

Energy Savings and Durability of Phase Change Materials in Residential Attics

*Robert Hendron, Stephen Chally, Frontier Energy
Chad Asay, Sonoma Clean Power*

ABSTRACT

This paper describes an applied research project to evaluate the energy savings potential, durability, and best practices for installation of encapsulated phase change materials (PCMs) in residential attics based on laboratory testing and field testing in five test houses in Sonoma County, California. PCM is an appealing technology because it can reduce the temperature difference across attic insulation while it freezes or melts, potentially reducing heat transfer into or out of the conditioned space. Interest in the use of PCM to reduce heating and cooling loads has increased greatly in the past 10-15 years due to advances in higher performance PCM compositions and the availability of a broader range of products that can be readily integrated into building envelopes. Most applications have focused on commercial buildings, so minimal information is available about benefits in residential applications.

Three conditions must be met to take advantage of PCM in a building application. First, the PCM must be exposed to temperature changes on both sides of its melting point over the course of the day. Second, the duration of these temperature swings must be long enough to freeze and melt the PCM. Third, the heat transfer rate to and from the PCM must be fast enough to store a significant amount of energy within the duration of the temperature swing. The results of this study characterize how variables such as melting point, weather conditions, thermostat settings, and installation above or below the insulation affect each of these variables and the resulting savings.

Introduction

Phase change materials (PCMs) are a promising technology for reducing and shifting building envelope thermal loads by storing and discharging energy over the course of a day. Interest in the use of PCMs to reduce heating and cooling loads has increased greatly in the past 10-15 years due to advances in higher performance PCM compositions and the availability of a broader range of commercial products that can be readily integrated into building envelopes, especially in commercial buildings and new construction (Gibson 2022; James and Delaney 2012). Potential cooling savings of 15%-20% along with reduced peak demand have been demonstrated (Kosny, Shukla, and Fallahi 2013). However, most studies have focused on commercial applications (Biswas et al. 2016; Southern California Edison 2012), wall applications (Childs and Stovall 2012), or PCM embedded in insulation materials or drywall (Miller et al. 2012; Kosny et al. 2006). No studies identified by the authors had focused on field testing the combined effect of stand-alone PCM sheets on heating and cooling in residential attic retrofit applications. Seeking a way to incorporate PCM in existing homes, the project team identified a new product that appeared promising based on its high heat capacity and ability to be easily installed above ceilings of existing homes (see Figure 1).

The product consists of a salt-based PCM encapsulated in cells that are about ¼-inch thick and two inches wide by four inches long. The cells are sealed in flexible mats that are 16 or 24 inches wide by 48 inches long which can be placed between ceiling joists above or below the insulation. The PCM material, which consists of hydrated inorganic salts, is non-toxic and fire resistant. Unlike PCM embedded in construction materials like gypsum board, this product can be installed between the ceiling drywall and attic insulation in existing homes and has higher heat capacity per unit area. The chemical composition can be designed to melt and freeze at any temperature in the 66-84°F range and offers the potential for shifting summer peak loads and reducing electricity demand. By reducing indoor temperature swings in both seasons, it also has the potential to reduce energy use through fewer heating and cooling thermostat calls.



Figure 1. PCM mat used for residential attic application.

The objective of this applied research project, which was performed by Frontier Energy and sponsored by Sonoma Clean Power (SCP) with funding from a California Energy Commission (CEC) grant administered by Kadir Bedir, was to characterize the energy savings for PCM installed in residential attics and to determine its long-term cost-effectiveness and viability for further deployment efforts through utility-based incentive programs. We performed the PCM evaluation using a combination of field testing, laboratory testing, and energy modeling.

Field Testing

We installed PCM in five houses within SCP service territory, which includes Sonoma and Mendocino Counties. This region of California experiences relatively mild weather conditions in both summer and winter but is also very sunny most of the year. It also has large daily temperature swings (40°F to 60°F on sunny winter days, 50°F to 85°F in the summer) that can increase the frequency and duration of freezing and melting processes. Sonoma County weather is unusual in terms of its very sunny weather for the vast majority of the year, combined with mild summer and winter temperatures. Homeowners volunteered for the program through a large-scale recruitment effort conducted by SCP in 2018, which included surveys, interviews, and site visits. We selected the test sites based on a rigorous scoring process that considered house size, existing attic insulation type and R-value, heating and cooling equipment type, attic accessibility, safety, and homeowner attitudes. A summary of site characteristics for the selected homes is provided in Table 1, including information about the PCM installed at each site.

Table 1. Field Test Site Characteristics

	Site 52	Site 54	Site 56	Site 53	Site 55
Location	Sonoma	Santa Rosa	Santa Rosa	Santa Rosa	Petaluma
Year built	1983	1954	1965	2001	1920
Number of stories	1	1	1	2	1
Conditioned floor area	1551 ft ²	1505 ft ²	1338 ft ²	1300 ft ²	1361 ft ²
Attic area covered by PCM	1240 ft ²	1204 ft ²	1070 ft ²	520 ft ²	1088 ft ²
PCM location	Above insulation	Below insulation	Below insulation	Below insulation	Below insulation
PCM melting point	77°F	77°F	77°F	77°F	77°F
Heating system	Heat pump	Furnace	Furnace	Furnace	Furnace
Cooling system	Heat pump	Window A/C	Central A/C	Central A/C	Central A/C

