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Phase Change Materials in Residential Applications Final Report

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PREFACE

Project Overview

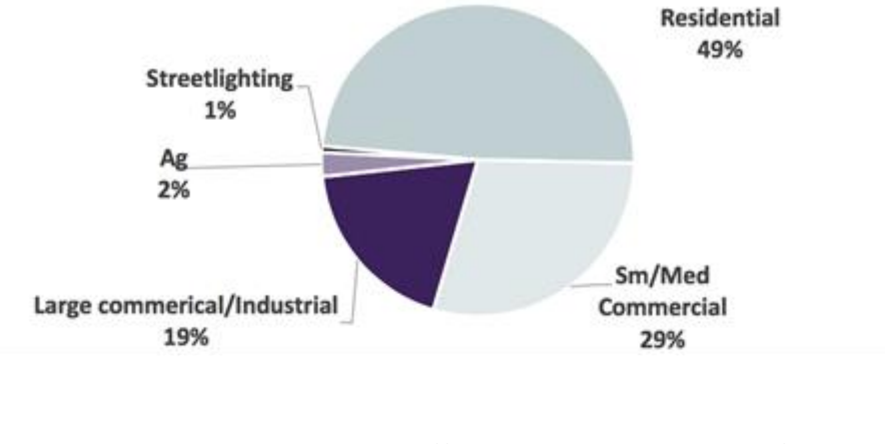
Sonoma Clean Power's (SCP) "Lead Locally" project, funded through the California Energy Commission's (CEC) GFO-17-304 aims to identify strategies and technologies that can assist with the State's goals of doubling the efficiency of existing buildings by 2030. The Project includes applied research and technology deployment activities, each of which will propose innovations that could stimulate the energy efficiency market. With the applied research work, the team is investigating a series of innovative technologies that have the potential to be integrated into existing program models. Lessons learned from the applied research projects will be funneled directly to consumers, contractors, real estate professionals, and building officials through SCP and its local partner organizations. The technology deployment work is driven in part through the SCP Advanced Energy Center (AEC), a physical storefront where consumers can directly procure energy efficient products and services. The AEC has the potential to speed deployment of energy efficiency, make energy efficiency programs more accessible to all customers, and increase customer knowledge of energy efficiency and energy code requirements.

About Sonoma Clean Power and its Customers

SCP is a public power provider operating as a Community Choice Aggregator (CCA) and is the default electricity provider for Sonoma and Mendocino Counties. SCP exists to provide broad public benefits relating to affordability, reliability, climate change and sustainability, coordination with local agencies, customer programs, and to support the local economy. The default service for SCP customers is CleanStart, which provides customers with 45% renewable power and 87% carbon free power (2017 Climate Registry certified values). SCP customers also have the option to select EverGreen service, which is 100% renewable power produced entirely within the SCP service area.

SCP serves just over 220,000 accounts, of which 86% are residential accounts. On an annual basis, SCP's load is comprised of about 50% residential energy use as shown in Figure P-1.

Figure P-1. SCP Customer Load for 2017



SCP, its employees, agents, contractors, and affiliates maintain the confidentiality of individual customers' names, service addresses, billing addresses, telephone numbers, email addresses, account numbers, and electricity consumption, except where reasonably necessary to conduct SCP's business or to provide services to customers as required by the California Public Utilities Commission (CPUC). SCP shall not, under any circumstance, disclose customer information for third-party telemarketing, e-mail, or direct mail solicitation. Aggregated data that cannot be traced to specific customers may be released at SCP's discretion.

Any questions or concerns regarding the collection, storage, use, or distribution of customer information, or those who wish to view, inquire about, or dispute any customer information held by SCP or limit the collection, use, or disclosure of such information, may contact Erica Torgerson, Director of Customer Service, via email at etorgerson@sonomacleanpower.org.

Project Team, Roles and Responsibilities

The applied research team was comprised of the following parties (referenced in this document as the Team), with roles and responsibilities outlined below.

Sonoma Clean Power served as the prime coordinator with the CEC, and was responsible for identifying project sites, initial outreach to customers, and reporting Project progress to the CEC.

Frontier Energy's lead roles were management of the applied research activities and associated subcontractors, execution of laboratory testing, installation of instrumentation at test sites, analysis of monitored data, energy modeling, and technical reporting.

DNV provided independent Evaluation, Measurement, and Verification (EM&V) for the Project, specified required measurement points and accuracy levels for the instrumentation package, and evaluated performance relative to the metrics for success.

California Lighting Technology Center managed the commercial daylighting project, selected and evaluated daylighting technologies in both laboratory and field test settings, and assisted in extrapolating field performance to estimate energy savings and peak electricity demand reduction for other space types and locations across California.

Winwerks/Insolcorp served as the vendor for phase change materials and provided informal design guidance, installation training, and field test support throughout the project.

Huvco served as a vendor for daylight enhancement technologies and provided informal design guidance and field test support throughout the project. Additional product vendors joined the Team and provided support as the Project proceeded.

ABSTRACT

This report documents the results of an applied research project to evaluate the energy performance, cost-effectiveness, and durability of macro-encapsulated phase change materials (PCMs) installed in residential attics in Sonoma County, California. The project was part of Lead Locally, an initiative managed by Sonoma Clean Power and funded primarily by the California Energy Commission. PCM has showed potential for significant energy savings and load shifting in other applications but is unproven in the context of residential attics. The project consisted of field testing in five occupied houses, laboratory testing in Davis, California, and calibrated building simulations to extrapolate the results to other applications and climate regions. The results indicate that the PCM product used for this project, given the mild weather conditions observed in Sonoma County, does not provide sufficient energy savings to justify the initial cost. There were also durability concerns with the product that prevented the project team from incentivizing the installation of residential PCM during the deployment phase.

Keywords: (phase change materials, Infinite R, retrofit measures, existing homes, residential attics, energy storage, peak load reduction, Lead Locally, Sonoma Clean Power)

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EXECUTIVE SUMMARY

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. U.S. drywall manufacturers have made unsuccessful attempts to enter the market with gypsum board containing PCMs. Seeking a way to incorporate it in existing homes the project team identified a new product called Infinite R™ sold by Insolcorp that appeared promising based on its ability to be easily installed above ceilings of existing homes (see Figure ES-1).

Infinite R 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, Infinite R is much less costly to install in existing homes. This PCM format offers a low-cost option that is appropriate for retrofit applications because it can be easily installed between ceiling drywall and attic insulation. This product can be designed to melt and freeze at any temperature in the 66-84°F range and is of greatest value in shifting summer peak loads and reducing electricity demand. By reducing indoor temperature swings in both seasons, it has the potential to reduce energy use by minimizing heating and cooling thermostat calls.

Figure ES-1: Insolcorp Infinite R PCM mat

The objective of this applied research project was to characterize the energy savings for PCM installed in residential attics and to determine its cost-effectiveness and viability for further deployment efforts. 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 the Sonoma Clean Power (SCP) service territory, which includes Sonoma and Mendocino Counties. This region of California experiences relatively mild weather conditions in both summer and winter, but also has large daily temperature swings. 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 ES-1, including information about the PCM installed at each site.

Table ES-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

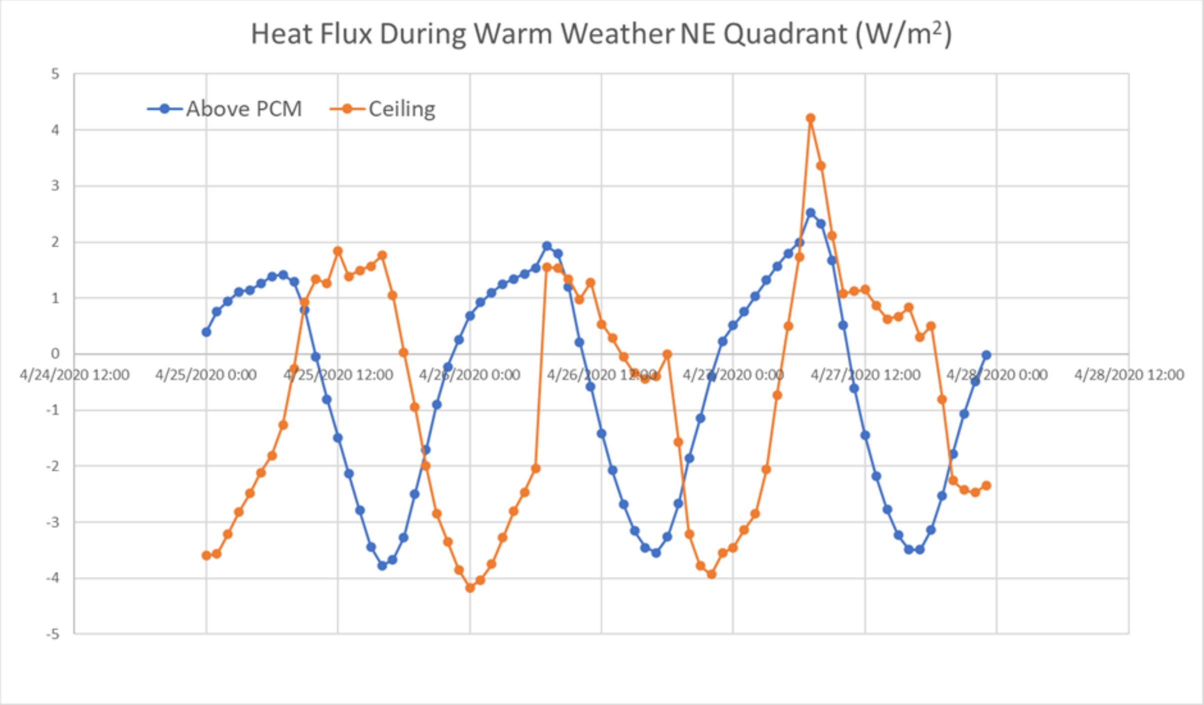
We monitored each house for about 9 months prior to the PCM retrofit to develop a baseline. A contractor installed the PCM in December 2019, and we performed another 9-10 months of monitoring. We conducted homeowner surveys at the end of each monitoring period, and SCP and Pacific Gas & Electric (PG&E) 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)

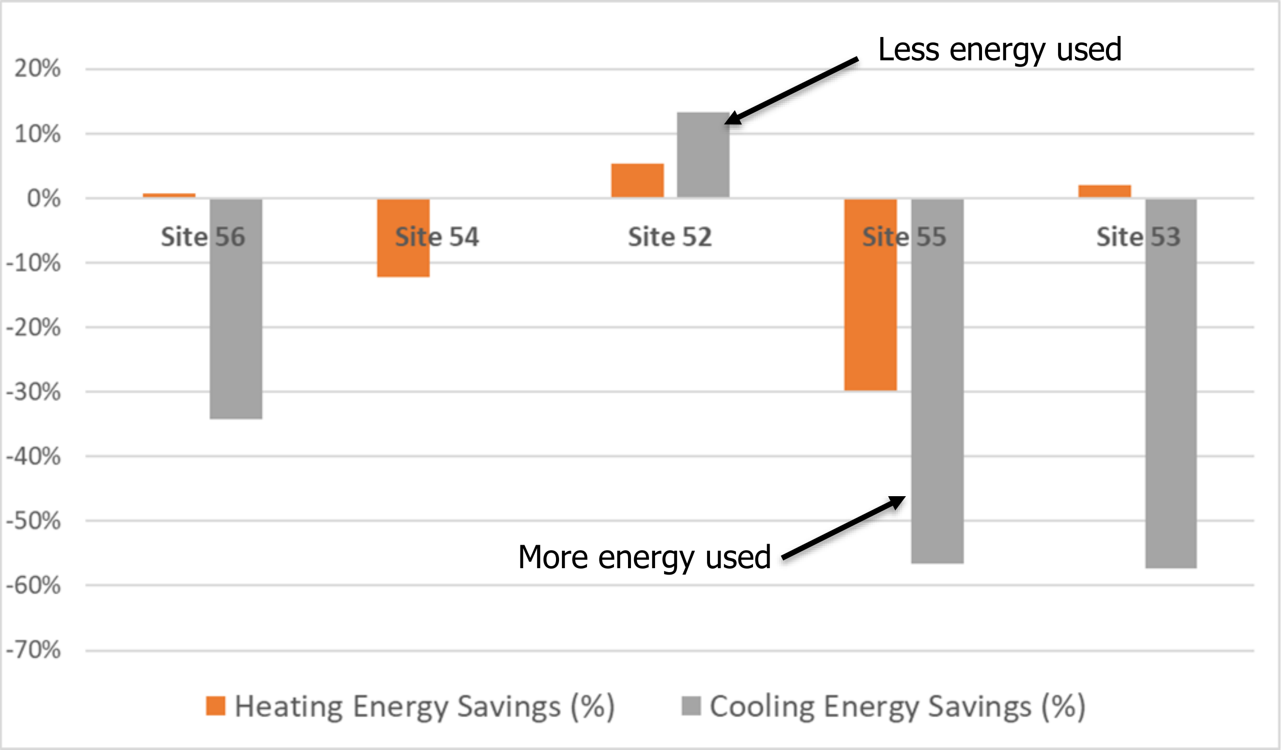
We ultimately judged that the heat flux measurements across the PCM were not reliable for the field test sites, due to apparent data conversion errors by a company that provided data collection and storage services for the project, along with measurement inaccuracy resulting from expansion and contraction 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 ES-2 shows heat flux readings from sensors on each side of a PCM mat positioned above the ceiling during a 3-day warm period in April 2020. Positive heat flux is upward from the interior to the attic. The heat flux occurs in opposite directions above and below the PCM, indicating that the PCM was melting (absorbing heat) during mid-day and solidifying (releasing heat) at night over this period.

Figure ES-2: Site 56 heat flux in and out of PCM from Apr 25-27, 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 at the outdoor and indoor air conditioning or heat pump units, and a gas meter at the furnace. Figure ES-3 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. 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 occupancy and behavior changes raises additional challenges when interpreting the field test results. Unfortunately, the energy use data does not support the hypothesis that the PCM reduced heating season energy use, and contrary to expectations the data show an increase in summer cooling energy at several sites.

Figure ES-3: Heating and cooling energy savings for 5 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 tool that performed regression analysis of whole-house energy use as a function of heating and cooling degree days. 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 ES-2.

Table ES-2: Weather normalized utility billing data at 5 test sites (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%**

Durability issues arose for the PCM material when two test sites reported numerous leaks about 18 months after installation (see Figure ES-4), and a contractor discovered leaks at a third site that weren’t evident until 27 months after installation. Some of the leaks consisted of PCM leaking out of pinhole sized 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 likely water extracted from the air because of hydrophilic salt residue on the surface of the PCM mats (see Figure ES-5) based on explanations from the factory that manufactured Infinite R. 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 ES-4: PCM mat with multiple leaks near scuff marks from Site 54

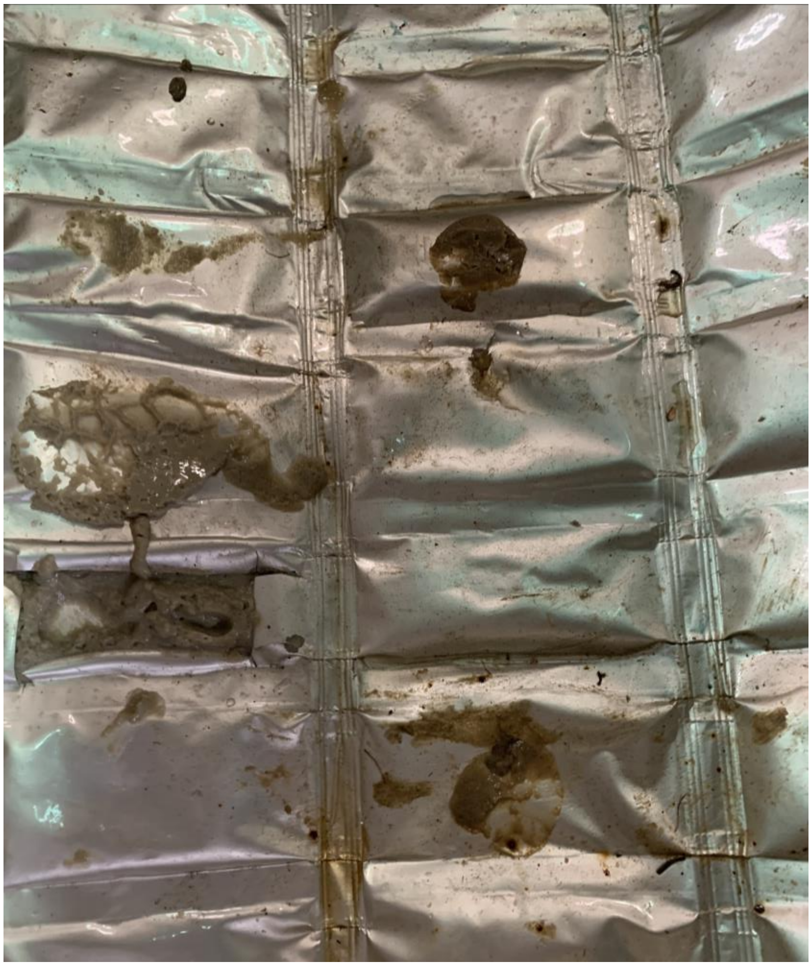
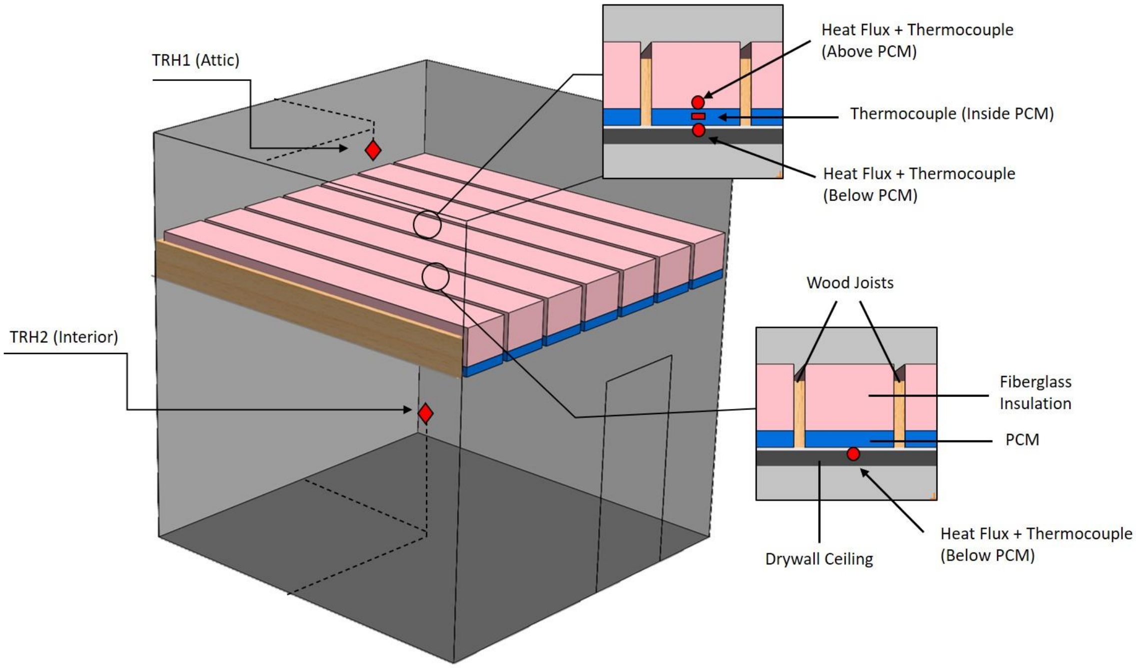


Figure ES-5: PCM mat with water accumulation

Lab Testing

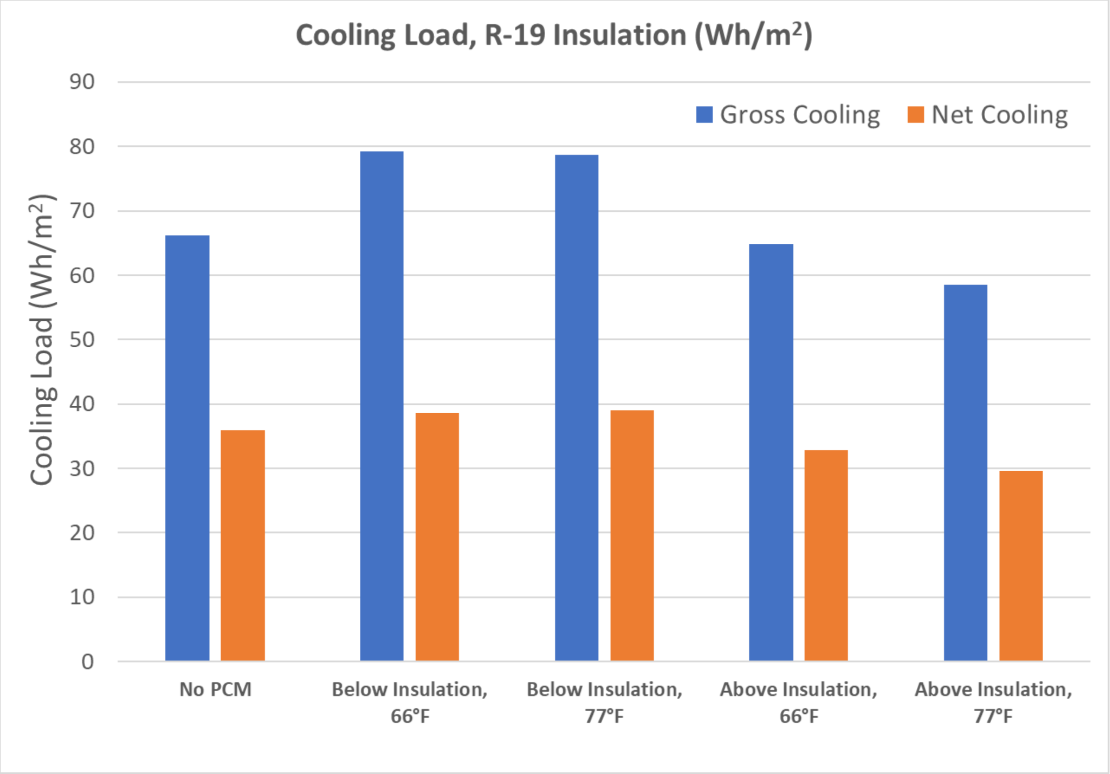
We also tested the PCM in one of the environmental chambers at the Frontier Energy Building Science Research Laboratory (BSRL). We configured the test chamber with a simulated attic that could be controlled separately from the interior space. Lab testing provided an opportunity to remove both weather and occupant behavior from the evaluation through strict control over the temperature profiles. We conducted tests using typical summer and winter attic temperature profiles obtained from field tests and using interior thermostat settings based on Title 24 modeling guidelines. We performed lab tests using a variety of PCM installation configurations, attic insulation levels, and simulated melting points. We simulated the different melting points using 84F PCM and adjusting all chamber temperatures upward or downward to create the temperature differences that would be present if a different 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 ES-4.

