch-deep wall construction with a layer of PCM instead of an insulated six-inch-deep wall construction, potentially reducing overall construction costs. Policy and regulatory adjustments could catalyze PCM's integration into mainstream construction practices. Policy changes that incorporate PCM into building codes as an option to achieve a specific insulation requirement, along with outreach to increase awareness among homeowners and builders, could drive adoption.

The modeling demonstrated that insulating attics and walls is the most important step in home envelope retrofits with large energy saving potential, particularly for reducing heating energy consumption (58 to 87 percent heating reduction, 45 to 240 therms, depending on climate). Modeling showed that wall insulation beyond R-15 had diminishing returns for energy savings (approximately 200 to 300 kWh annually), so it would be difficult to reduce the installed product cost of PCM enough to motivate consumers to pursue retrofits, which are more expensive than new construction. The addition of PCM only contributed between $25 to $142 to annual retrofit savings. PCM, while still providing a cost benefit, increased the simple payback time for the retrofit package for all climate zones on the scale of two to three years (excluding Climate Zone 1). Retrofit aerosol sealing of envelopes in attics and crawlspaces was effective and fast, and promises to improve indoor air quality and reduce heating energy use in existing homes. The final application in Los Angeles, where the method was refined, achieved a measured 58 percent reduction in envelope leakage. Further research on sealing is underway with funding from the U.S. DOE and CalNEXT.

The team also explored nighttime ventilation through modeling as a way to increase the benefits of available PCM storage and reduce the impacts of building sealing on the potential loss of "free cooling" during summer nights (which is lost when infiltration is reduced). Nighttime ventilation was shown to have important benefits on cooling energy use regardless of whether PCM or sealing measures were applied, and increased nighttime ventilation further increased the forecasted cooling energy savings associated with PCM. Interestingly, the occupants of the retrofit home in Los Angeles reduced the time they ran their whole house fan at night (because the home cooled faster), which correlated with a reduction in median PM2.5 indoors. The interaction of nighttime ventilation with envelope properties, HVAC energy use, and indoor air quality was identified as an important area for future research.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
3D	three-dimensional
ACH	air changes per hour
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
Btu	British thermal unit
°C	degree Celsius
CEC	California Energy Commission
CFM	cubic feet per minute
CO_2	carbon dioxide
°F	degree Fahrenheit
ft^2	square foot; square feet
HVAC	heating, ventilation, and air conditioning
in^2	square inch; square inches
kWh	kilowatt-hour
Pa	pascal
PCM	phase change material
PG&E	Pacific Gas and Electric Company
PM2.5	particulate matter less than 2.5 microns
TEC	thermoelectric cooler
U.S. DOE	United States Department of Energy
W/m^2	watts per square meter
WCEC	Western Cooling Efficiency Center

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Project Deliverables

The following project deliverables provide greater technical detail on aspects of this research project and are available by email request at pubs@energy.ca.gov.

- Task 2: Market Characterization of Advanced Insulation Products for Single Family Residences in California
- Task 3 and Task 4: Energy and Heat Transfer Modeling and Laboratory Testing Results
- Task 5: Pilot Site Testing Results
- Task 6: Commercialization Assessment of PCM-Enhanced Insulation Solution for Single Family Residences in California
- Task 8: Technology/Knowledge Transfer Report