We monitored each house for about 9 months prior to the PCM retrofit to develop a baseline. A contractor installed the PCM in December 2019, and we performed another 9-10 months of monitoring. Initial modeling predicted better savings with PCM installed below the insulation, and that approach was used for four of the five homes. We conducted homeowner surveys at the end of each monitoring period, and SCP and Pacific Gas & Electric (PG&E) provided utility bills for the relevant period with permission from the homeowner partners. Data collected during this period included the following:

- Temperatures and relative humidity at key points in the attic and interior of the house, including near the thermostat
- Heat flux at four points above and below the PCM
- Gas or electric space heating energy and electric cooling energy
- Whole-house gas and electricity use

- Occupancy patterns and other behavioral information
- Weather conditions (temperature, wind, and solar radiation)

We ultimately judged that quantitative heat flux measurements across the PCM were not reliable for the field test sites, due to apparent data conversion errors by a company that provided data collection and storage services for the project, along with measurement inaccuracy resulting from expansion and contraction of the PCM that may have affected contact with the flat heat flux sensors. However, we decided that we could draw qualitative conclusions about the extent of load shifting. Figure 2 shows heat flux readings for Site 56 from sensors on each side of a PCM mat positioned above the ceiling but below the insulation during a 3-day warm period in April 2020. Positive heat flux is upward from the interior space to the attic. The heat flux occurs in opposite directions above and below the PCM most of the time, indicating that the PCM was melting (absorbing heat) during mid-day and solidifying (releasing heat) at night over this period. However, as the PCM becomes fully frozen around 7 am, the heat flux realigns on both sides of the PCM and the peak heat transfer toward the attic occurs at about the same time. The cooling load during the afternoon never align, indicating that the PCM didn't fully melt during this three-day period. During colder (see Figure 3) and warmer weather, the heat flux was generally the same above and below the PCM, because little or no phase change occurred.

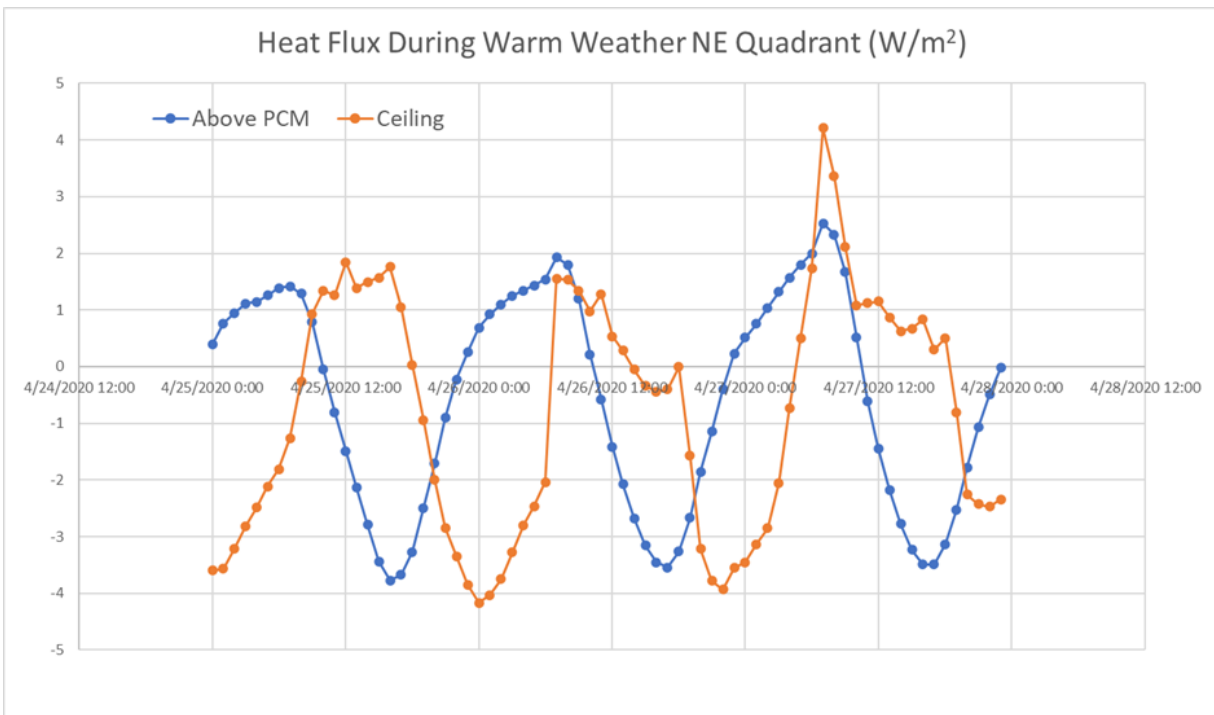


Figure 2. Site 56 heat flux in and out of PCM from Apr 25-27, 2020.