Figure ES-4: Instrumentation used for PCM testing in the BSRL indoor environmental chamber



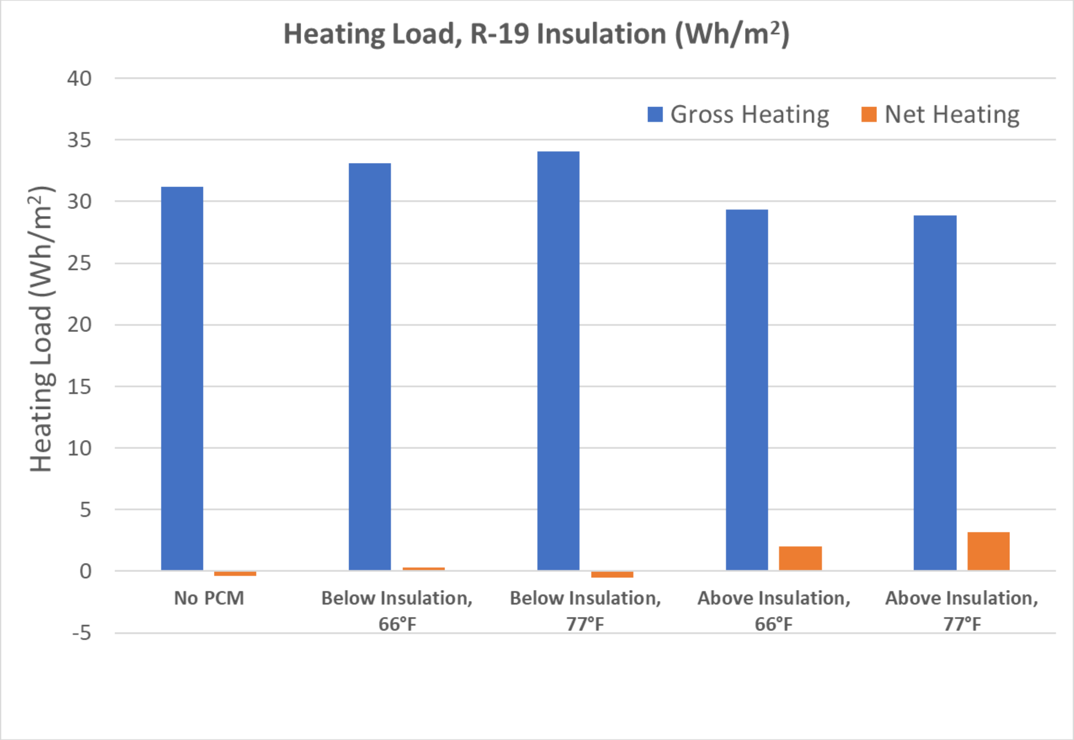
The results of the lab testing show modest cooling savings potential of 10-15% compared to the case with no PCM (see Figure ES-5), with the best-case scenario being 77°F melting point PCM installed above the insulation. PCM installed below the insulation resulted in negative cooling savings, which was 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.

Figure ES-5: Cooling load reduction for alternate melting points and installation configurations using R-19 insulation and Title 24 thermostat settings



Heating energy savings for the same lab test scenarios are shown in Figure ES-6. 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.

Figure ES-6: 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 ES-3 through ES-5. We used 73°F instead of the 66F melting point used in lab tests because we had already concluded that 77°F was closer to the optimal value, and we wanted to narrow it down further. 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. We also performed modeling in the warmer Fresno climate, and the colder Truckee climate, but the results were even less encouraging.

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

Case	Base Elec kWh	Base Elec Utility Bill	PCM Elec kWh	PCM Elec Utility Bill	Elec kWh Savings	Elec 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 ES-4. Modeled 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 Therms Savings	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

Table ES-5. Modeled 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 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 do not recommend this PCM technology for further deployment through Lead Locally. However, it is possible that there may be a more favorable combination of house design, thermostat settings, melting point, and climate zone that we did not test or simulate.

Conclusions

Several key conclusions were drawn from this applied research project:

- Field testing, lab testing, and energy modeling all indicate that the energy savings potential is small in the mild Sonoma County climate and may even be negative in some applications.
- 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 saving standpoint in the unique Sonoma County climate, though it would still reduce peak loads.
- PCM appears to have more potential for reducing cooling energy use than heating energy use.
- Lab testing indicates that PCM above the insulation performs better than PCM below the insulation, while energy modeling predicts the opposite.
- A melting point of 77°F appears to be near the optimum value for the Sonoma County climate.
- PCM leakage and water accumulation observed at the end of field testing present manufacturing and durability concerns for the Infinite R product.
- At this time, the 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 the Advanced Energy Center.

CHAPTER 1: Introduction

1.1: Background

The Lead Locally Grant is an innovative programmatic approach to existing buildings research, development and demonstration that includes a range of innovative technologies, program features, and market strategies to engage new customers in energy efficiency upgrades and deliver benefits to California's electric ratepayers. The Grant is led by Sonoma Clean Power (SCP) under funding by the California Energy Commission (CEC) through the Electric Program Investment Charge (EPIC) program. SCP offers Community Choice Aggregation, providing electricity to 189,000 residential and 31,000 commercial customers in Sonoma and Mendocino Counties. This robust existing building initiative also serves to complement current fire recovery efforts in Sonoma and Mendocino Counties, enabling SCP programs to have impact far and beyond the scope of this project.

The applied research portion of Lead Locally focused on several innovative technologies that are being evaluated through laboratory and field testing with the objective of expanding the portfolio of cost-effective retrofit options available to SCP and other energy efficiency program administrators. These applied research projects have been designed to help remove uncertainty around the installed performance and cost of the technology, especially in combination with other retrofit measures, prior to broad deployment of the technology through the Lead Locally Advanced Energy Center (AEC). Lead Locally has focused on adapting proven technologies and concepts to new applications by optimizing their performance in creative ways, providing building owners and contractors with the knowledge and tools they need to select the right applications, and installing the technologies in a manner that yields the expected energy savings.

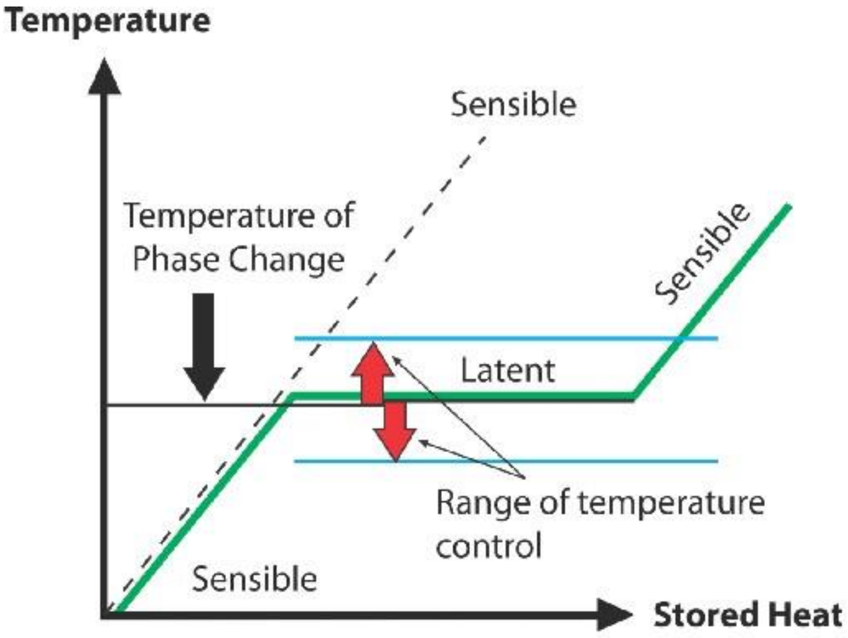
Four applied research projects were split into Phase 1 and Phase 2 technologies, allowing accelerated planning and preparation for the projects with the tightest timelines. Phase 1 technologies included radiant panels with air-to-water heat pumps and enhanced commercial daylighting. Phase 2 technologies included efficiency optimizing control strategies for grid interactive heat pump water heaters and attic-mounted phase change materials (PCMs) for residential buildings. This report documents the results from laboratory testing of PCMs under controlled conditions, field testing of PCMs in five pilot homes, and modeling of PCMs to extrapolate savings to other house types and climates based on the lab and field test results.

1.2: Technology Overview

When a liquid evaporates and changes state to become a gas or when a solid melts and is converted to its liquid state, heat energy is absorbed. The converse is true when the change of state is in the opposite direction, that is, the substance gives up heat to its environment. It is this change in state that is used by evaporative coolers that evaporate water, and air conditioners and heat pumps that the change the state of a refrigerant between liquid and gas to maintain indoor comfort.

The quantity of thermal energy involved in the change of state is referred to "latent" heat, as distinguished from "sensible" heat, which is the heat involved in changing the temperature of a material but not changing its state. PCMs are materials that absorb heat as they melt and release heat as they solidify or freeze. The most common example of a solid PCM is ice, but there are many other materials in everyday life that melt at a variety of temperatures, including wax, plastic, and even most metals. Unlike traditional materials used in buildings to add thermal mass such as concrete and masonry, energy storage through phase change occurs over a relatively constant temperature and requires much less volume. The phase change phenomenon is illustrated in Figure 1.

Figure 1: Latent and sensible heat storage in PCMs



Credit: RGEES (https://rgees.com/technology.php)

PCM melting points can be tuned to match the needs of the application, making PCMs an appealing technology for use in building envelopes, including in walls and attics. PCMs do not contribute to the R-value of the building envelope in any significant way, but when installed adjacent to the insulation, the PCM can reduce the temperature difference across the insulation while it freezes or melts, thereby reducing heat transfer into or out of the conditioned space. Three conditions must be met to take advantage of the PCM in a building application:

1. The PCM must be exposed to temperature changes on both sides of its melting point over the course of the day.
2. The duration of these temperature swings must be long enough to freeze and melt the PCM at least partially.

3. The heat transfer rate to and from the PCM must be fast enough to melt and freeze it within the duration of the temperature swing.

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 (James & Delaney, 2012). Products range from PCM embedded in wallboard to thin sheets with encapsulated PCM cells. Past studies have indicated heating and cooling loads in buildings can be reduced by 10-30%, depending on many factors such as the thermal conductivity of the PCM, the melting point selected for the application, and the range of outdoor temperatures. Most applications have focused on commercial buildings, so very little information is available about potential benefits in residential applications, especially in Northern California where the climate is generally milder than other locations. However, the presence of large diurnal outdoor temperature swings in California for much of the year, especially in attics, offered an appealing application for study.

The encapsulated PCM product Infinite R, sold by Insolcorp through Lead Locally partner Winwerks, was the technology selected for evaluation in this project. Infinite R had almost exclusively been used for commercial building applications but has similar potential for certain residential applications with standard wood-framed vented attics. The application of this technology had minimal risk for this technology because the original insulation could remain in place, and the worst-case scenario would be that the PCM would either not melt and freeze consistently or would merely shift load from one time of day to another without significantly reducing peak or total loads.

1.3: PCM Test Product

The PCM that was used during both the laboratory and field-testing phases of the project was an inorganic compound developed by Insolcorp called Infinite R. It is made of hydrated salts, hydrated magnesium aluminum silicate, and hydrated sodium calcium aluminosilicate. The compound is stored and sealed in a multilayer white poly film pocket. The poly film packaging is available in 24” X 48” sheets and 16” X 48” as seen in Figure 2. The PCM can be manufactured with a variety of melting points ranging from 66-84°F and beyond.

Figure 2: Insolcorp Infinite R PCM mat

Image credit: Insolcorp, LLC

The Infinite R PCM sheets have the characteristics and performance values shown in Table 1 and Table 2. Compared to an identical volume of water (which has the highest specific heat of any liquid or solid), the total heat capacity of Infinite R is about 5.8 times greater over its melting temperature range, and it is about 26% lighter. Infinite R is also thin and lightweight and is very fire resistant.

Table 1: Infinite R Physical Properties

Physical Properties	Values
Melting Point	66 - 84°F
Latent Heat	~86 Btu/lb
Thermal Conductivity	~0.09 W/ft/°F Liquid
	~0.18 W/ft/°F Solid
Dimensions	24.5″ X 48″
	16.5″ X 48″
Thickness	0.25″
Weight	0.75 lb/ft^2

Table 2: Infinite R Fire Ratings

Fire Testing	UL 723

Flame Spread	5
Smoke Development	10

Three different installation configurations are possible for PCM in residential attics, as shown in Figure 3 through Figure 5 below. If the PCM is located above the insulation, as shown in Figure 3, the weight of the PCM is partially supported by the ceiling joists so that the insulation is not compacted by the PCM over time. If PCM placement is below the insulation then the existing insulation is removed and the PCM mats are placed directly on top of the drywall, between the ceiling joists. The insulation is then placed directly on top of the PCM sheets as shown in Figure 4. If PCM is installed below the roof deck, then the PCM is placed between the rafters to reduce the magnitude of attic temperature swings, as shown in Figure 5. Only the configurations where PCM is installed above or below attic insulation were studied for this project, because we were advised by Insolcorp that the roof deck application would be unlikely to moderate the attic temperature in a significant way. The attic insulation level should be inspected and upgraded to the current minimum requirement for existing homes in Title 24 for the relevant climate zone (R-19 in Sonoma County), as part of the installation.

Figure 3: Example attic retrofit with PCM above the insulation

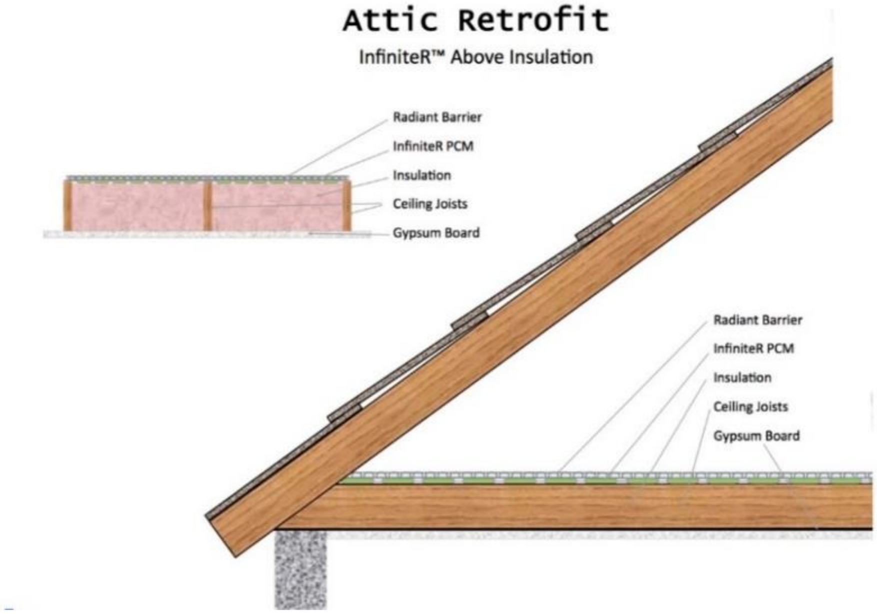


Image credit: Insolcorp, LLC

Figure 4: Example attic retrofit with PCM below the insulation

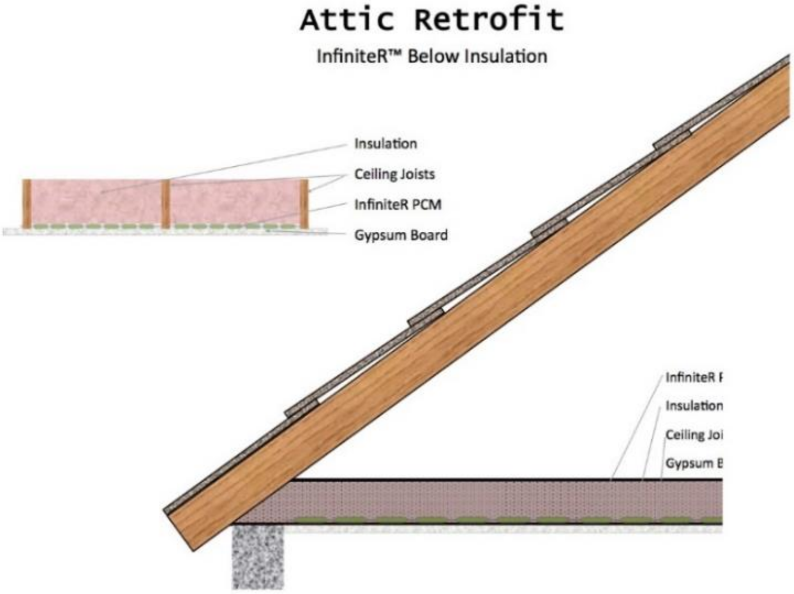


Image credit: Insolcorp, LLC

Figure 5: Example attic retrofit with PCM at the roof deck

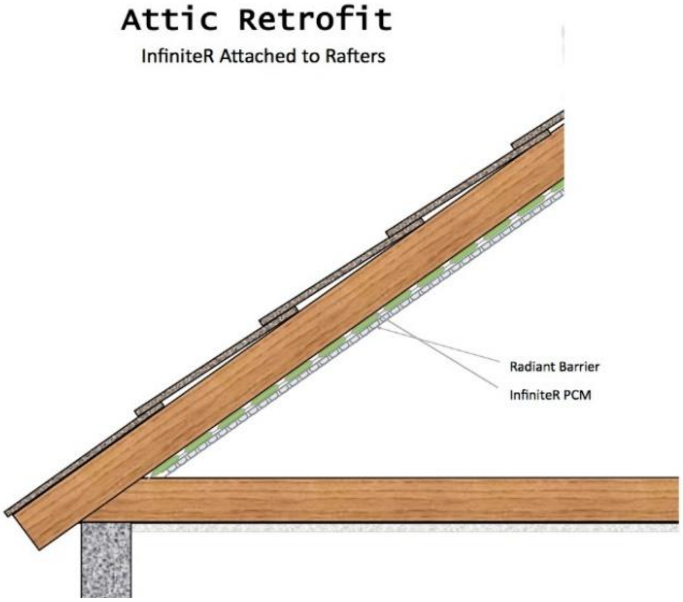


Image credit: Insolcorp, LLC

Numerous standards exist for PCM products, including methods for evaluating thermal properties, fire resistance, and durability. However, these standards do not address the installed performance of PCMs in building applications, including complex interactions with insulation and attic/interior temperatures, which are the focus of this project.