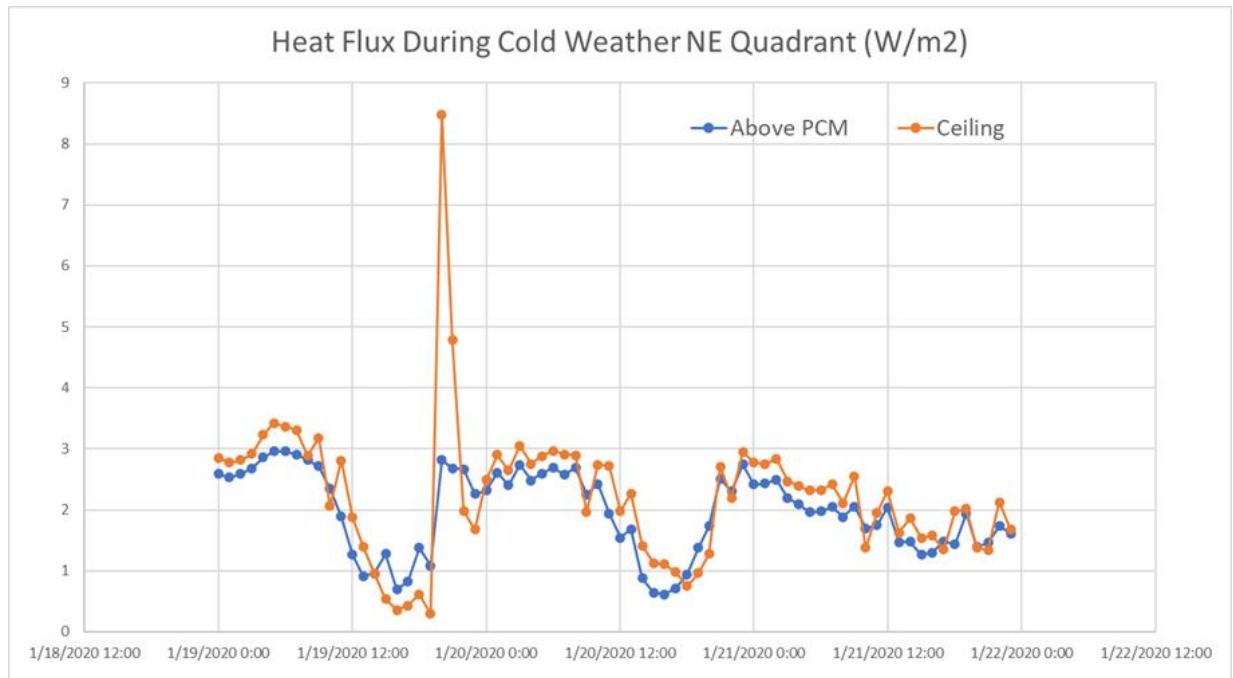


Figure 3: Site 56 heat flux in and out of PCM from Jan 19-21, 2020.

Despite this evidence showing the PCM was absorbing and releasing heat as intended, no benefit was seen in measured heating and cooling energy, except at Site 52 where the PCM was installed above the insulation. We obtained these direct heating and cooling measurements using watt nodes to measure electrical energy at the outdoor and indoor air conditioning or heat pump units, and a gas meter at the furnace to measure gas heating energy. Figure 4 summarizes measured heating and cooling energy savings for all five sites. These results were weather normalized and adjusted based on post-retrofit changes to occupancy and thermostat settings to create a fair comparison. Because the retrofit occurred just prior to the onset of the COVID-19 pandemic and subsequent stay-at-home guidance, the inability to account for the full effects of behavior changes means that caution must be used when interpreting the field test results. Unfortunately, the energy use data do not support the hypothesis that the PCM reduced either heating or cooling energy, except in the single case when it was installed above the insulation.

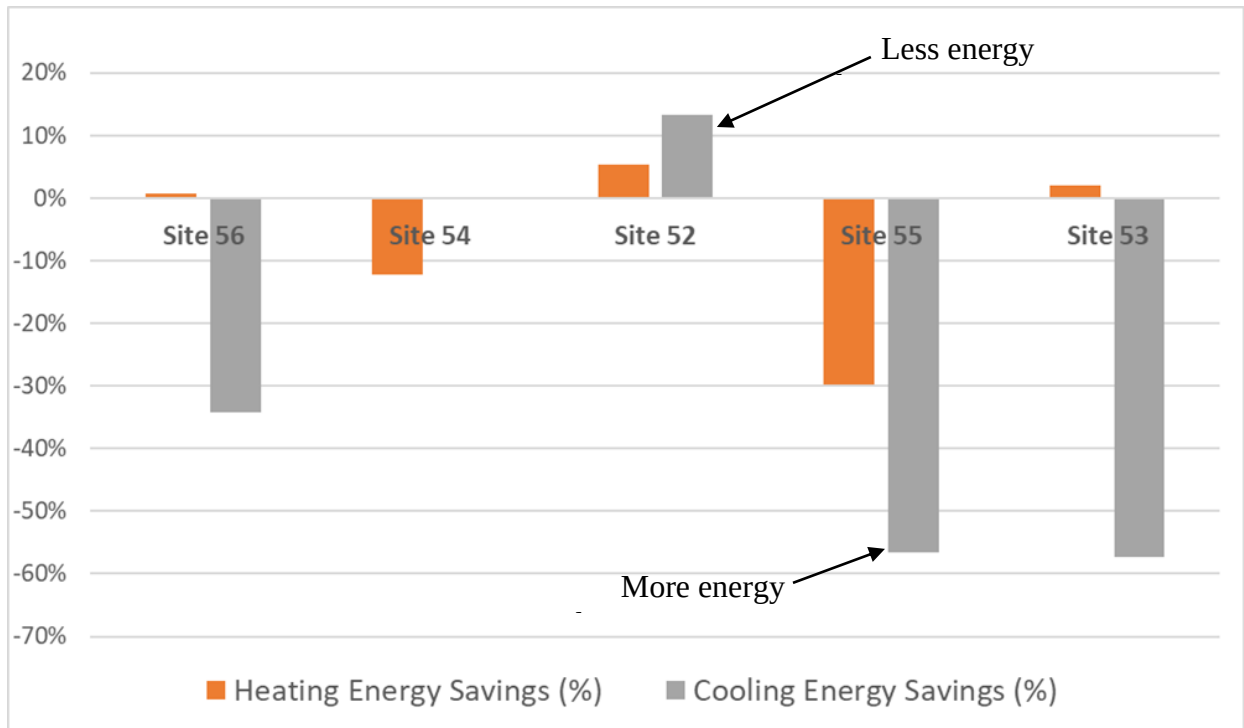


Figure 4. Heating and cooling energy savings for five test sites based on HVAC measurements normalized for weather and changes to occupant behavior.

Separately, we performed weather normalized utility bill analysis for the five test sites, using an on-line tool¹ that performed regression analysis of whole-house energy use as a function of heating and cooling degree days. The results suggest significant though highly variable energy savings. However, it is extremely difficult to separate heating and cooling energy from other activities at these sites, especially when occupant behavior changed significantly during the COVID-19 pandemic. The direct measurements of heating and cooling energy obtained during the field tests are much more reliable. For completeness, the utility bill analysis is provided in Table 2.

Table 2. Weather normalized utility billing data at five test sites over 11 months

Site	Pre-retrofit weather normalized electrical energy (kWh)	Post-retrofit weather normalized electrical energy (kWh)	Weather normalized electrical energy savings (%)	Pre-retrofit weather normalized gas energy (therms)	Post-retrofit weather normalized gas energy (therms)	Weather normalized gas energy savings (%)
52	5839	4651	20.3%	72	63	11.6%
53	7512	8039	-7.0%	580	580	-0.04%
54	3915	4873	-24.5%	377	234	37.9%
55	5660	4664	17.6%	439	409	6.7%
56	5134	4739	7.7%	487	509	-4.4%
Total	28,059	26,966	3.9%	1954	1796	8.1%

¹ <https://www.degreedays.net/>

Durability issues arose for the PCM material when two test sites reported numerous leaks about 18 months after installation (see Figure 5), and a contractor discovered leaks at a third site that weren't evident until 27 months after installation. Some of the leaks appeared to consist of PCM leaking out of small holes that may have begun as pinhole-size flaws created during the sealing process when the mats were manufactured, while others seemed to be the result of the material scraping against a rough surface. Some of the reported leaks were simply water extracted from the air because of hydrophilic salt residue on the surface of the PCM mats (see Figure 6) based on explanations from the factory that manufactured the product. Simple condensation was ruled out because water accumulated on some of the leftover PCM mats at the laboratory while the PCM was at the same temperature as the surroundings, but more water was present when conditions were humid. Although the factory owner has reported that these manufacturing issues have been resolved, we remain concerned about pursuing the deployment of this product further until durability has been more firmly established. Despite the significant number of leaks, they represented only a small fraction of the PCM cells present in the installation, and they would not have affected the energy savings in any meaningful way.



Figure 5. PCM mat with multiple leaks near scuff marks from Site 54.



Figure 6. PCM mat with water accumulation but no apparent leaks.

Lab Testing

We also tested the PCM in one of the environmental chambers at the Frontier Energy Building Science Research Laboratory (BSRL). We configured the test chamber with a simulated attic that could be controlled separately from the interior space. Lab testing provided an opportunity to remove both weather and occupant behavior from the evaluation through strict control over the temperature profiles. We performed lab tests using two PCM installation configurations, attic insulation levels, and simulated melting points. We simulated the different melting points using 84°F PCM and adjusting all chamber temperatures upward to create the temperature differences that would be present if a lower melting point were used. We tested melting point this way for two reasons: (1) to eliminate the difference in thermophysical properties for PCM materials designed for higher or lower melting point, and (2) to avoid the risk of freezing the pipes at the laboratory when simulating cold attic temperatures. A graphical depiction of the test chamber and instrumentation is shown in Figure 7.