PCMs in residential attics have the potential to provide several benefits:

- **Energy savings**. When installed in an application that allows frequent melting and freezing of the PCM, a significant reduction in the space conditioning load is possible. Some of the heat that would have flowed through the insulation is instead stored as latent heat in the PCM, which is eventually released either into the attic or the interior space. The frequency and extent of phase change depends on several variables, including exterior temperature swings from day to night, heat transfer to the attic through solar gains, roof absorption and reradiation, attic ventilation, PCM location relative to insulation, and indoor thermostat settings.
- **Peak demand reduction**. In theory, energy stored in the PCM can help houses stay cool longer during hot days that follow cool nights. Pre-cooling the house using the air conditioner or a whole-house fan can be used to ensure the PCM fully reaches its frozen state, thereby further extending the number of hours a house can avoid cooling during peak demand periods.
- **Thermal comfort**. PCMs freeze and melt across a narrow temperature range, therefore, the ceiling above the conditioned space should remain cooler during the summer and warmer in the winter whenever the PCM is activated. This can reduce the radiative effects on occupants, increasing thermal comfort.
- **Ease of installation**. PCMs come in flexible mats that can be easily installed above or below insulation with minimal complications except the occasional need to shape the PCM sheets around joists, ductwork, and ceiling penetrations. There are no moving parts, and no other building components need to be replaced or modified (except insulation, depending on the application). Unlike insulation, it is not essential that the PCM covers all hard-to-reach areas of the attic floor.

There are several aspects of PCMs that can negatively affect its performance and cost-effectiveness:

- **Cost.** The cost of purchasing and installing PCMs in a typical 1500 ft^2 attic is in the range of $5,000-$10,000. The amount of energy savings necessary to make this measure cost-effective within a 5-10 year timeframe may be difficult to achieve.
- **Dependence on weather.** To be effective, PCMs require significant diurnal swings to charge and discharge over the course of a day. Most areas in both Sonoma and Mendocino Counties have relatively mild weather, which could greatly reduce the amount of energy that can be stored in the PCM, and the amount of cooling energy that can be saved. Sunny and hot days with clear and cool nights are necessary to achieve optimal performance during the cooling season. Sunny days in winter that can warm the attic to well above the melting point of the PCM are necessary for heating energy savings.
- **Dependence on thermostat settings.** Interior temperatures also have a significant effect on the energy savings potential of PCMs. Occupants that use temperature setup and setback or use a whole house fan will likely see greater energy savings for

configurations where the PCM is placed under the attic insulation. If the melting point is selected to give the best performance for the current occupants, and the house is sold and different thermostat settings are used, the PCM may not perform as well.

- **Verified durability.** PCMs have rarely been used in residential applications, and the long-term durability of commercially available products has not been verified in homes.
- **Unfamiliarity.** Most home contractors and trades have minimal if any experience with PCMs in residential applications. The energy savings potential of the technology is less intuitive than insulation and may not be readily accepted by homeowners.

1.4: Objectives

The objective of this applied research project was to answer several key research questions related to best practices for design and installation, and readiness of the technology for broad deployment in SCP service territory and throughout Northern California. Several of these questions are provided below, but more specific questions for each phase of the project (field testing, lab testing, modeling) are provided in Chapter 2: Technical approach.

- What is the optimal placement of PCM in residential attic retrofits to maximize the reduction of heating and cooling loads in Sonoma County?
- What is the preferred melting point for the PCM in each configuration?
- Is the heat transfer rate sufficient to fully charge and discharge the PCM under realistic attic conditions?
- What is the heating/cooling load reduction generated by the addition of PCM in vented attic spaces?
- What is the correlation between insulation level and the performance of the PCM?
- What is the cost-effectiveness of PCM added to vented attics in Sonoma and Mendocino Counties?
- Does PCM demonstrate durability and effectiveness after being installed in attic spaces for an extended period?
- Which climates in Northern California provide the best environmental conditions for PCM in attic spaces to achieve significant energy savings?

CHAPTER 2:
Technical Approach

The technical approach for the residential PCM applied research project included three primary components:

- Laboratory testing
- Field testing
- Modeling

These components were complementary, and all three were needed to answer the research questions described in Section 1.4. Details are presented in the following sections, and further discussion of the research plan can be found in the Lead Locally *Phase 2 Research, Instrumentation, and Monitoring Plan* (Hendron, et al., 2019).

2.1 Laboratory Test Approach

Laboratory testing was conducted at Frontier Energy's Building Science Research Laboratory (BSRL) in Davis, California. The purpose of the laboratory testing was to determine the optimal melting point and placement of the PCM in the attic, and to verify the PCM's cooling/heating load reduction potential under controlled conditions. The PCM was evaluated in two configurations: below the ceiling insulation and above the insulation. The PCM manufacturer did not consider the third configuration (under the attic roof deck) as a promising retrofit option when compared to the other two configurations. The impacts of insulation level, summer vs winter attic temperatures, and interior temperature settings were also evaluated.

Research Questions and Success Metrics

The research questions for the laboratory phase of the project included the following:

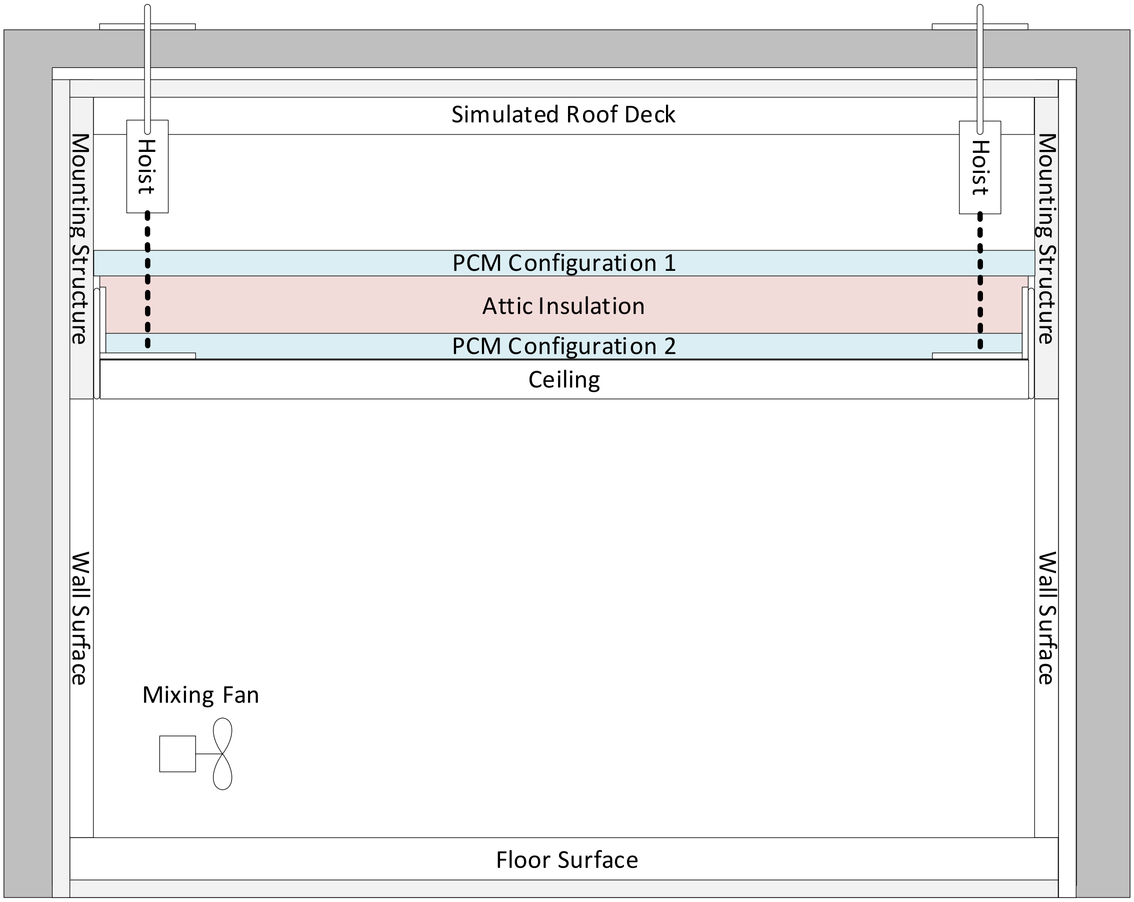
- What is the optimal placement of PCM in residential attic retrofits to reduce heating/cooling loads in Sonoma and Mendocino Counties?
- What is the preferred melting point for the PCM in each configuration?
- Is the heat transfer rate sufficient to fully charge and discharge the PCM under realistic conditions?
- What heating/cooling load reduction can be achieved by the addition of PCM in attics?
- What is the correlation between insulation level and the performance of the PCM?
- How does thermostat setup/setback affect PCM performance?

Test Facility

The BSRL facility has two environmental simulation chambers: one larger chamber that can simulate outdoor conditions and a smaller chamber that is used to simulate indoor conditions and buffer spaces, like attics. A schematic of the small chamber, which was used for testing the PCM mats, is shown in Figure 6. Upgrades to the indoor chamber for Lead Locally included a simulated attic section and addition of radiant panels to all indoor chamber surfaces to control indoor and attic air temperatures independently. For the PCM testing, the attic portion of the chamber was temperature controlled by a hydronic fan coil unit that simulated the ambient air temperature of a vented attic. The simulated attic included a moveable wood-framed ceiling assembly to safely allow adjustments to the insulation level and installation of the PCM in various configurations. To ensure there was minimal air exchange between the attic and the interior zones, the perimeter of the attic assembly was sealed against a gasketed surface on the mounting structure during the test. Indoor air temperatures were controlled using a second fan coil at the floor of the chamber, which proved to be necessary because the radiant panels were not able to change temperatures rapidly enough. The mixing fans were directed away from the attic assembly to limit the amount of convective heat transfer.

Instrumentation upgrades for the PCM lab tests included a National Instruments Compact DAQ system and a redundant data backup system for data acquisition and controls. A variety of heat flux and temperature sensors, described later in this section, were installed to characterize the performance of the PCM.

Figure 6: Diagram of PCM configurations in the BSRL indoor environmental chamber



Test Overview

Two PCM configurations were tested, along with two levels of insulation, two melting points, and attic temperatures representing realistic conditions for an average heating day and cooling day in Climate Zone 2. Control cases were also run with no PCM installed. It was not necessary to test every combination, because some combinations are of minimal interest (e.g. cases where no freezing or melting occurs). Below are the various cases that were tested.

- PCM configurations – above ceiling insulation, below ceiling insulation
- Insulation levels – R-19, R-38
- PCM Melting Points – 66°F, 77°F
- Typical cooling and heating day attic temperatures
- Indoor temperature – constant, setup/setback

Insulation Levels

Two levels of insulation were tested to compare the effectiveness of the PCM when installed in both retrofit projects and new construction. The two levels of insulation were determined based on the minimum attic insulation required for alterations (R-19) and for new housing (R-38) outlined in the 2019 update to California Title 24, Part 6, for Climate Zone 2 (CEC, 2019).

In addition to testing two levels of insulation, the position of the PCM in relation to the insulation was tested. As previously mentioned, the manufacturer of the PCM provided three placement options when installing their product: along the roof deck, under the insulation, and above the insulation. The manufacturer advised based on their own analysis that installing the PCM along the roof deck would be the least effective location of the three. Thus, a variety of tests were conducted to compare the energy savings when installing the PCM either above or below the insulation.

Simulated Melting Points

Purchasing PCM with multiple melting points for every test scenario could have introduced uncertainty in the results, because the thermophysical properties and chemical composition of the PCM changes based the targeted melting point. Although we wanted to isolate the effect of melting point independent of chemical composition, and we were primarily interested in comparing PCMs with melting points of 77°F and 66°F, we chose an 84°F melting point for all tests, and the indoor and attic temperatures were shifted by the difference between the melting point installed in the chamber relative to the desired melting point. For example, if a test of PCM with a melting point of 77°F was desired, we used PCM with a melting point of 84°F but shifted the attic and indoor temperatures up by 7°F so the temperature differences of the test (and consequently all heat flows) would be consistent with a 77°F melting point. Similarly, the 66°F melting point was tested using an 18°F shift in attic and indoor temperatures. Multiple melting points could be simulated using this method because every melting point offered by Insolcorp has approximately the same material properties shown in Table 1. The enthalpy curves for each of the melting points differed slightly, but this difference was small enough that the test results were unlikely to be significantly affected. However, one test was run using actual 77°F melting point PCM for comparison with 84°F PCM with temperature adjustments to simulate a 77°F melting point.

An additional benefit of using a single 84°F melting point with chamber temperatures shifted upward by 7-18°F was that the water temperature delivered to the chamber remained well above freezing. Actual attics in Sonoma County drop below 45°F on occasion, but a glycol mix would have been required to maintain such cold temperatures in the simulated attic portion of the test chamber. This would have added significant cost and complexity to the test set-up and would have required a system cleanout prior to conducting tests for other projects.

Temperature Profiles

Indoor and attic temperatures were chosen to best represent a typical home in the Santa Rosa climate for a typical winter and summer day. The indoor temperatures used in the test were the California Energy Commission's (CEC's) Title 24 hourly suggested set points outlined in the 2019 Residential ACM Reference Manual (CEC, 2019, p. 70), which are presented in Table 3. These higher indoor daytime temperatures and cooler nighttime temperatures have the potential to increase energy savings for PCM, because they can enhance the nighttime freezing and daytime melting processes driven by diurnal attic temperature cycles.

Table 3. Hourly Thermostat Set Points (CEC, 2019, p. 70)

Hour	Cooling	Heating	Hour	Cooling	Heating
1:00 AM	78 °F	65 °F	1:00 PM	83 °F	68 °F
2:00 AM	78 °F	65 °F	2:00 PM	82 °F	68 °F
3:00 AM	78 °F	65 °F	3:00 PM	81 °F	68 °F
4:00 AM	78 °F	65 °F	4:00 PM	80 °F	68 °F
5:00 AM	78 °F	65 °F	5:00 PM	79 °F	68 °F
6:00 AM	78 °F	65 °F	6:00 PM	78 °F	68 °F
7:00 AM	78 °F	65 °F	7:00 PM	78 °F	68 °F
8:00 AM	83 °F	68 °F	8:00 PM	78 °F	68 °F
9:00 AM	83 °F	68 °F	9:00 PM	78 °F	68 °F
10:00 AM	83 °F	68 °F	10:00 PM	78 °F	68 °F
11:00 AM	83 °F	68 °F	11:00 PM	78 °F	68 °F
12:00 PM	83 °F	68 °F	12:00 AM	78 °F	65 °F

Since we know these Title 24 recommended set points are not representative of every home, a constant indoor temperature was also used for several tests. For these tests, the indoor temperature was set to a constant 68°F for heating and a constant 78°F for cooling. These tests helped isolate the energy savings of the PCM driven only by fluctuations in attic temperature.

The representative attic temperatures applied in the test (shown in Table 4) were selected from typical summer and winter days measured at one of the field test houses (Site 56). The dates from which these attic temperatures were selected were August 23, 2020 – August 24, 2020, for the cooling tests and February 26, 2020 – February 27, 2020, for the heating tests. The daily 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. However, the extent of freezing and melting can vary significantly depending on the other test parameters.

Table 4. Hourly Summer and Winter Attic Temperatures

Hour	Summer	Winter	Hour	Summer	Winter
1:00 AM	68 °F	53 °F	1:00 PM	113 °F	92 °F
2:00 AM	65 °F	51 °F	2:00 PM	118 °F	96 °F
3:00 AM	62 °F	50 °F	3:00 PM	119 °F	95 °F
4:00 AM	60 °F	49 °F	4:00 PM	118 °F	91 °F
5:00 AM	58 °F	47 °F	5:00 PM	116 °F	86 °F
6:00 AM	57 °F	47 °F	6:00 PM	111 °F	81 °F
7:00 AM	56 °F	46 °F	7:00 PM	104 °F	75 °F
8:00 AM	59 °F	46 °F	8:00 PM	95 °F	69 °F
9:00 AM	67 °F	54 °F	9:00 PM	91 °F	64 °F
10:00 AM	79 °F	65 °F	10:00 PM	83 °F	60 °F
11:00 AM	91 °F	76 °F	11:00 PM	77 °F	57 °F
12:00 PM	103 °F	86 °F	12:00 AM	72 °F	55 °F

To ensure consistent results for every test case, the start times for the heating and cooling tests were chosen when the PCM would likely be fully frozen or fully melted, respectively. Referring to the attic temperature profiles shown in Figure 7 and Figure 8, the test period for the cooling test spanned from 9:00 PM – 8:59 PM (fully melted to start the test) and for the heating test spanned from 8:00 AM – 7:59 AM (fully frozen to start the test). These temperature profiles do not show the upward adjustment that allows the simulation of alternate melting points while avoiding freezing temperatures for the radiant panels, as previously discussed.

Figure 7. Cooling Season Lab Test Temperature Profiles

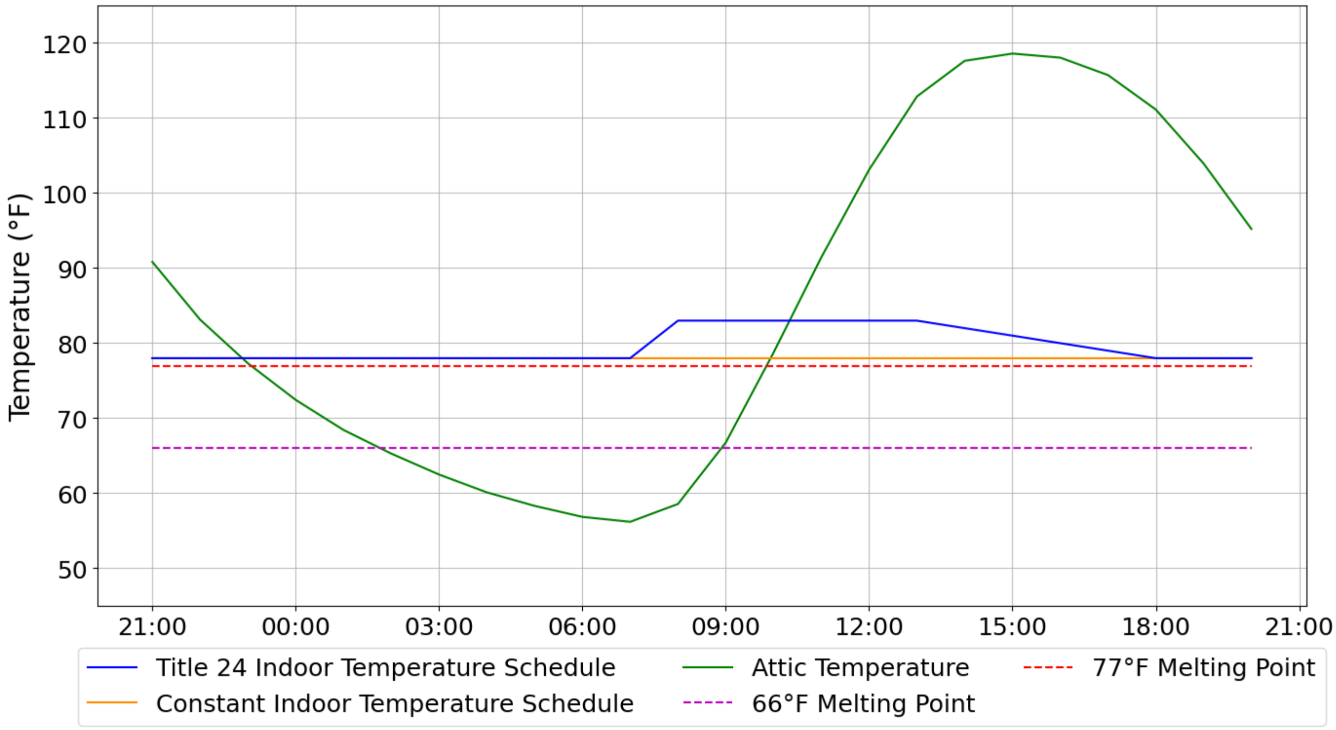
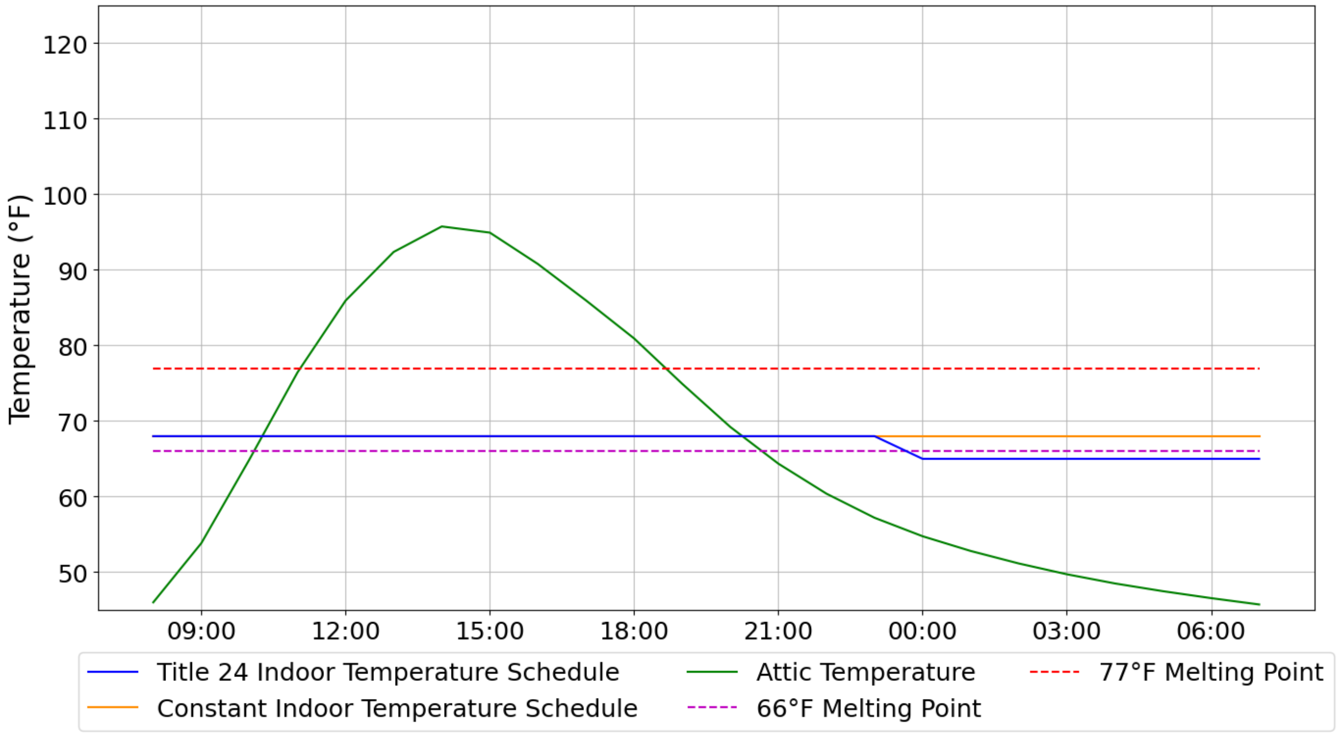