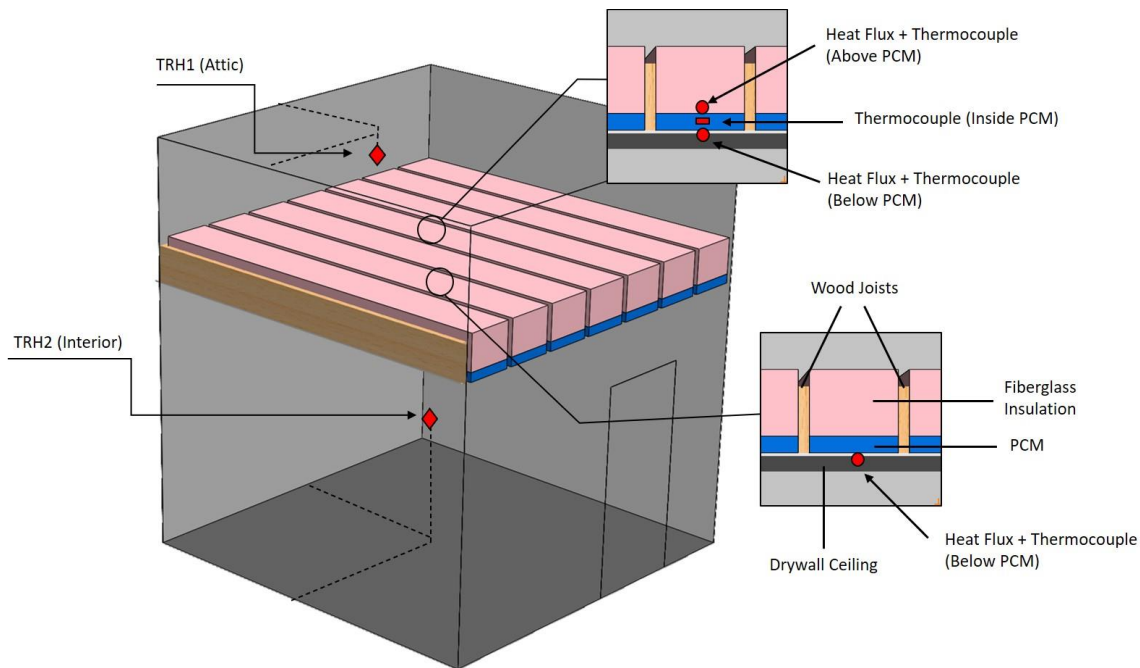


Figure 7. Instrumentation used for PCM testing in the BSRL indoor environmental chamber.

The representative attic temperatures applied in the test were selected from typical summer and winter days measured at one of the field test houses in Santa Rosa (Site 56). The daily attic temperature swings based on field test data were larger in summer (69°F) than in winter (50°F) but were sufficiently large in both seasons to freeze and melt the PCM. The indoor temperatures used in the test were the CEC's Title 24 hourly set points specified in the 2019 Residential ACM Reference Manual (CEC 2019). These temperature profiles, along with the tested PCM melting points, are shown in Figures 8 and 9 for cooling and heating seasons respectively.

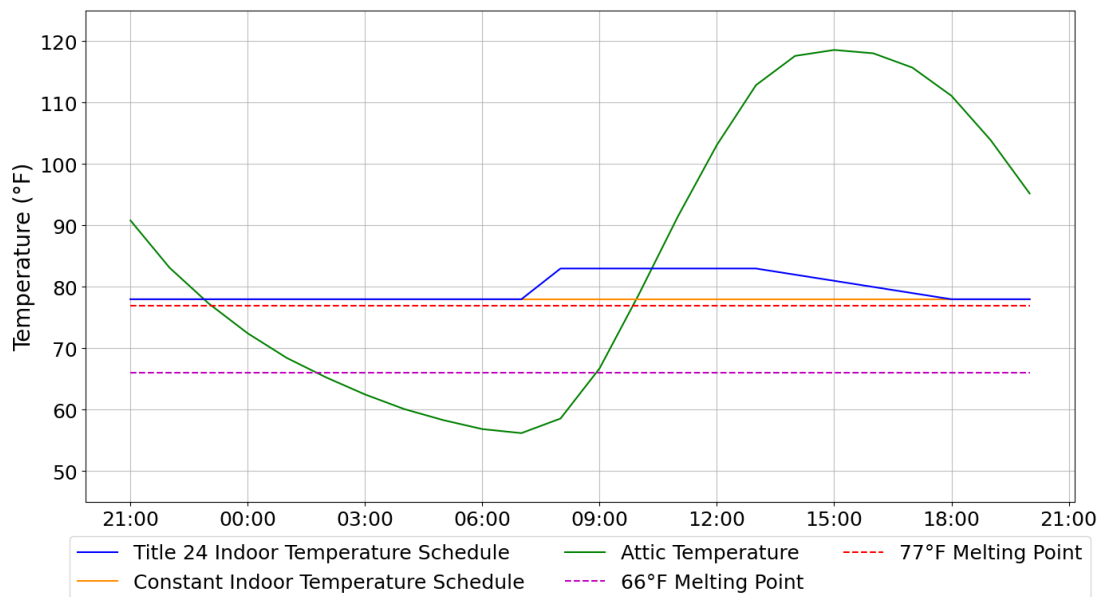


Figure 8. Cooling season lab test temperature profiles.

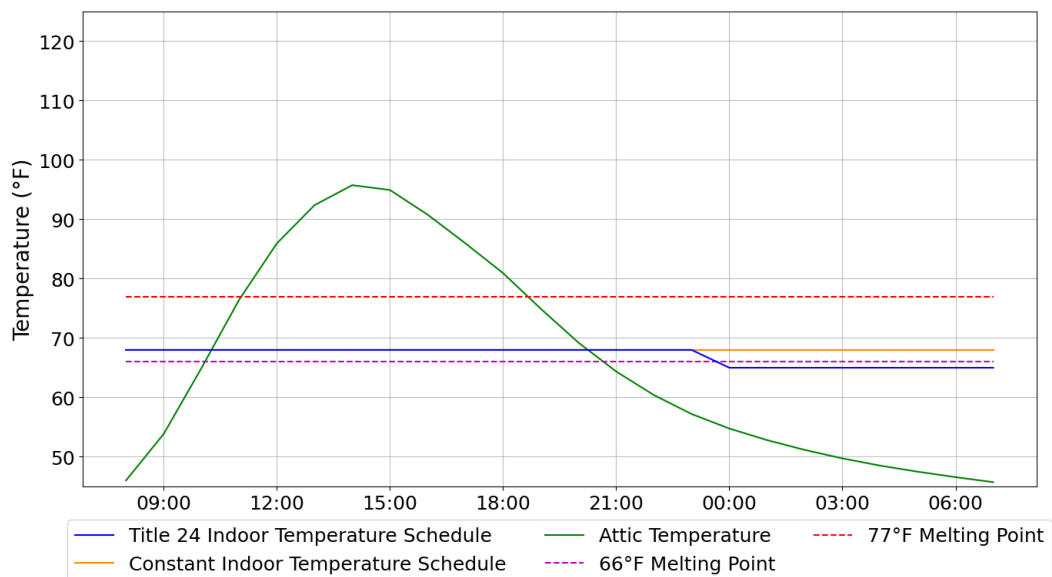


Figure 9. Heating season lab test temperature profiles

The results of lab testing using typical summer conditions show modest cooling load reduction potential of 10-15% compared to the case with no PCM (see Figure 10), with the best-case scenario being 77°F melting point PCM installed above the insulation. PCM installed below the insulation resulted in negative cooling savings, which was a significant concern because four field test sites have PCM installed in this configuration. Gross cooling is the total daily cooling load using only the hours when a cooling load is present. Net cooling includes the effects of both the cooling load (heat transfer from the attic to the interior) and free cooling (heat transfer from the interior to the attic). It is debatable which is more relevant, but the most important metric is the effect on air conditioner energy use, which is best calculated using whole-building energy modeling.

Heating energy savings for the same lab test scenarios are shown in Figure 11. PCM above the insulation provides a small reduction in gross heating, but all PCM configurations result in negative impacts on net heating load. In fact, the sunny winter weather in Sonoma County suggests there is actually no net heating load from the attic to the interior without PCM, because the attic heats up so much during the day.

Sources of uncertainty in lab test results include similar questions about the accuracy of heat flux sensors when placed against rounded PCM packaging that could change shape as it melts and freezes. In addition, the temperature controls for the chamber did not result in perfect repeatability, because the rate of change in attic temperature pushed the limits of the chamber's capacity at times. We do not believe these uncertainties affected the overall conclusions, but it is very difficult to quantify the impact without a much more comprehensive test program than was possible for this project.

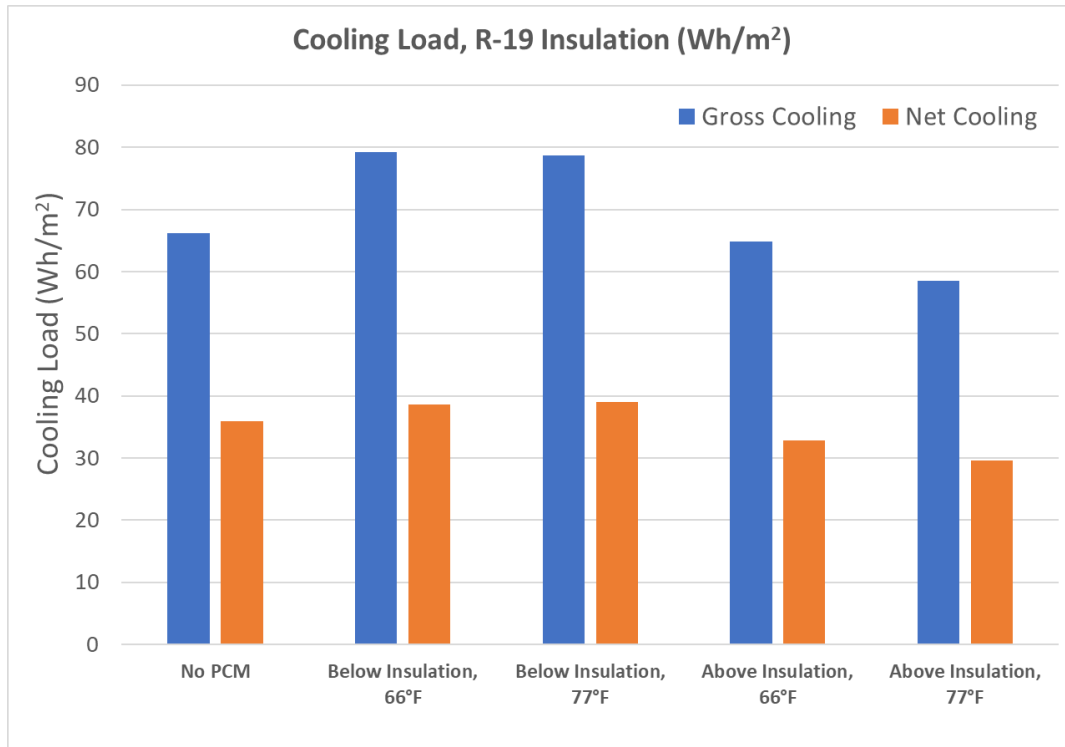


Figure 10. Cooling load reduction for alternate melting points and installation configurations using R-19 insulation and Title 24 thermostat settings.