Figure 8. Heating Season Lab Test Temperature Profiles



Initially, to ensure consistent PCM starting conditions for each test cycle, the indoor air temperature was adjusted to well above 110°F (summer test) or below 55°F (winter test) for several hours to make certain the PCM would be fully melted or frozen as appropriate. However, we discovered that if the test was run for 48 hours, the second 24-hour period gave very different results than the first 24-hour period. Subsequently, each 24-hour test was begun with a 12-hour lead-in using the temperature profiles for the final 12-hours of the cycle for that day, which allowed the thermal mass of the attic assembly to reach the same transient state at the beginning and end of the test. In other words, each test was run for 36 hours, and only the last 24-hours were used as the official test period.

Test Matrix

Since each test cycle required at least 36 hours, due to time constraints it was not possible to test all combinations of variables described above. To economize, a baseline test was set up (for example PCM with 77°F melting point installed below R-19 insulation using the Title 24 indoor temperature schedule), and the effects of changing one variable at a time was examined. The combinations that were planned are summarized in Table 5, although a couple of changes were made during the test based on the early results, as will be discussed in Section 4.1.

Table 5. Lab Test Variables

No PCM				
Heating and Cooling Schedule	**Insulation Level**			
Title 24 Temperature Schedule	R-19		R-38	
Constant Indoor Temperatures	-		-	
PCM Below Insulation				
Heating and Cooling Schedule	**Insulation Level**			
	66 °F Melting Point		**77 °F Melting Point**	
Title 24 Temperature Schedule	R-19	R-38	R-19	R-38
Constant Indoor Temperatures	-	-	R-19	-
PCM Above Insulation				
Heating and Cooling Schedule	**Insulation Level**			
	66 °F Melting Point		**77 °F Melting Point**	
Title 24 Temperature Schedule	R-19	-	R-19	R-38
Constant Indoor Temperatures	-	-	R-19	-

Instrumentation

Key data points collected during each test are shown in Figure 9 and included the following:

- Air temperatures in the simulated attic and interior space (temperature and relative humidity sensors)
- Water flow rates and inlet and outlet water temperatures for fan-coils as a potential check for heat transfer into each zone
- Heat flux at the ceiling in the middle of the attic (heating or cooling load from the attic) using a Hukseflux HFP01 heat flux plate (See Figure 10)

- Heat flux above the PCM in the middle of the attic (see Figure 11), and at the ceiling in the corner of the attic
- Surface temperature above and below the PCM at several locations (thermocouples)
- Interior temperature of a PCM cell at one location (thermocouple)

Figure 9: Instrumentation used for PCM testing in the BSRL indoor environmental chamber

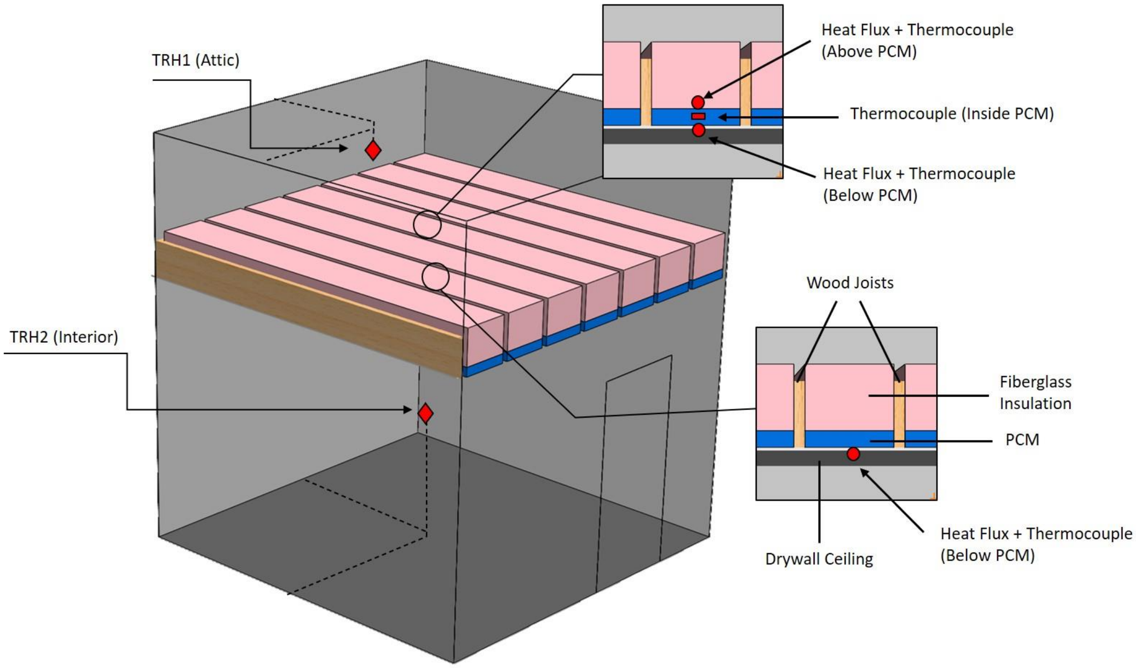


Figure 10: Heat flux sensors installed under insulation during lab testing

Figure 11. Heat flux sensors attached to top of PCM

Sensor data were collected at 1-second intervals. This sampling rate allowed the data acquisition system to capture rapid changes in temperature and heat flux on both sides of the PCM to help characterize the freezing and melting phenomena. The data also provided feedback to the chamber control system, which adjusted water supply temperatures using proportional–integral–derivative (PID) controls in LabView to achieve smooth transitions between specified hourly temperature conditions for the attic and interior spaces.

The test data were used to quantify the change in heating and cooling load experienced by the interior space as a result of adding a layer of PCM to the attic insulation in different configurations. This information was then used to identify the preferred design and installation practices for Sonoma County, including installation configuration and melting point. The data were also used to help verify material properties of the PCM published by the manufacturer, specifically melting point and heat of fusion, to ensure that modeling inputs were accurate.

2.2: Field Test Approach

The field-testing portion of the project was conducted at five single family homes that underwent attic retrofits, including installation of PCM in the attic space and insulation upgrades to R-19 when existing insulation was below the Title 24 requirements for alterations. The energy use of each home prior to retrofit served as the baseline. No other changes were made to the homes by the installer or the field test team that would complicate interpretation of the results, and homeowners were instructed not to perform any energy-related retrofits during the test period. Each home was monitored in two stages. The first stage was the baseline period prior to the retrofit, and the second stage began after the retrofit. After adjusting for weather and behavioral changes before and after the retrofit, data for the two periods were compared to evaluate energy savings and non-energy impacts.

Research Questions

The following research questions were addressed during the field-testing phase:

1) What is the cost-effectiveness of PCM installed in vented attics in five test houses in Sonoma County?
2) What are the cooling and heating load reductions for PCM installed in vented attics?
3) Does the PCM demonstrate durability and effectiveness after being installed in attic spaces for an extended period?

Site Selection

The first step in the site selection process was to develop a screening matrix that identified the essential and desired characteristics of the PCM field test sites, as shown in Table 6. Essential criteria were mandatory for the site to be considered, while criteria with numerical values were used to score the sites based on likelihood of cost-effective PCM performance. The site selection criteria allowed the identification of homes that would provide a best-case scenario for residential attic PCM within the constraints of the project goals and resources. The criteria were driven primarily by technology performance considerations, cost limitations, and practical issues. Additional considerations included potential health and safety issues for both homeowners and installers. All field test sites were selected from the SCP customer base located within Sonoma and Mendocino Counties.

Table 6: Residential PCM site selection criteria

Category	Criterion	Criterion Value	Criterion Weight
Occupant	Currently occupied?	Yes	Essential
	Owned by current residents?	Yes	Essential
	Occupants will remain for 2 years?	Yes	Essential
	Full time residence?	Yes	Essential
	Homeowner enthusiastic?	Yes	8
	Realistic homeowner expectations?	Yes	Essential
	Employees of energy industry	No	5
Site	Dwelling Type	Single Family	Essential
	California Climate Zone	Zone 2	10
	Sq. feet of conditioned living space	<1500	Essential
	Utility data available	Yes	10
	Located near other sites	Yes	6
	Safe work environment	Yes	Essential
	Practical installation barriers	No	Essential

	Practical installation challenges	No	10
	Features similar to other sites	Yes	4
Building Envelope	Attic type	Vented	9
	Asbestos on site	No	Essential
Mechanical	HVAC system functional	Yes	8
	Central cooling	Yes	9
	Central heating	Yes	9
	Heating fuel	Electric	8
	HVAC asbestos ducts	No	Essential
	HVAC whole house fan	Yes	6
	Smart thermostat	Yes	4

Initial customer outreach was performed through digital channels (e-mail, social media, etc.). Approximately 200 interested customers were directed to an SCP-hosted web page with additional details on Lead Locally, expectations and benefits for customer participation, and a list of qualifying questions based on the identified screening criteria in Table 6. Customers interested in the residential PCM field test project completed a web-based questionnaire, which was then merged with data sets to which SCP had access, including internal customer billing data and account information, participation in SCP programs, parcel data from the Sonoma County and Mendocino County Assessor's and Recorder's Offices, and building department data from Sonoma and Mendocino County. Customer Care Representatives used the screening matrix to filter incoming interest from homeowners to determine which sites met the minimum criteria to be considered further. A preliminary score, combined with the time stamp for application submission, was used to establish the order of qualified sites for further qualification steps.

The recruitment efforts included a range of customer engagement activities to reach the target number of candidate sites. Some customers were excited about the opportunity to participate in the project and have a new technology installed in their home at no cost to them. However, some customers were skeptical or risk-averse, especially when they were asked to accept certain responsibilities through a Customer Participation and Access Agreement.

Once a manageable number of candidate sites were identified, two additional steps were required to fully score each site. First, a Customer Care Representative conducted a phone interview where the technology was explained to the homeowner and several simple technology specific questions were asked. Following another round of scoring, a short site visit was conducted by a field engineer to determine if there were any unexpected features of the building or its occupants that could affect the viability of the site for field testing. Any remaining scoring criteria were addressed during the site visit, and photographs were taken of the attic space, HVAC equipment nameplates, and other key areas of the house. Site visits identified discrepancies in scored building attributes, unsafe conditions, non-functioning equipment, and other issues. Homeowners were also interviewed to make sure their expectations were realistic and consistent with the goals of the program.

Following this final filtering step, the remaining candidates were ranked and narrowed down to approximately ten highly qualified sites, as shown in Figure 12. Several of these sites overlapped with qualified sites interested in other Lead Locally technologies, specifically radiant ceiling panels and ducted mini-split heat pumps. Because the number of viable sites for these HVAC technologies was more limited, they were given the right of first refusal over PCM. The top five remaining sites were selected, and the homeowners were asked to sign a Lead Locally Customer Participation and Access Agreement. These agreements provided access to utility data and allowed field engineers to enter the residence for data collection, maintenance, or repairs with reasonable notice. Homeowners also agreed to respond to questionnaires that would document their satisfaction with the technology, and any changes to operating conditions or HVAC equipment that might affect interpretation of the test results. Customers that were not selected were thanked for their interest and encouraged to participate in future Lead Locally activities and offerings.

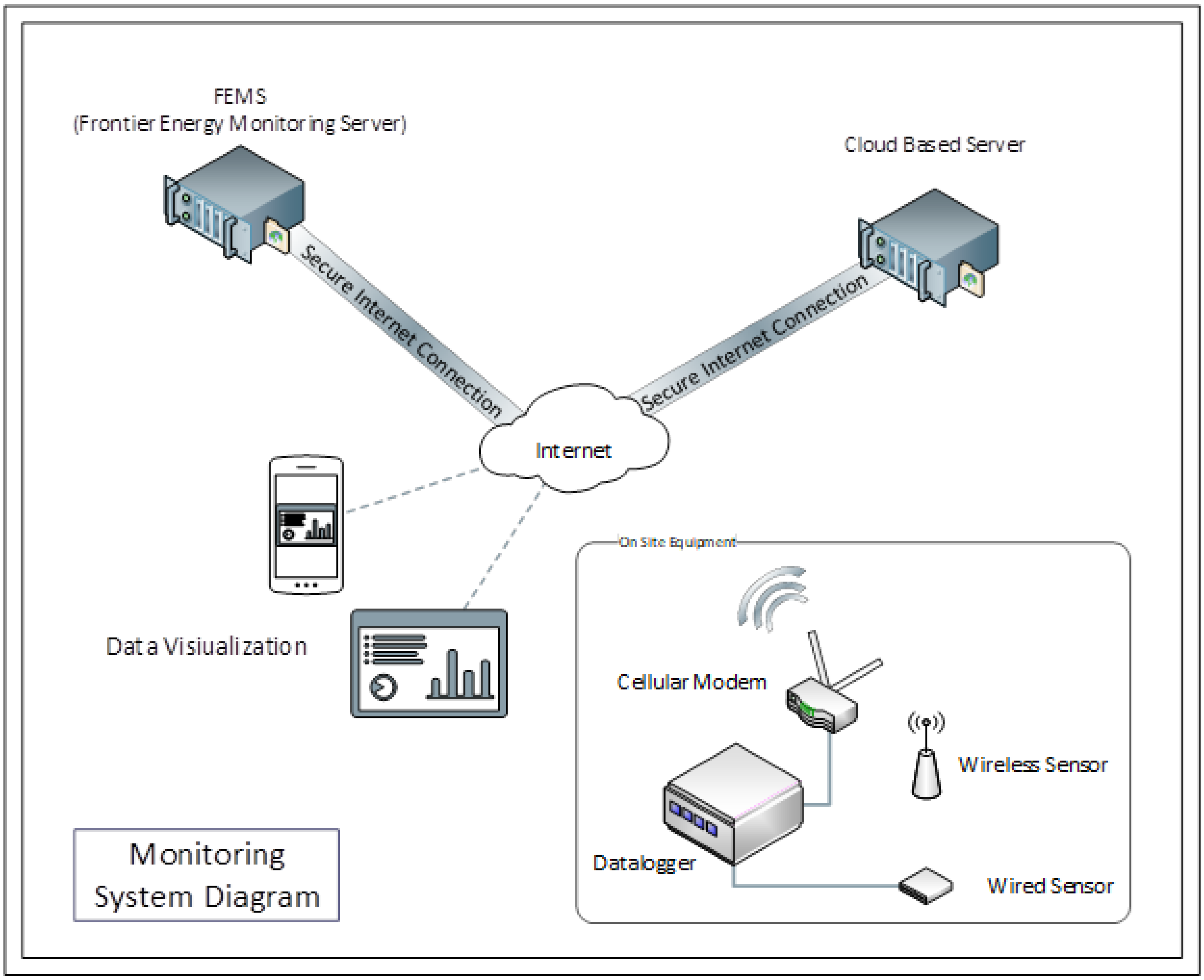
Figure 12: PCM test site selection process

Monitoring Approach

Field test data was gathered at all five test sites (baseline and post-retrofit) for 9-10 months, which was a sufficient length of time to ensure performance was measured under a wide range of weather conditions. The specific monitoring approach was tailored to the building features and research goals for each site, though basic methods and instrumentation were kept as uniform as possible for consistency. Figure 13 provides a high-level diagram of the monitoring systems used at the test sites.

In general, the monitoring systems and sensors used during the baseline monitoring period were also used following the retrofit. Data were collected from both wireless and wired sensors by data loggers. The dataloggers securely transmitted data over the internet through a program-supplied cellular modem independent from the site internet service, while providing some on-site data storage to prevent data loss due to internet connection issues and power outages.

Figure 13: PCM energy monitoring system.



The Frontier Energy Monitoring Server (FEMS) centrally collected and managed monitoring data from all data sources for all five sites. The FEMS is a secure industrial computer system with redundant data backup and redundant secure internet connections. The FEMS automated data collection by retrieving data from field monitoring sites, checking retrieved data for errors and common equipment issues, and automatically notifying test engineers about possible problems. The FEMS also tracked the internet connection status of monitoring equipment and sent weekly data summaries to key personnel.

One advantage of the FEMS was that it could be set up to retrieve data in any file format from any datalogger at any specified interval. Data from EMS dataloggers were automatically downloaded through a secure login to the EMS cloud server and typically retrieved daily. Custom dataloggers communicated directly with the FEMS over a secure connection, uploading data files directly to the FEMS secure FTP server. The FEMS provided secure storage for all retrieved data by project and by site. In addition to retaining the raw data files, the FEMS automatically combined all data for each site into a site-specific binary data file for use in analysis. Direct access to the FEMS was kept limited to specific personnel for security and reliability reasons. Access to data collected by the FEMS was provided to other Team members via Frontier Energy's secure SharePoint service once a signed non-disclosure agreement was on-file to protect Personally Identifiable Information (PII).

Initially, the field test data was collected using a third-party energy monitoring and data reporting system. However, issues related to parameter calculations and ready access to raw data led to the need for an alternative approach. Following the retrofit, some of the instrumentation and data collection equipment was replaced to allow more direct control over field test data by the Lead Locally research team. The raw third-party data was downloaded and corrected/adjusted to ensure consistent data quality to the extent possible before and after retrofit. Because no changes were made to the sensors themselves, there should have been no impact on raw data accuracy or precision. However, some of the raw data was unavailable from the data service provider, and the resulting processed data was sometimes implausible or difficult to interpret because of apparent conversion errors. These data analysis challenges are discussed further in Section 4.

Instrumentation

The baseline, or pre-retrofit, test period lasted approximately nine months, during which the homes were monitored using multiple sensors and a data logging system to capture the conditions of the attic and conditioned space before the PCM was installed. Four heat flux sensors were installed in various quadrants of the attic to measure heat flow through the ceiling prior to PCM installation. Following the retrofit, two of the heat flux sensors were moved above the PCM, aligned vertically with the other two heat flux sensors, to monitor the amount of heat entering and leaving the PCM. Data from the heat flux sensors were used to determine the reductions and shifting of both the heating and cooling loads through the ceiling, and to characterize the freezing and melting cycles that have taken place. Both the baseline and post-retrofit period used ambient temperature and humidity sensors in the attic space to evaluate attic conditions, and three additional temperature sensors logged the indoor conditions at the thermostat, the living room, and the master bedroom (or a similar combination of key locations). Changes in total heating and cooling energy were measured directly using gas meters at the furnace and power meters at the indoor and outdoor units of the air conditioner or heat pump. The full list of instrumentation for the pre-retrofit period is shown in Table 7, with the only post-retrofit change being the relocation of two heat flux sensors, which is described in more detail for each site in Section 3.2.

Table 7: Residential PCM Field Test Instrumentation

Monitoring Equipment	Parameter	ID	Location
Datalogger (1)	N/A	N/A	Attic
Power meter (1)	Voltage	P0	Panel
Current transformers (4)	A/C power (outdoor)	P1	Panel
	A/C power (outdoor)	P1	Panel
	A/C power (indoor)	P2	Panel
	A/C energy (outdoor)	E1	Panel

	A/C energy (outdoor)	E1	Panel
	A/C energy (indoor)	E2	Panel
16 channel input/output module (1)	N/A	N/A	Attic
Data acquisition unit (1)	N/A	N/A	Attic
Cellular modem (1)	N/A	N/A	Attic
Heat Flux Sensor (4)	Heat flux	Q1	Against top of ceiling, middle of Northwest quadrant or representative of about 1/4 of attic over conditioned space
	Temperature	T1	Against top of ceiling, middle of Northwest quadrant or representative of about 1/4 of attic over conditioned space
	Heat flux	Q2	Against top of ceiling, middle of Northeast quadrant or representative of about 1/4 of attic over conditioned space
	Temperature	T2	Against top of ceiling, middle of Northeast quadrant or representative of about 1/4 of attic over conditioned space
	Heat flux	Q3	Against top of ceiling, middle of Southeast quadrant or representative of about 1/4 of attic over conditioned space
	Temperature	T3	Against top of ceiling, middle of Southeast quadrant or representative of about 1/4 of attic over conditioned space
	Heat flux	Q4	Against top of ceiling, middle of Southwest quadrant or representative of about 1/4 of attic over conditioned space
	Temperature	T4	Against top of ceiling, middle of Southwest quadrant or representative of about 1/4 of attic over conditioned space

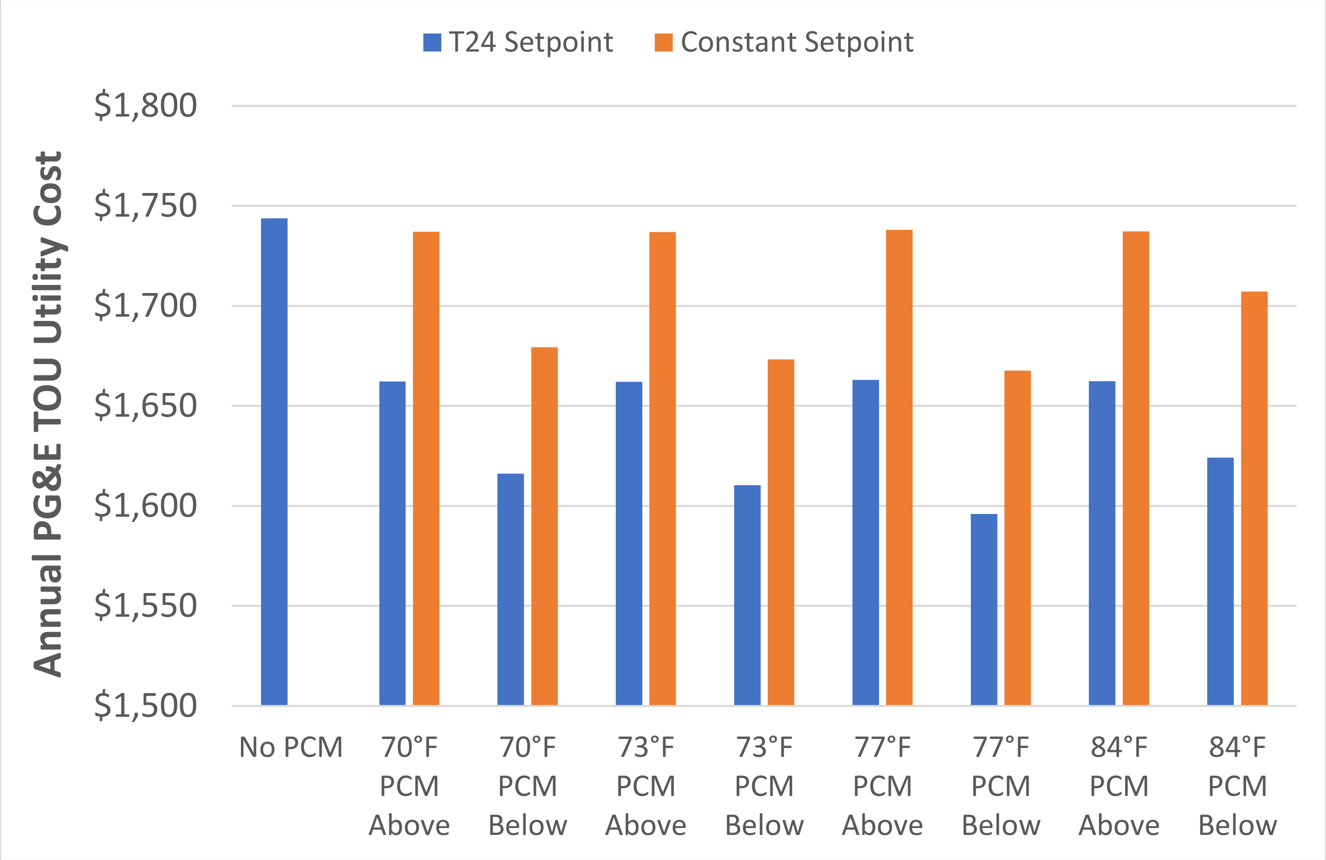
Thermocouples (2)	Temperature	T5	Attic, middle horizontally, high vertically
	Temperature	T6	Attic, touching insulation near middle
Wireless temperature/humidity sensors (6)	Temperature/RH	TRH1	Attic, middle horizontally, middle vertically
	Temperature/RH	TRH2	Attic, 3-4 ft from eave on East or North side, middle vertically, not next to a vent
	Temperature/RH	TRH3	Attic, 3-4 ft from eave on West or South side, middle vertically, not next to a vent
	Temperature/RH	TRH4	Interior, near thermostat
	Temperature/RH	TRH5	Interior, master bedroom
	Temperature/RH	TRH6	Interior, living room/family room/2nd bedroom furthest from thermostat
Gas meter (1)	Gas volume	V1	Near furnace, unless the house uses a heat pump for space heating

Retrofit Process

During the retrofit stage, the material and installation costs were tracked to evaluate the total cost for each retrofit. The payback period was calculated by comparing the total cost of the retrofit and the energy savings that resulted from the PCM addition to the attic through reduction in heating and cooling loads.

The original research plan called for the PCM to be placed in a configuration that was determined by the results of the laboratory phase of the project. However, delays in lab preparation led to an alternate strategy of modeling energy savings for both possible PCM configurations (above and below the insulation), using multiple melting points. The modeling also analyzed the effect of a constant thermostat set point compared to a setup/setback schedule consistent with Table 22 in the 2019 Title 24 Alternative Calculation Method Reference Manual (Ferris, et al., 2019). The model was constructed in EnergyPlus, using a prototype house representative of existing homes in Sonoma County. Results from these preliminary modeling studies predicted that a melting point of 77°F combined with installation under the insulation would provide the highest overall energy cost savings in Sonoma County, as represented by Santa Rosa (see Figure 14).

Figure 14: Predicted effect of PCM configurations and melting point on annual energy cost in Santa Rosa, California



Site Close-out

At the conclusion of the field test period, all instrumentation was removed, and the condition of each house was returned to its original state, except for the efficiency measures themselves. As described in Section 3.3, it was decided that the PCM should also be removed due to durability concerns following the discovery of leaking mats at two test sites in late 2021. The PCM removal process was underway at the time this report was written.

2.3: Modeling

The primary use of building simulation for this applied research project was to evaluate alternative configurations of the PCM in the attic for the purpose of designing the retrofits to be used in the field tests and for making recommendations in the PCM Installation Guide. While the laboratory tests provided important insights into the effectiveness of each configuration, it was important to understand performance under the full range of operating conditions experienced throughout the year using a model informed by the lab and field test results. Because residential building simulation tools such as BEopt have very few options for attic PCM configurations, and CBECC-Res does not yet have PCM modeling capability, EnergyPlus was the tool selected for this analysis. BEopt, which uses the EnergyPlus simulation engine, was used to generate typical California house specifications, then the EnergyPlus input file was directly modified to include PCMs.

Research Questions

The following research questions were addressed during the modeling phase:

1) What is the cost-effectiveness of PCM installed in vented attics in SCP service territory?
2) Which climates in Northern California provide the necessary environmental conditions for PCM in attic spaces to go through the proper thermal cycles for cost-effective energy savings?

CHAPTER 3:
Field Test Results

3.1: Test Sites

Five promising test sites were identified that met the mandatory criteria described in Section 2.2 and that scored highly on other criteria. Building attributes, occupant characteristics, instrumentation details, and other information about the five test sites are discussed in the following sections. Site, occupant, envelope and mechanical characteristics, and instrumentation details and related issues for each site are listed in Table 8 through Table 22. Homeowner survey responses are provided in Table 23. Certain information is anonymized for the purpose of ensuring the privacy of project participants.

Site 52

Site 52 is a small one-story home in Sonoma. Overall characteristics about the house and its occupants are summarized in Table 8. Details about the building envelope and HVAC systems are provided in Table 9. Specific information about PCM installation, along with instrumentation details and monitoring challenges are provided in Table 10. Sensor locations are shown in Figure 15.

Noteworthy features of Site 52 include the following:

- The PCM mats were installed above the insulation because the building department in Sonoma expressed concerns about moving the insulation. Placing the PCM above the insulation eliminated the need for a permit and it provided an opportunity to assess a different PCM configuration.
- Heating was provided by an air-source heat pump.

Table 8. Site 52 Site and Occupant Characteristics

City	Sonoma
Year Built	1983
House Square Feet	1551 ft^2
Number of Floors	1
Number of Bedrooms	3
Number of Bathrooms	3
Occupancy Level	2 adults, 1 child
Variations in Occupancy	Occasionally work from home, but not common Potential COVID impacts post-retrofit
Expected House Modifications	Two windows likely to be replaced during test period

Overall Score	102 (Ranked #1)

Table 9. Site 52 HVAC/Envelope Characteristics

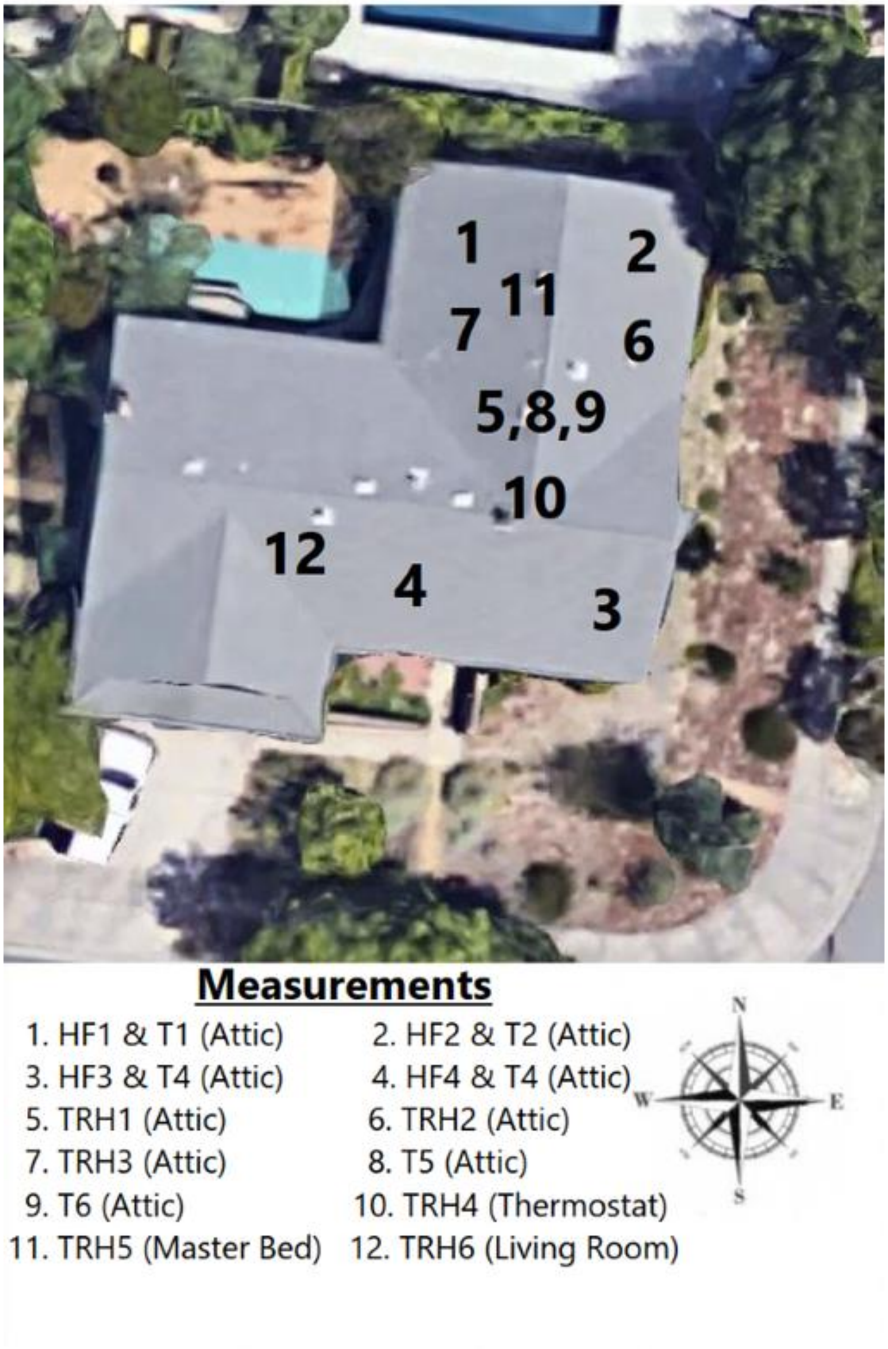
Cooling System	Variable Speed Electric Split System Heat Pump Mitsubishi Model PUZ-HA36NHA4 SEER 17 3 tons
Heating System	Variable Speed Electric Split System Heat Pump Mitsubishi Model PUZ-HA36NHA4 HSPF 10 Capacity 38,000 Btuh @ 47°F
Thermostat	Standard programmable
Whole House Fan	No
Supply Grille Location	Floor
Return Grille Location	Ceiling
HVAC Age	<5 yrs
Supplemental Systems	Solar PV
Duct Location	Crawlspace
Air Handler Location	Mechanical closet
Insulation	~R-12 blown cellulose Moderate degradation

Table 10. Site 52 Instrumentation and PCM Installation Summary

Pre-Retrofit Monitoring Period	2/26/2019-12/1/2019
PCM Installation Date	12/2/2019
Post-Retrofit Monitoring Period	12/26/2019-9/21/2020
Attic Area Covered	~1240 ft2
Insulation Added	~R-8
Installation Challenges Encountered	PCM installed above insulation to avoid permitting delays

	Damage to ceiling drywall when box of PCM was dropped
Actual Material Costs for PCM	$3300
Actual Installation Cost (Including hotel and 20% of administrative costs, shared materials, learning curve)	$7017
Projected Material Costs for PCM for Homeowners (75%)	$2475
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	$4210
Deviations from Monitoring Plan	9-month post-retrofit monitoring period instead of 1-year
Monitoring Changes from Pre-Retrofit	SE heat flux sensor moved above PCM in SW quadrant; NW moved above PCM in NE quadrant
Monitoring Issues Encountered	Initial difficulty monitoring electricity use of outdoor unit (resolved) Temperature sensors occasionally fell off wall (resolved) Temperature sensor broken on 3/25/19 (resolved) Temp and RH sensor stopped transmitting 4/16/19 (resolved) Intermittent temperature readings from third party data service provider (resolved) Heat flux sensor in SW quadrant above PCM appears to be upside down (Seems to have flipped on Feb 3, 2020) Heat flux sensor in NE quadrant above PCM appears detached

Figure 15: Site 52 Sensor Locations (Pre-Monitoring)



Site 54

Site 54 is a small one-story home in Santa Rosa. Overall characteristics about the house and its occupants are summarized in Table 11. Details about the building envelope and HVAC systems are provided in Table 12. Specific information about PCM installation, along with instrumentation details and monitoring challenges are provided in Table 13. Sensor locations are shown in Figure 16.

Noteworthy features of Site 54 include the following:

- Cooling was provided by two window air conditioners, which could not be monitored directly.
- The furnace broke down and was replaced about a month after the PCM retrofit. As a result of the change in heating efficiency and furnace usage, gas savings measurements may not be indicative of savings due to the PCM.
- The post-retrofit monitoring period began two months late because instrumentation was disconnected at the time of furnace replacement.

Table 11. Site 54 Site and Occupant Characteristics

City	Santa Rosa
Year Built	1954
House Square Feet	1505 ft^2
Number of Floors	1
Number of Bedrooms	3
Number of Bathrooms	2
Occupancy Level	4-5
Variations in Occupancy	Wife works part time Potential COVID impacts post-retrofit
Expected House Modifications	None
Overall Score	75 (Ranked #8)

Table 12. Site 54 HVAC/Envelope Characteristics

Cooling System	Two window A/C units
Heating System	Gas Furnace Lennox Model GS6-105M 84,000 Btuh (Second system installed in January following retrofit, model unknown)
Thermostat	Standard programmable
Whole House Fan	No
Supply Grille Location	Floor
Return Grille Location	Ceiling

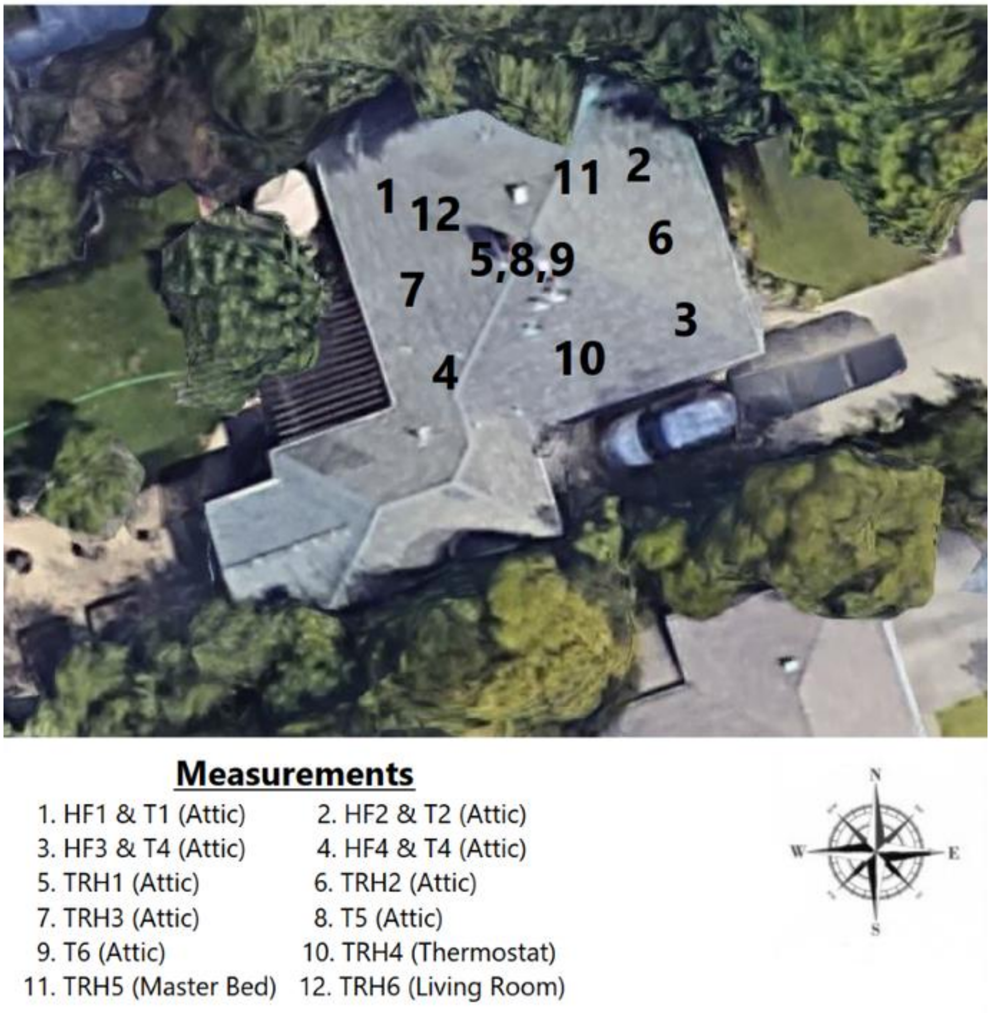
HVAC Age	<10 yrs
Supplemental Systems	Fireplace
Duct Location	Crawlspace
Air Handler Location	Attic
Insulation	~R-12 blown cellulose Minimal degradation

Table 13. Site 54 Instrumentation and PCM Installation Summary

Pre-Retrofit Monitoring Period	3/26/2019-12/3/2019
PCM Installation Date	12/4/2019
Post-Retrofit Monitoring Period	2/13/2020-8/17/20
Attic Area Covered	~1204 ft2
Insulation Added	~R-8
Installation Challenges Encountered	Unable to install PCM under air handler platform
Actual Material Costs for PCM	$3204
Actual Installation Cost (Including hotel and 20% of administrative costs, shared materials, learning curve)	$6684
Projected Material Costs for PCM for Homeowners (75%)	$2403
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	$4010
Deviations from Monitoring Plan	9-month post-retrofit monitoring period instead of 1-year
Monitoring Changes from Pre-Retrofit	SE heat flux sensor moved above PCM in SW quadrant; NE moved above PCM in NW quadrant
Monitoring Issues Encountered	Furnace had to be replaced in January 2020. Gas readings in fall 2019 are suspect and may include days when furnace was not working. Only spring 2019 heating data appears valid pre-retrofit. Before and after gas

	measurements may not be meaningful because of efficiency change. Window A/Cs were not monitored. Will rely on electric bills. T/RH sensor data very intermittent, and not transmitted after 8/17/2020. Also no heating data after 8/17/2020. NW heat flux temperature data below PCM is unreliable. Appears to be exposed to attic conditions.