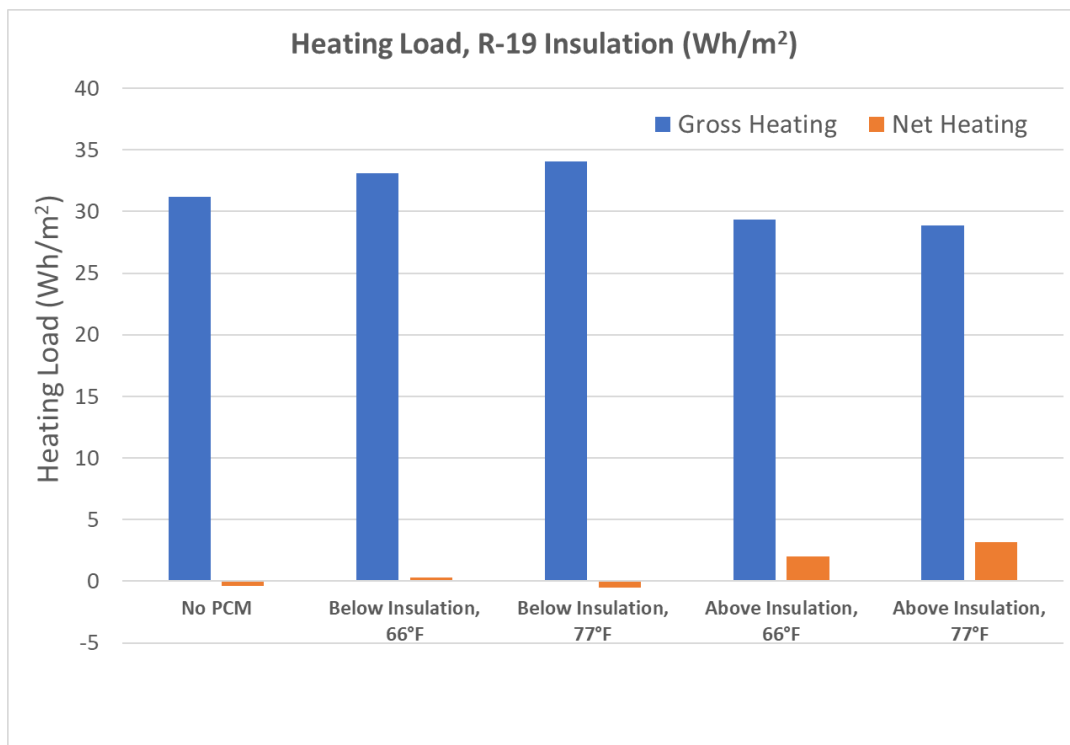


Figure 11. Heating load reduction for alternate melting points and installation configurations using R-19 insulation and Title 24 thermostat settings.

Energy Modeling

We performed modeling of PCM energy savings using the building simulation tool EnergyPlus, partially calibrated using field test data (primarily attic and indoor temperatures) and occupant surveys. We focused primarily on calibration relative to pre-retrofit test results and used the same operating schedules and weather conditions for the post-retrofit models to eliminate any complicating variables other than the PCM when calculating energy savings. We did not calibrate the models to match heat flux or heating and cooling energy because we wanted an independent estimate of PCM energy savings based on modeling of a house that behaves similarly to the test houses before the PCM was installed. We used heat flux as a sanity check on the modeling results but did not force the PCM to match the measured heat flux by changing its properties.

The results for two melting points (73°F and 77°F), and two configurations (above insulation and below insulation) are summarized in Tables 3-5. We used 73°F instead of the 66°F melting point used in lab tests because we had already concluded that 77°F was closer to the optimal value. The results again suggest that PCM actually increases energy use in many applications. One difference compared to the lab test results is the conclusion that PCM below the insulation performs slightly better than above the insulation. The reason is unclear, but the modeling included a full year of diverse weather conditions and the lab testing only looked at a representative day. It is also possible the model wasn't accurately capturing the behavior of the PCM or the house itself, despite our best efforts at calibration. We also performed modeling in the warmer Fresno climate, and the colder Truckee climate, but the results for both heating and cooling were slightly worse than Santa Rosa in both cases.

Table 3. Modeled annual electricity use and utility cost savings for PCM

Case	Base electricity kWh	Base electric utility bill	PCM electricity kWh	PCM electric utility bill	Electricity savings kWh	Electric utility bill savings
PCM above insulation, 73°F melting point	6576	\$2,036	6573	\$2,037	3	-\$1
PCM below insulation, 73°F melting point	6576	\$2,036	6560	\$2,032	16	\$4
PCM above insulation, 77°F melting point	6576	\$2,036	6575	\$2,037	1	-\$1
PCM below insulation, 77°F melting point	6576	\$2,036	6469	\$1,995	107	\$41

Table 4. Modeled annual natural gas use and utility cost savings for PCM

Case	Base gas therms	Base gas utility bill	PCM gas therms	PCM gas utility bill	Gas savings therms	Gas utility bill savings
PCM above insulation, 73°F melting point	392	\$632	407	\$659	-15	-\$26
PCM below insulation, 73°F melting point	392	\$632	404	\$654	-12	-\$21
PCM above insulation, 77°F melting point	392	\$632	407	\$659	-15	-\$27

PCM below insulation, 77°F melting point	392	\$632	406	\$658	-14	-\$25
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Table 5. Modeled annual total utility cost savings for PCM