Figure 16: Site 54 Sensor Locations (Pre-Monitoring)



Site 56

Site 56 is a small one-story home in Santa Rosa. Overall characteristics about the house and its occupants are summarized in Table 14. Details about the building envelope and HVAC systems are provided in Table 15. Specific information about PCM installation, along with instrumentation details and monitoring challenges are provided in Table 16. Sensor locations are shown in Figure 17.

Noteworthy features of Site 56 include the following:

- The house included a whole-house fan, with unknown operation during the test period.
- The attic was particularly difficult to navigate, and as a result, a few sections of the attic did not have PCM installed.

Table 14. Site 56 Site and Occupant Characteristics

City	Santa Rosa
Year Built	1965
House Square Feet	1338 ft^2
Number of Floors	1
Number of Bedrooms	3
Number of Bathrooms	2
Occupancy Level	1-3
Variations in Occupancy	Someone home most of the time Potential COVID impacts post-retrofit
Expected House Modifications	None
Overall Score	94 (Ranked #3)

Table 15. Site 56 HVAC/Envelope Characteristics

Cooling System	Split Air Conditioner, 2-stage Lennox Model XC21-036-230 SEER 20 3 Tons
Heating System	Gas Furnace Lennox Model SLP98UH07UXV36B AFUE 97.4% 64,000 Btuh
Thermostat	Lennox Smart Thermostat
Whole House Fan	Yes
Supply Grille Location	Floor
Return Grille Location	Ceiling
HVAC Age	~2 yrs
Supplemental Systems	Air Scrubber Plus, Model A1013C
Duct Location	Crawlspace
Air Handler Location	Attic

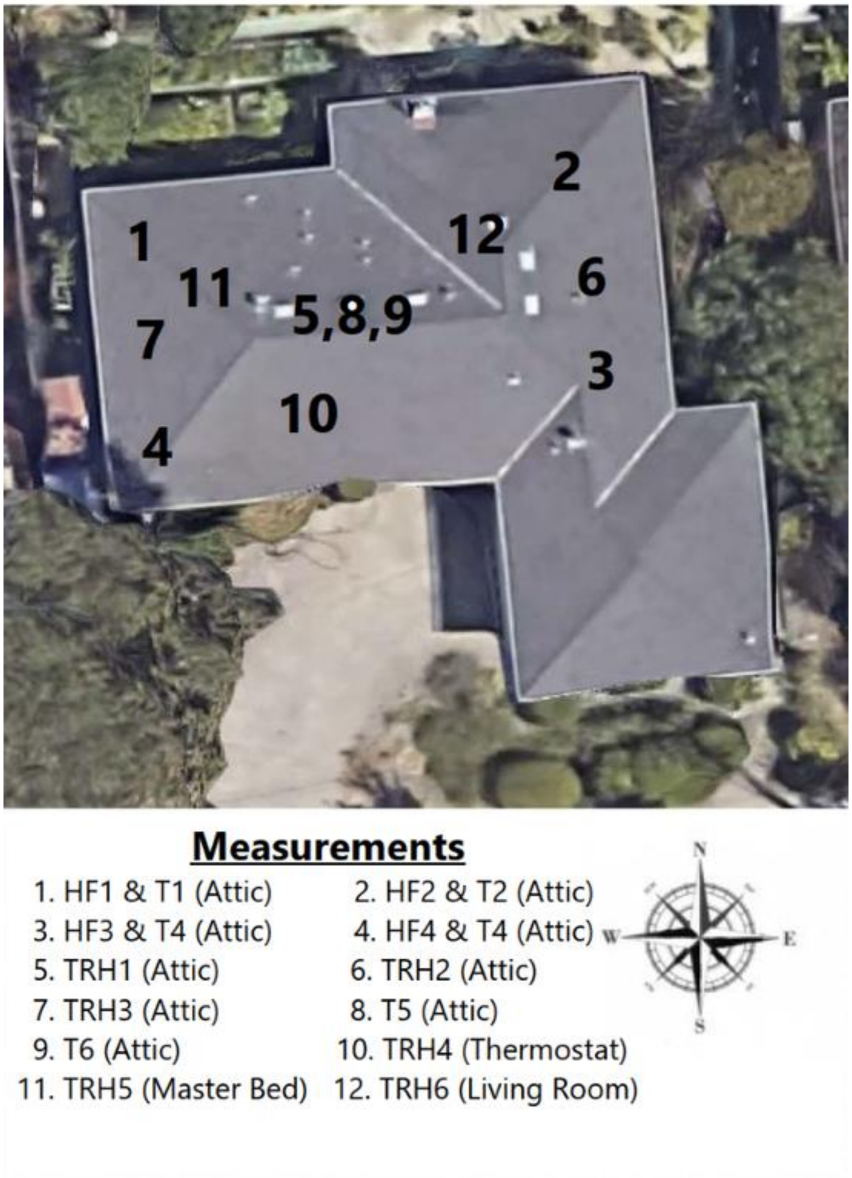
Insulation	~R-12 combination of loose-fill and fiberglass batts Moderate degradation

Table 16. Site 56 Instrumentation and PCM Installation Summary

Pre-Retrofit Monitoring Period	2/25/2019-12/5/2019
PCM Installation Date	12/6/2019
Post-Retrofit Monitoring Period	1/14/2020-9/27/2020
Attic Area Covered	~1070 ft2
Insulation Added	~R-8
Installation Challenges Encountered	Unable to install PCM under air handler platform Difficult access to many areas of attic
Actual Material Costs for PCM	$2848
Actual Installation Cost (Including added insulation, hotel, and 20% of administrative costs, shared materials, learning curve)	$8589
Projected Material Costs for PCM for Homeowners (75%)	$2136
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	$5153
Deviations from Monitoring Plan	9-month post-retrofit monitoring period instead of 1-year
Monitoring Changes from Pre-Retrofit	SE heat flux sensor moved above PCM in SW quadrant; NW moved above PCM in NE quadrant
Monitoring Issues Encountered	NW heat flux sensor had reversed polarity until 12/19/19 (resolved) Attic East Perimeter temperature sensors was not installed until 12/19/19 (resolved)

	Attic West Perimeter stopped recording data on from 5/20/19 to 12/19/19 (resolved)

Figure 17: Site 56 Sensor Locations (Pre-Monitoring)



Site 53

Site 53 is a small two-story home in Santa Rosa. Overall characteristics about the house and its occupants are summarized in Table 17. Details about the building envelope and HVAC systems are provided in Table 18. Specific information about PCM installation, along with instrumentation details and monitoring challenges are provided in Table 19. Sensor locations are shown in Figure 18.

Noteworthy features of Site 53 include the following:

- The house is small but has two floors, resulting in very limited attic area for PCM.
- An unmonitored space heater was sometimes used.
- The house was sold a few months after the conclusion of the test.

Table 17. Site 53 Site and Occupant Characteristics

City	Santa Rosa
Year Built	2001
House Square Feet	1300 ft^2
Number of Floors	2
Number of Bedrooms	3
Number of Bathrooms	2
Occupancy Level	4-5
Variations in Occupancy	Oldest child is sometimes home from college. May work from home 2 days a week Potential COVID impacts post-retrofit
Overall Score	78 (Ranked #7)

Table 18. Site 53 HVAC/Envelope Characteristics

Cooling System	Central air conditioner Goodman Model CK24-1D 2-tons SEER 10
Heating System	Gas furnace Goodman Model GMP050-3 REV B 36 kBtuh AFUE: 80%
Thermostat	Standard programmable
Whole House Fan	No
Supply Grille Location	Ceiling
Return Grille Location	Ceiling
HVAC Age	>16 yrs

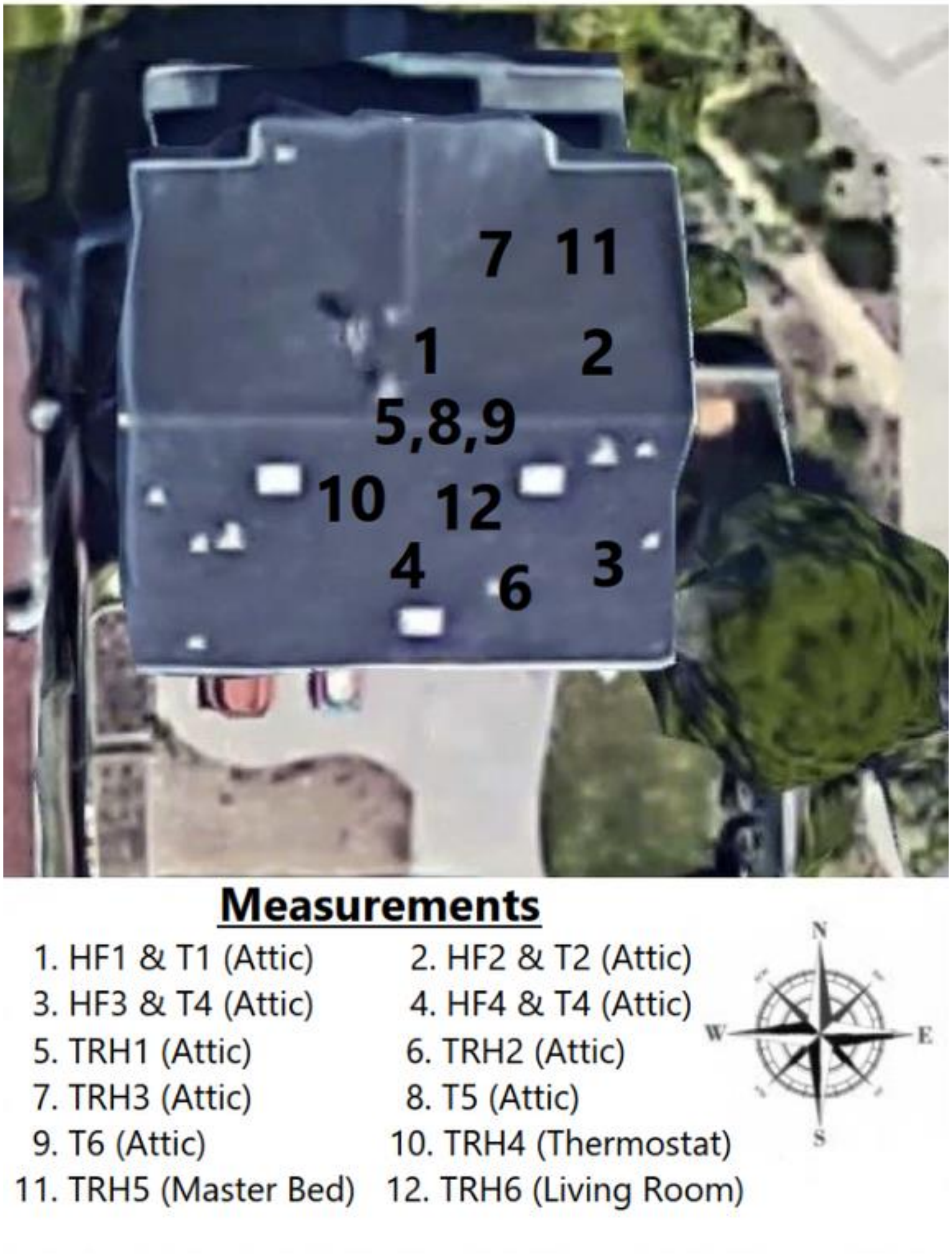
Supplemental Systems	Space heater in bathroom
Duct Location	Attic
Air Handler Location	Attic
Insulation	R-18 loose-fill fiberglass Minimal degradation

Table 19. Site 53 Instrumentation and PCM Installation Summary

Pre-Retrofit Monitoring Period	2/27/2019-12/2/2019
PCM Installation Date	12/3/2019
Post-Retrofit Monitoring Period	1/6/2020-9/21/2020
Attic Area Covered	~520 ft2
Insulation Added	~R-2
Installation Challenges Encountered	Difficult to install PCM under air handler and ducts (~30% of attic area)
Actual Material Costs for PCM	$1384
Actual Installation Cost (Including hotel and 20% of administrative costs, shared materials, learning curve)	$6631
Projected Material Costs for PCM for Homeowners (75%)	$1038
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	$3979
Deviations from Monitoring Plan	9-month post-retrofit monitoring period instead of 1-year
Monitoring Changes from Pre-Retrofit	SW heat flux sensor moved above PCM in SE quadrant; NW moved above PCM in NE quadrant
Monitoring Issues Encountered	Heat flux sensor data not transmitted from 2/27/2019-6/7/2019 (resolved) Interior temperature sensor at thermostat failed

	on 7/1/2020, living room on 8/24/2020

Figure 18: Site 53 Sensor Locations (Pre-Monitoring)



Site 55

Site 55 is a small one-story home in Petaluma. Overall characteristics about the house and its occupants are summarized in Table 20. Details about the building envelope and HVAC systems are provided in Table 21. Specific information about PCM installation, along with instrumentation details and monitoring challenges are provided in Table 22. Sensor locations are shown in Figure 19.

Noteworthy features of Site 55 include the following:

- An unmonitored fireplace was often used.
- Ducts and extensive wiring were located in the attic, presenting installation challenges.

Table 20. Site 55 Site and Occupant Characteristics

City	Petaluma
Year Built	1920
House Square Feet	1361 ft^2
Number of Floors	1
Number of Bedrooms	3
Number of Bathrooms	2
Occupancy Level	2
Variations in Occupancy	Husband home during summer and winter breaks (presumably a teacher/professor). Potential COVID impacts post-retrofit
Overall Score	78 (Ranked #6)

Table 21. Site 55 HVAC/Envelope Characteristics

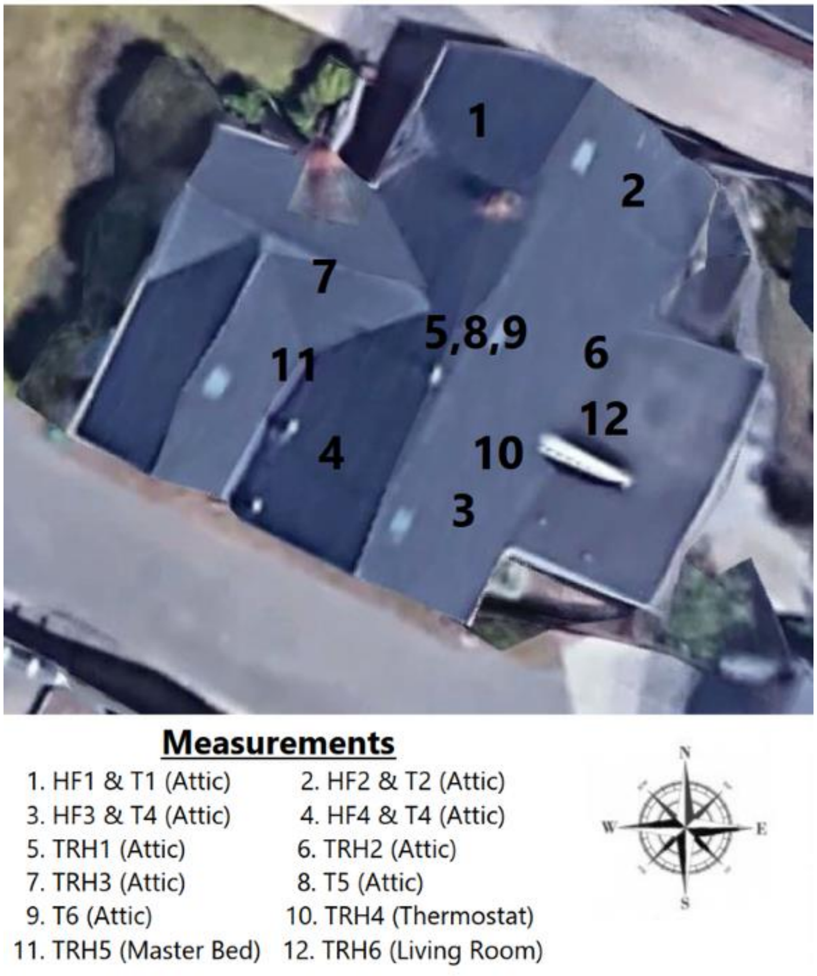
Cooling System	Central air conditioner Carrier Model 38CKB036-330 3 tons SEER 10
Heating System	Gas furnace Unknown capacity and AFUE
Thermostat	Standard programmable
Whole House Fan	No
Supply Grille Location	Ceiling
Return Grille Location	Ceiling
HVAC Age	>10 yrs
Supplemental Systems	Fireplace often used
Duct Location	Attic

Air Handler Location	Attic
Insulation	R-16 loose-fill fiberglass Moderate degradation

Table 22. Site 55 Instrumentation and PCM Installation Summary

Pre-Retrofit Monitoring Period	3/4/2019-12/4/2019
PCM Installation Date	12/5/2019
Post-Retrofit Monitoring Period	1/14/2020-11/1/2020
Attic Area Covered	~1088 ft^2
Insulation Added	~R-4
Installation Challenges Encountered	Moderate safety concern with old wiring in attic
Actual Material Costs for PCM	$2895
Actual Installation Cost (Including hotel and 20% of administrative costs, shared materials, learning curve)	$6878
Projected Material Costs for PCM for Homeowners (75%)	$2172
Projected Installation Cost for Homeowners (Excluding travel, prevailing wage, learning curve) (60%)	$4127
Deviations from Monitoring Plan	9-month post-retrofit monitoring period instead of 1-year
Monitoring Changes from Pre-Retrofit	SW heat flux sensor moved above PCM in SE quadrant; NW moved above PCM in NE quadrant
Monitoring Issues Encountered	All third-party data provider temperature sensors stopped recording data from 12/18/2019 to 2/28/20 Multiple data gaps in hourly thermostat temperature reading had to be interpolated

Figure 19: Site 55 Sensor Locations (Pre-Monitoring)



Homeowner Survey Results and Data Analysis Impacts

Table 23 lists survey responses from homeowners before and after installation of PCM material. These surveys provide context for the field measurements and insights into occupant satisfaction with the technology. One notable issue was a cited furnace replacement that occurred at Site 54 in January 2020, just after PCM installation, which made pre- and post-retrofit energy use comparisons challenging, particularly due to failure of the furnace during the baseline monitoring period. Sites 53 and 56 experienced a reduction of occupancy levels when compared to the pre-installation monitoring period which would have likely caused a decrease in internal heat gains. Along with permanent occupancy changes, during the post installation monitoring period, two sites had 1-2 additional visitors for two weeks, and one site had 4 less occupants for approximately three weeks. These changes would have likely caused short-term changes in equipment use and internal heat gains. The uncertain use of alternative comfort control methods such as ceiling fans, open windows, space heaters, and fireplaces were cited both before and after PCM installment, complicating the analysis of PCM effects. Another significant factor influencing changes in energy use was the increased amount of time spent at home beginning mid-March of 2020, when the COVID-19 pandemic began. This would have affected both the magnitude and temporal distribution of internal heat gains and possibly thermostat set points when compared to the months prior. Finally, wildfires in the Sonoma County area occasionally affected occupancy levels and HVAC operation.

The surveys also indicated changes in occupant thermal comfort. It is highly improbable that the PCM could have a negative effect on temperature uniformity, but it is something to consider in the review of field test results.

Table 23: Homeowner Survey Responses Comparing Activity Before and After PCM Installation

	Pre-installation Home Activity				
Site ID	53	55	54	56	52
# of Residents	4+	2	4+	2-3	3
Increased occupancy for 2+ weeks	Yes	No	Yes	No	Yes
Decreased occupancy for 2+ weeks	No	No	No	Yes	Yes
Changes in home activity	None	Increased time at home May-Aug	None	Occasional additional occupant	None
Alternate Temperature Regulation	Windows	Windows, gas fireplace	Windows, fan, gas fireplace	Windows, gas fireplace	Windows
	Post-Installation Home Activity				
Site ID	53	55	54	56	52
# of Residents	3	2	5	1	3
Changes in Occupancy	1 moved out June 2020	1 additional occupant for 2 weeks	4 less from 10/19-11/1/2020 2 additional 7/25-8/9/2020	None	None
Changes in Home Activity	None	None	Increased kitchen use 7/25-9/30/2020	None	None
Alternate Temperature Regulation	Windows	Windows, fan, gas fireplace	Windows, fan, space heater	Windows and gas furnace	Windows

Experienced Evacuations	None	None	4 occupants evacuated	Evacuated 4-5 days during wildfires	None
Other Wildfire Related Changes	Increased use of AC	None	None	Filters replaced in December	Replaced filter and ran fan more often
Experienced Power Shutdown	None	None	None	Numerous events during evacuation	None
COVID-Related Changes	More time at home as of March 17	More time at home as of March 17	More time at home as of March 16	More time at home as of March 15	More time at home as of mid-March
Thermostat Adjustments	None	Increased set point	Increased heater run time	None	Increased heater run time
Change in Thermal Comfort	Whole house is uncomfortable	Always comfortable	Variation between rooms	Variation between rooms	No experienced changes
Additional Considerations			Replaced furnace in January 2020	Thermostat broke for 1-2 days in November	

Winter Weather Validation

The instrumentation and baseline data collection for all Lead Locally PCM sites was initiated between the middle of February and the beginning of March 2019, which was later than the targeted mid-winter date of January 15. There was a concern that the coldest days of the winter season had already passed, and there may not be adequate pre-retrofit cold weather data for an accurate comparison to post-retrofit heating energy. To determine if sufficient cold weather data was collected, temperature measurements for the coldest stretch during our test period were compared to the coldest weather data of the entire winter using the Gladstone Family Weather Quality Report (https://weather.gladstonefamily.net/) for the closest weather station to each site. After analyzing the weather data, we are confident that four of the sites include several days of cold-weather data that are comparable to the coldest weather of the season (within 5°F). However, for Site 54 there was a larger average temperature difference of 8.5°F. Ultimately, the pre-retrofit test period extended into early December 2019, but the lack of an extended period of cold weather raises concerns about using data from that site to evaluate gas energy savings.

3.2: Monitoring Challenges

Pre-Retrofit Data Quality Challenges

During the pre-retrofit monitoring period, a variety of data processing problems occurred which ultimately led to switching from third-party data acquisition equipment to a monitoring system developed by Frontier Energy. Problems included difficulty acquiring raw data files, data formatting errors, and inconsistencies in the processed data delivered by the third-party data service provider that raised concerns about the validity of several of the measurements. Initially, the data was acquired from downloading the processed 15-second CSV data from the third-party data visualization website. The CSV files were well-formatted for visualization using Excel, but not ideal for using Python-based data checking and verification. In addition, the CSV files included empty and non-existent measurements that took up a large amount of memory, incorrectly named measurements, and data from the wrong PCM test site. Python scripts were created to remove the empty measurement columns and to move incorrectly identified sensor data to the correct files. After several months of using this process, the third-party data service provider ceased allowing large data downloads directly from their website and resorted to e-mailing these large datasets as attachments

The data service provider continued to allow small files to be downloaded directly from their browser. But this change made it necessary to download processed 5-minute data in 15 or 30-day increments to carry out the analysis, because downloading raw 15-second data would have been excessively time-consuming given the file size limit. Since a large part of the analysis was to be done on hourly and daily data, this was not necessarily an issue. However, it was noticed that these data files were not being aggregated correctly. One example of this was the gas usage data from the furnace being measured with a pulse meter. The newer 5-minute data files showed that there was very little to no gas data, while significant gas usage was evident from the 15-second data. It appeared likely that the third-party was averaging these pulses over 5-minutes rather than summing them. To remedy this, the data service provider was asked to upload all the processed 15-second data to Frontier Energy's secure FTP. This took a few iterations to perfect, but eventually Frontier was able to obtain the raw data and perform the aggregation independently.

In addition to acquiring and cleaning the processed data files from the third-party provider, other data required correction and validation. A few months after initiating monitoring it was noticed that the magnitude of HVAC, thermocouple, and heat flux measurements decreased significantly. It was discovered that the data service provider stopped using the necessary equations for converting the Modbus signal to the correct units, or used a different conversion midway through the monitoring period while not correcting the units in the headers. For example, the header label for the processed energy data "kWh", but both Watt-hours and Kilowatt-hours were being used at various times during the monitoring period.

Heat flux and thermocouple sensors were more difficult to diagnose. The values from these sensors required a calculation to convert their Modbus voltage signal to their correct units. The data service provider was performing this calculation for several months, but then abruptly stopped. Once this was verified, the measurements were corrected using the appropriate equations. However, awareness of these data conversion issues led to concerns that there may be other errors in the measurements, such as incorrect heat flux readings that may have been difficult to diagnose through normal data checking methods because they were within reasonable bounds. Each of the heat flux sensors had a unique equation to convert the voltage signal to W/m^2, and using the wrong equation resulted in inaccurate readings. After the post-retrofit period began, it was noticed that heat flux measurements were larger than for the pre-retrofit data by a factor of 20. Following extensive study, it was concluded that the data service provider probably used an incorrect multiplier in their equations. Unfortunately, without the raw Modbus data, we were unable to determine what conversion factor was used. It is also possible that the heat flux sensor had poor surface contact with the ceiling and/or insulation during the pre-retrofit period because we relied on pressure from the insulation to minimize air gaps instead of thermal paste or grease (an installation error), and contact improved when the sensors were re-installed under the PCM. Our analysis suggests that an air gap of 0.1 mm increases the thermal resistance of the sensor by 200%, which could affect the accuracy of the readings. But there was no change in the installation protocols before and after the retrofit, and poor sensor contact cannot explain an order of magnitude difference in heat flux readings. We believe the most likely explanation is a data conversion error.

Data Communication and Sensor Issues

During both the pre- and post-retrofit test periods, there were times when data was not being communicated from the site or individual sensors malfunctioned. These occurrences are to be expected for any large field test project, and they were generally corrected during a site visit a few days after they were discovered, or faster if they could be resolved remotely. Where data loss was of short duration (less than 2-3 hours) gaps were filled using interpolation. If data loss was more extensive the data were excluded from the analysis process.

3.3 Field Test Results

The following sections provide the results and conclusions derived from the field testing of PCM at five residential sites.

Interior Temperatures

The daytime and nighttime heating and cooling set points for several sites changed following the PCM installation, as shown in Figure 20 and Figure 21. Set points were estimated based on the temperature sensor readings near the thermostat while the heating or cooling system was operating. At several sites, the mild weather conditions in Sonoma County led to insufficient night-time cooling data to estimate the cooling set point. Key observations include the following:

- Heating set points changed significantly before and after the retrofit, sometimes higher and sometimes lower. The COVID 19 pandemic may be a partial explanation.
- All heating set points were consistently below 68°F, possibly because homeowners were energy conscious. However, low heating set points can also reduce the energy savings and cost-effectiveness of the measure.
- Three sites used significant thermostat setbacks at night during the heating season. Two sites did not use setbacks.
- Cooling set points were significantly lower for three of the sites following the retrofit, and there was no change in cooling set point for the others. Use of air conditioning was likely affected by COVID 19 stay-at-home guidance.

- Night-time thermostat settings were impossible to determine with confidence during the cooling season due to limited cooling loads and night-time air conditioner operation.

Figure 20: Heating set points before and after PCM installation

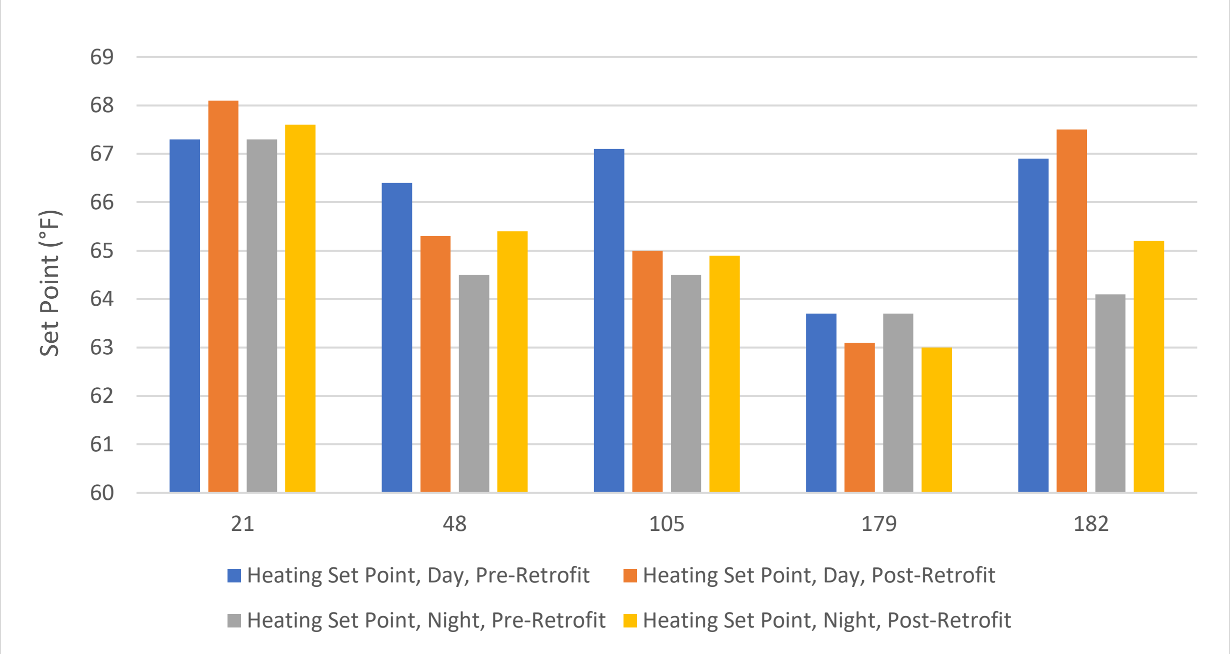
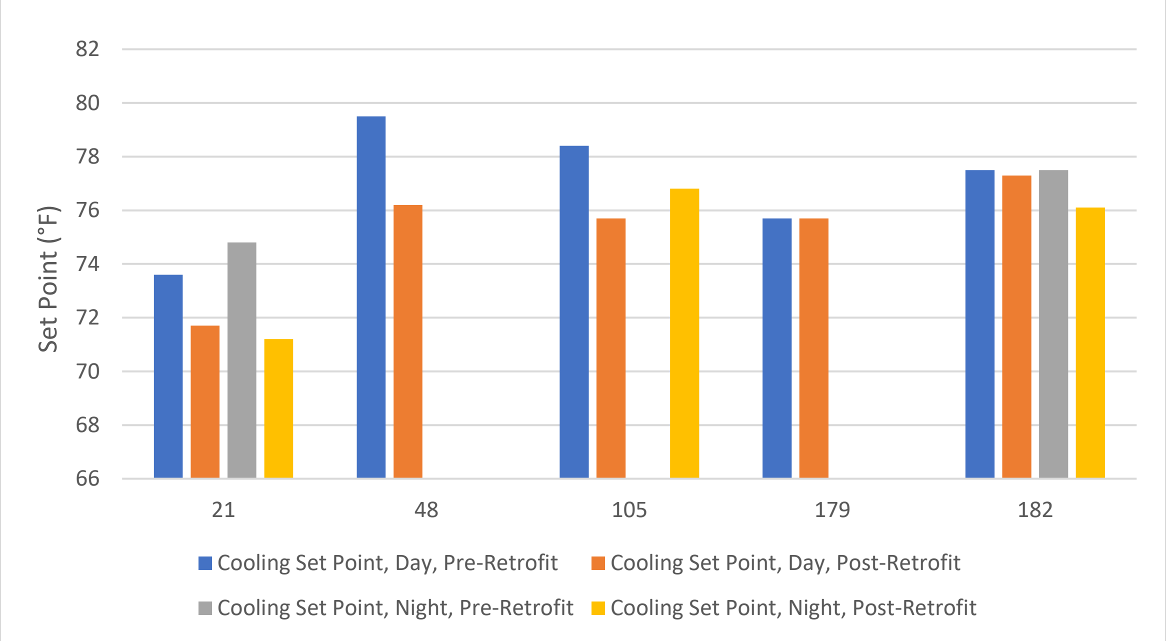


Figure 21: Cooling set points before and after PCM installation



These changes in set point could be a result of COVID 19 stay-at-home policies, changes in comfort associated with the PCM, greater use of fireplaces for heating or windows for cooling, or other behavioral changes that could not be measured. The post-retrofit survey results shed some light on potential reasons for the differences in set point, as discussed in Section 3.1. Changes to thermostat settings were accounted for in the energy savings analysis performed using direct heating and cooling measurements, as described in the next section.

Energy Savings

Changes in heating and cooling energy use following the PCM retrofits were measured using the three methods identified in Table 24.

Table 24: Three methods used to determine energy savings for field test sites

Test Method	Advantages	Disadvantages
Heat Flux Sensors	• Direct measurement of heat flow to or from the attic • Quantifies heat going into and out of the PCM • Does not require weather normalization to be meaningful	• Heat flux may be highly variable across the attic, and even across the PCM • Heat flux sensors placed against freezing and melting surface may not provide accurate readings
HVAC Monitoring	• Direct measurement of heating and cooling energy	• Includes all heating and cooling energy use, not just from the attic • HVAC efficiency is reflected in the measurements • Does not capture supplemental space conditioning (windows, fireplaces, space heaters, whole-house fans) • Requires weather normalization
Utility Bills	• Accurate whole-house energy use • Independent of monitoring issues	• Includes all energy uses in the house • Impossible to disaggregate PCM effects on cooling from other effects, unless the savings is very large • Requires weather normalization

Heat Flux Measurements

Heating and cooling loads from the attic were measured using heat flux sensors above and below the PCM layer. These measurements provide both the heat transfer into the living space, and the amount of energy storage in the PCM. Although the heat flux sensors did not generally provide reliable enough accuracy to be used in a quantitative manner, especially for the pre-retrofit period, the magnitude was consistent over time, and the direction of heat flow was reliable. As a result, the data presented in this section should be viewed primarily from a qualitative perspective, as an indicator of when freezing and melting of the PCM occurred.

The general trend is best illustrated at Site 56. During a 3-day period with cold conditions for Sonoma County (46°F average daily temperature), the PCM temperature never reached the melting point of 77˚F, as shown in Figure 22. As a result, the heat flux in and out of the PCM was similar (positive heat flux is from the house to the attic), suggesting there was no reduction in heating load during this period (see Figure 23). This is not surprising, because the value of PCM lies in its ability to store energy while it changes phase. The spike in heat flux around 7pm on January 19 corresponds to a rapid drop in temperature, perhaps due to a window being opened for ventilation. Such spikes occur frequently in the data and are usually associated with intermittent short-term changes in internal load that are unrelated to long-term performance of the PCM (cooking, steam from showers, change in thermostat setting). It must be noted that even though the heat flux values are similar to each other, they are only reading about 60-70% of the heat flux that modeling indicates should be passing through the ceiling given the temperature difference and R-values of the assembly. This again illustrates the challenge of obtaining accurate heat flux readings with the sensors adjacent to the PCM, at least for the purpose of quantifying energy savings.

Figure 22: Site 56 temperature profiles from Jan 19-21, 2020

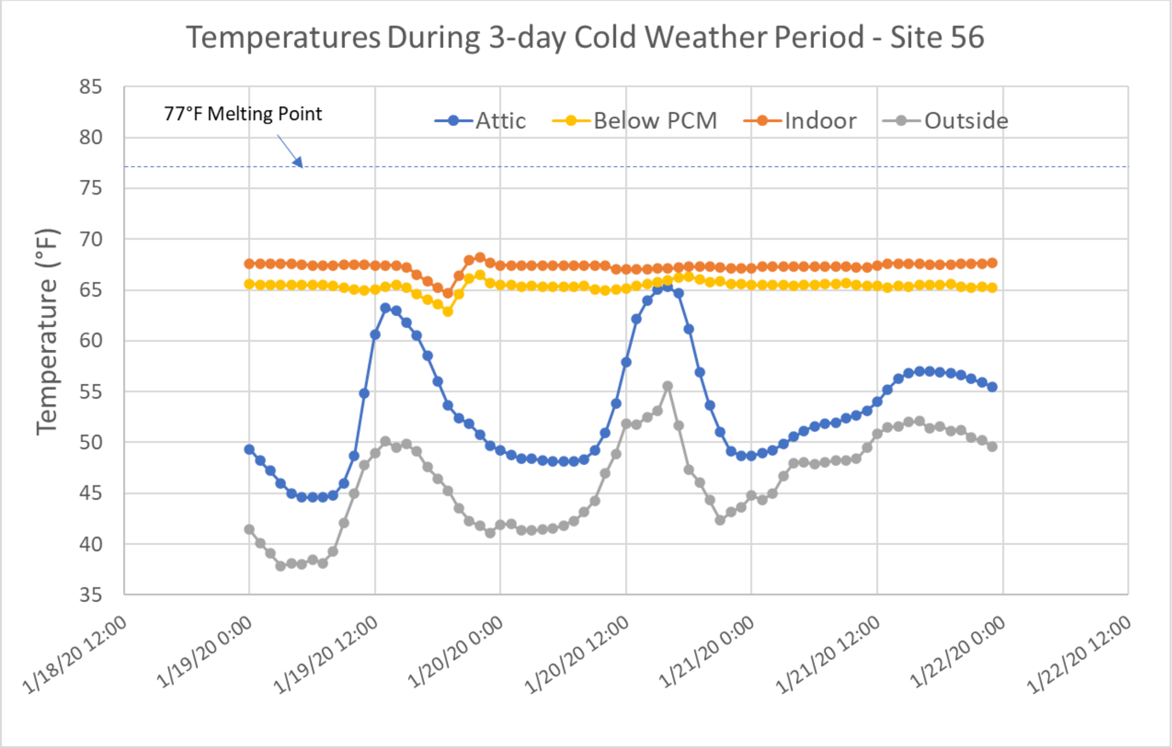
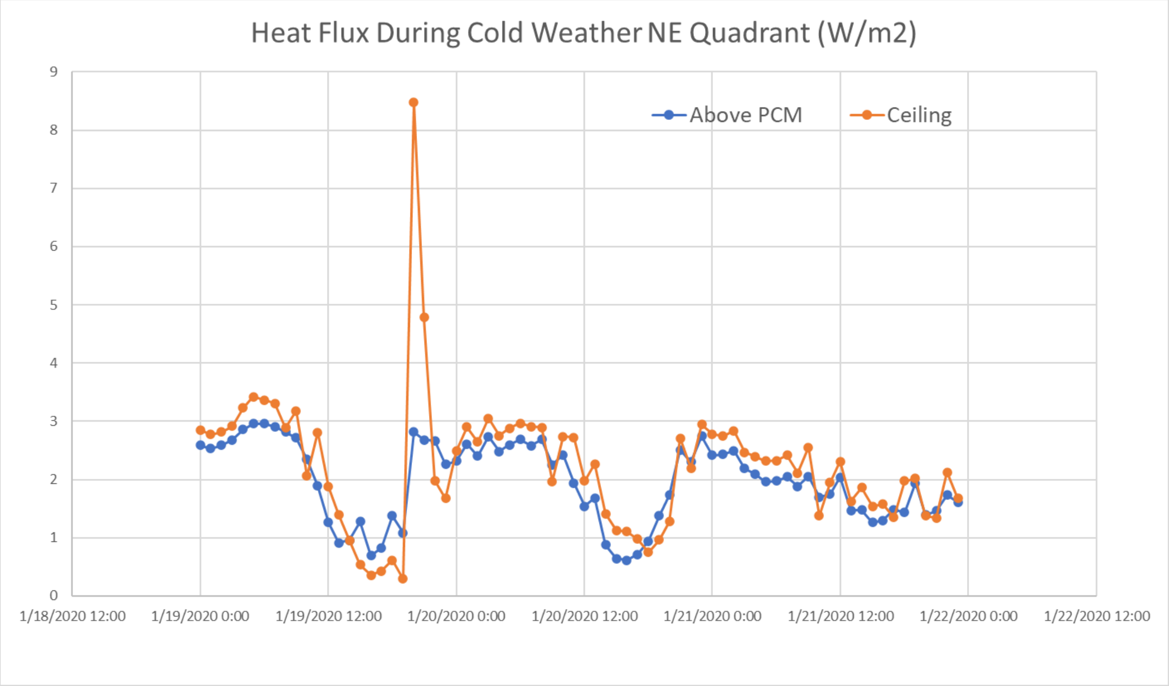


Figure 23: Site 56 heat flux in and out of PCM from Jan 19-21, 2020



During a similar period with mild weather conditions (60˚F average temperature), there is evidence of melting of the PCM as its temperature begins to get closer to 77˚F during the afternoon, as shown in Figure 24 and Figure 25. However, even though the actual melting point is spread out over a published range of 75-79˚F, the PCM does not appear to reach this range. Yet the heat flux data suggests melting and freezing activity. We're unsure if the melting point is much lower than expected, or if there is an issue with our heat flux measurements even from a qualitative standpoint. Assuming the heat flux sensors are reasonably accurate, the heat transfer into the attic appears to be delayed due to the PCM, shifting from the nighttime hours to the warmer daytime hours, though it is unclear if there is a net reduction in heating load given the uncertainty in the heat flux readings. Net heating and cooling load impacts will be examined more closely using direct HVAC system measurements in the next section.