Case	Base total utility bill	PCM total utility bill	Total utility bill savings
PCM above insulation, 73°F melting point	\$2,668	\$2,696	-\$27
PCM below insulation, 73°F melting point	\$2,668	\$2,686	-\$17
PCM above insulation, 77°F melting point	\$2,668	\$2,696	-\$28
PCM below insulation, 77°F melting point	\$2,668	\$2,652	\$16

The cost analysis for all test homes is summarized in Table 6. Actual costs included several items that are not likely to be part of the projected cost of installing PCM once it reaches the deployment stage, with multiple trained contractors located in Santa Rosa, and more accurate PCM quantities aligned with the needs of each home. The final cost-effectiveness calculation based on the best-case scenario from energy modeling (\$16/year) and long-term predicted installation and material costs of \$6,341 per site is a payback period of 396 years. As a result, we did not recommend this PCM technology for further deployment through SCP's energy efficiency and demand response programs.

Table 6. Average installation and material costs for the tested PCM product

	Site 52	Site 54	Site 56	Site 53	Site 55	Average
Actual Material Costs for PCM	\$3,300	\$3,204	\$2,848	\$1,384	\$2,895	\$2,726
Actual Installation Cost (Including hotel and 20% of administrative costs, shared materials, learning curve)	\$7,017	\$6,684	\$8,589	\$6,631	\$6,878	\$7,160
Projected Material Costs for PCM for Homeowners (75%)	\$2,475	\$2,403	\$2,136	\$1,038	\$2,172	\$2,045
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	\$4,210	\$4,010	\$5,153	\$3,979	\$4,127	\$4,296
Total Projected Cost at Deployment	\$6,685	\$6,413	\$7,289	\$5,017	\$6,299	\$6,341

Conclusions

This project evaluated the performance of salt based PCM mats above and below attic insulation as a potential residential retrofit measure in SCP service territory. Three methods of evaluation were used: (1) field testing in five homes, (2) laboratory testing under controlled conditions using simulated attic and interior spaces, and (3) energy modeling calibrated to field and laboratory test results. Each method offered its own benefits and drawbacks, but also aided in the interpretation of results using other methods.

Field testing, lab testing, and energy modeling all indicate that significant energy savings is unlikely in the mild Sonoma County climate. Reductions in free heating on sunny winter afternoons and free cooling during cool summer nights can equal or outweigh direct reductions in heating and cooling load for the PCM. This effect was also evident in our lab testing of additional attic insulation with no PCM, suggesting that better attic insulation may at times be counterproductive from an energy savings standpoint in the unique Sonoma County climate, though it would still reduce peak loads. PCM leakage and water accumulation observed at the end of field testing presented manufacturing and durability concerns for the tested product.

Lab testing indicates that PCM above the insulation performs better than PCM below the insulation, while energy modeling predicts the opposite. The impact of PCM is relatively small in either case, and the difference may be due to modeling inaccuracies, limitations of the PCM algorithm in EnergyPlus, or inaccurate heat flux readings when flat sensors are placed against melting and freezing PCM packaging. A melting point of 77°F appears to be near the optimum value for the Sonoma County climate. PCM seems to have more potential for reducing cooling energy use than heating energy use.

At this time, poor expected cost-effectiveness of the PCM technology combined with durability issues experienced at the test sites makes this technology unattractive for investment in full-scale deployment for residential attic applications through SCP incentive programs.

References

- Biswas, K., S. Shrestha, N. Josefik, A. Nelson, L. Stephenson, J. Lattimore, and R. DeVries. 2016. *Field Demonstration of an Attic Retrofit Strategy Using Cellulose Insulation and Phase-Change Material*. Buildings XIII Conference. ASHRAE.
- CEC. 2019. 2019 *Residential Alternative Calculation Method Reference Manual*. Sacramento, CA: California Energy Commission. Retrieved from California Energy Commission: www.energy.ca.gov/sites/default/files/2020-10/2019%20Residential%20ACM%20Reference%20Manual_ada.pdf.
- Childs, K., and T. Stovall. 2012. *Potential Energy Savings Due to Phase Change Material in a Building Wall Assembly: An Examination of Two Climates*. Oak Ridge National Laboratory.
- Gibson, S. 2022. *The Potential of Phase Change Materials*. Retrieved from Green Building Advisor: www.greenbuildingadvisor.com/article/phase-change-materials-a-promising-building-technology.

- James, B., and P. Delaney. 2012. *Phase Change Materials: Are They Part of Our Energy Efficient Future?* 2012 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE.
- Kosny, J., D. Leuthold, A. Desjarlais, D. Yarbrough, K. Wilkes, and A. Syad. 2006. *PCM-Enhanced Cellulose Insulation Thermal Mass in Lightweight Natural Fibers*. Oak Ridge, TN: Oak Ridge National Laboratory.
- Kosny, J., N. Shukla, and A. Fallahi. 2013. *Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climates*. Fraunhofer CSE. Washington, DC: U.S. Department of Energy.
- Miller, W., S. Skrestha, K. Childs, and E. Stannard. 2012. *Field Study and Energy-Plus Benchmarks for Energy Saver Homes having Different Envelope Designs*. ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE.
- Southern California Edison. 2012. *Phase Change Materials for Building Cooling Applications*. Los Angeles, CA: Southern California Edison. <https://phasechange.com/wp-content/uploads/2020/07/ETCC-PCM-for-Bldg-Cooling-Applications-Dec-2012.pdf>.