Figure 24: Site 56 temperature profiles from Feb 25-27, 2020

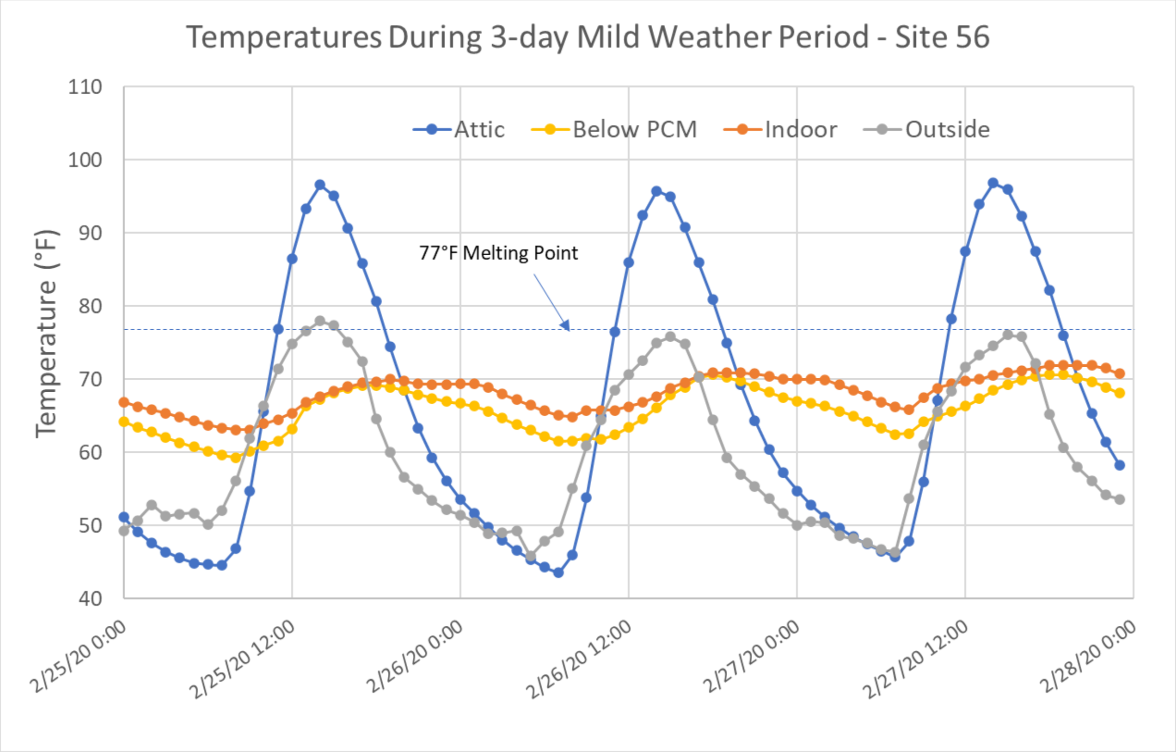
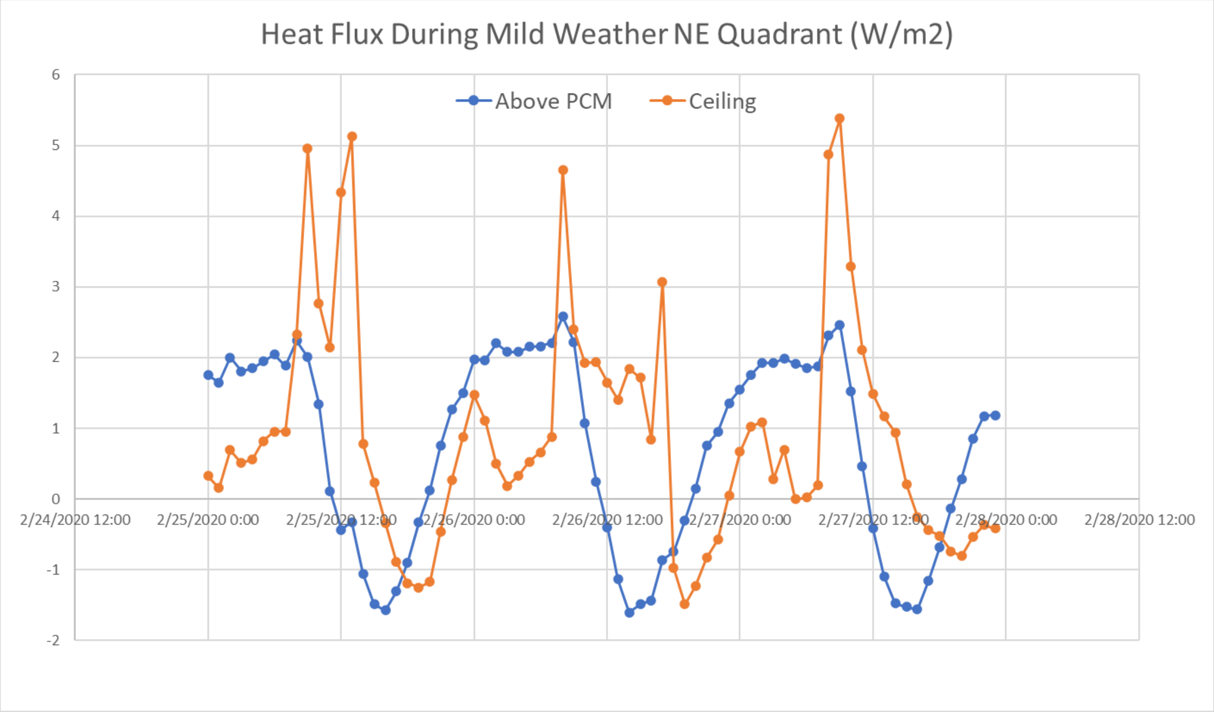


Figure 25: Site 56 heat flux in and out of PCM from Feb 25-27, 2020



Under warmer weather conditions (67˚F average temperature) the heat flux is clearly reversed above and below the PCM, as shown in Figure 26 and Figure 27. This indicates that the PCM is freezing and melting nearly continuously, as the PCM temperature now begins to exceed the low end of the melting point range (75-79˚F). The result is cooling of the interior space during hot afternoons and heating of the interior space during cool nights, which is the intended effect of PCM during warmer weather. The magnitudes of the overall heating and cooling loads appear comparable, but they may occur at more beneficial times during the day.

Figure 26: Site 56 temperature profiles from Apr 25-27, 2020

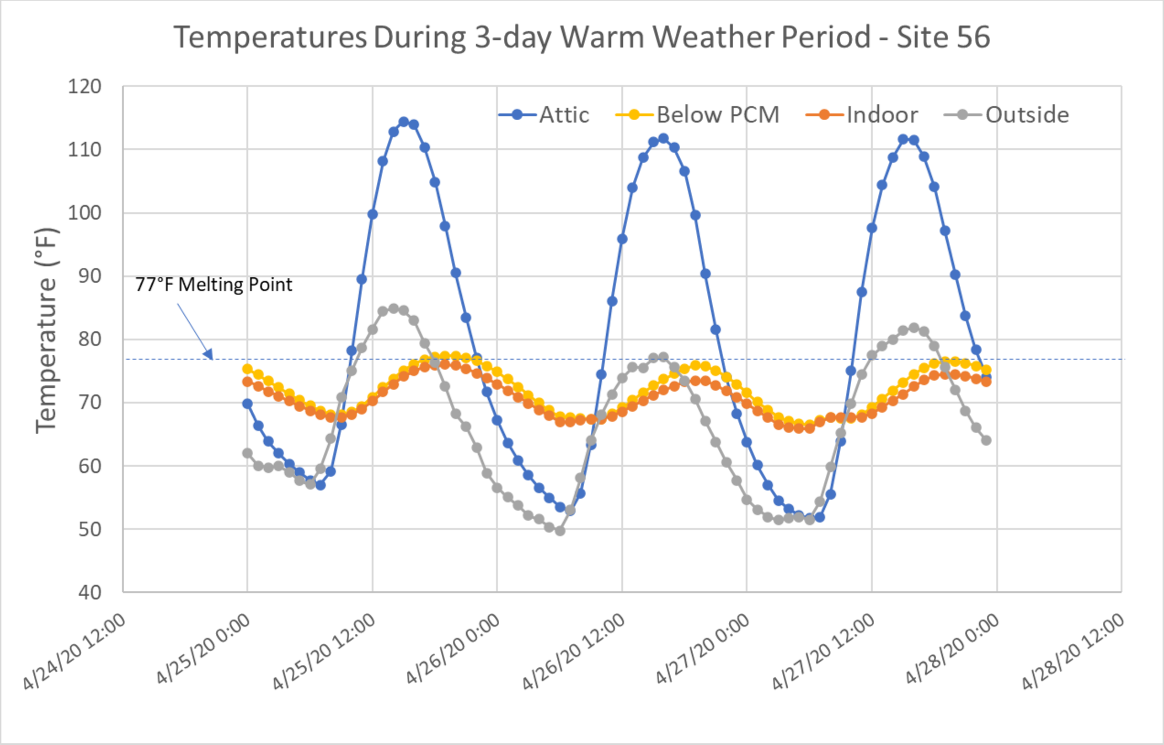
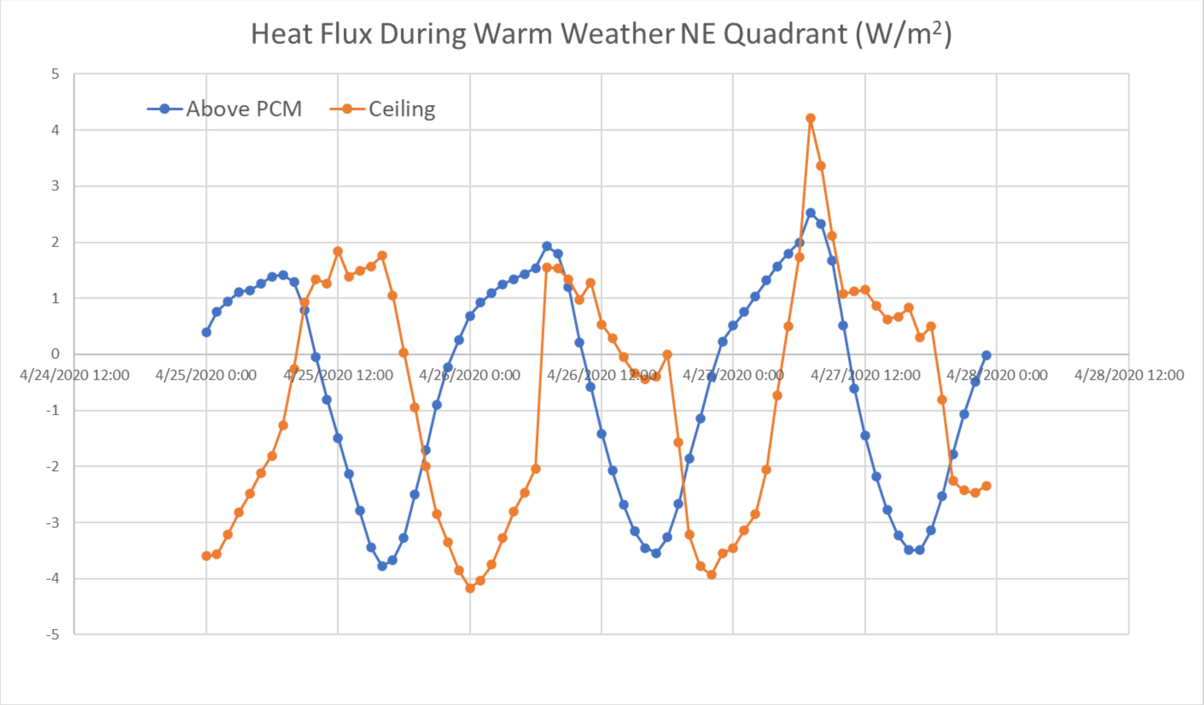


Figure 27: Site 56 heat flux in and out of PCM from Apr 25-27, 2020



During the hottest weather (80°F average temperature), the results begin to resemble the cold weather data, as shown in Figure 28 and Figure 29. Although the PCM temperature appears to hover around the melting point all day, there is minimal evidence of freezing and melting in the heat flux data. It appears the PCM offers very little benefit at this test site under very hot conditions, and for many of the test sites this is the only time the air conditioner is used.

Figure 28: Site 56 temperature profiles from Aug 13-15, 2020

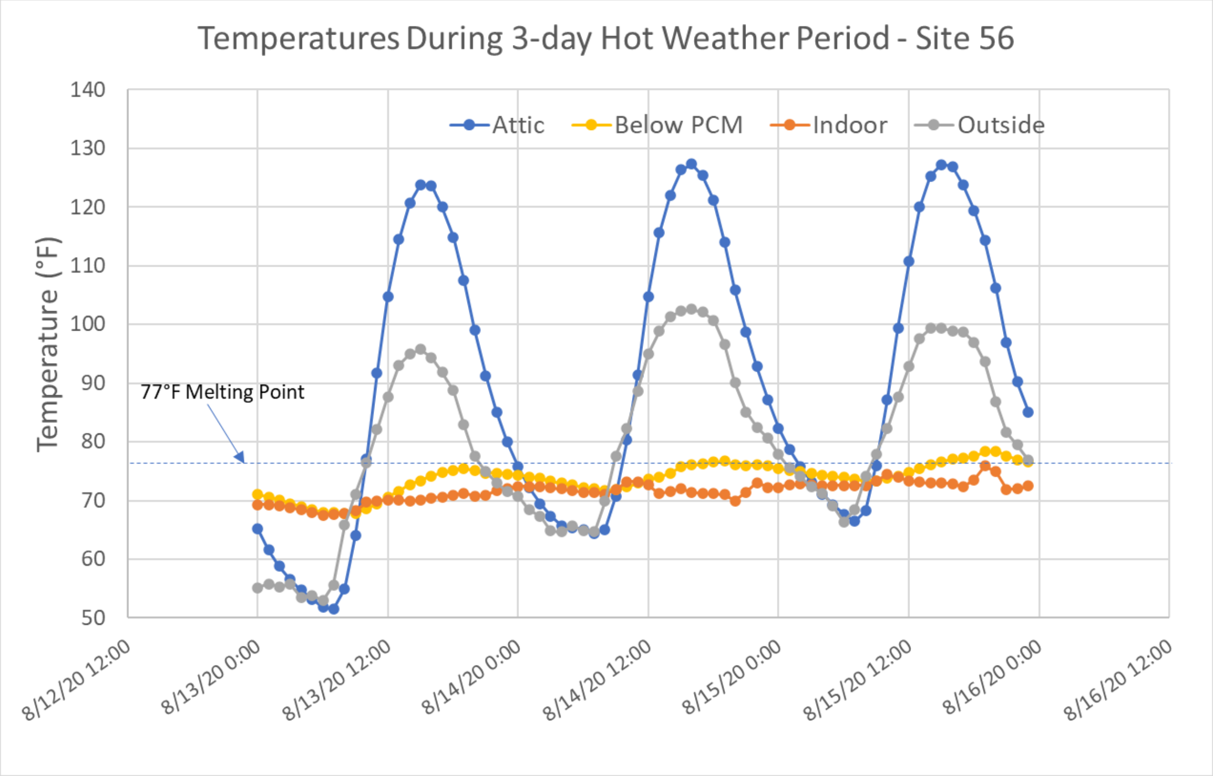
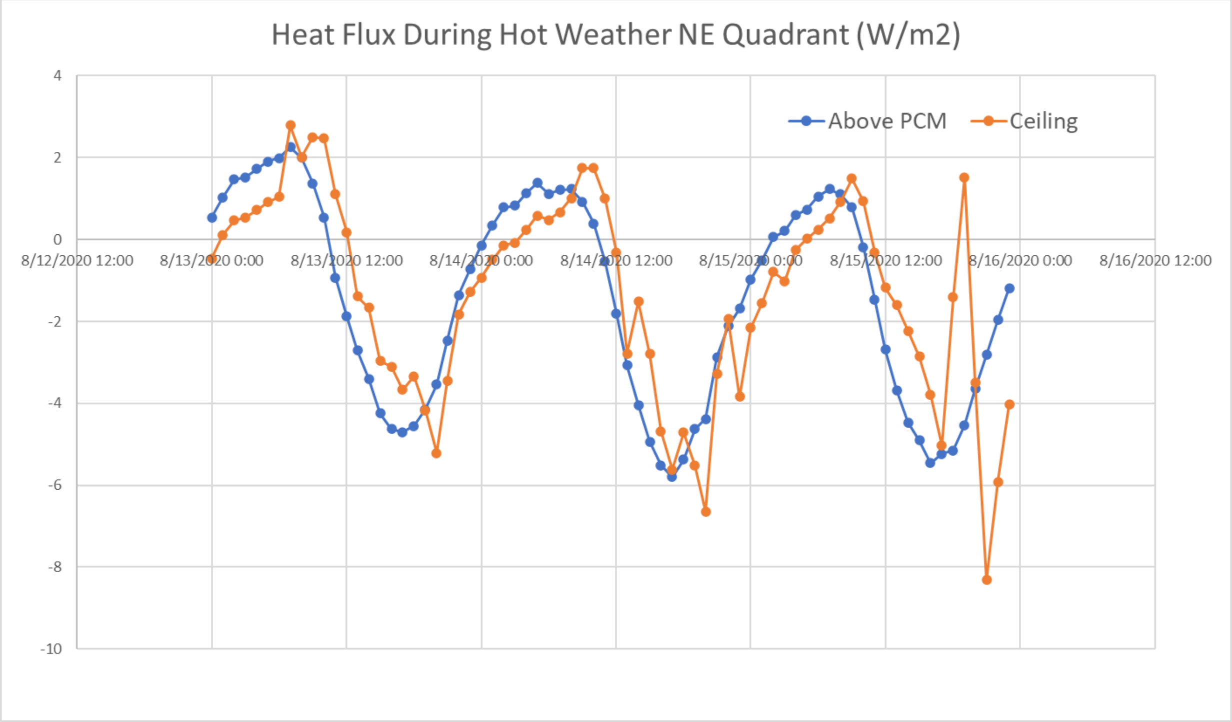


Figure 29: Site 56 heat flux in and out of PCM from Aug 13-15, 2020



HVAC Measurements

The energy use of the gas furnaces, air conditioners, and heat pumps were measured directly before and after the PCM retrofit. Due to the data conversion issues with fan measurements discussed earlier, and frequent use of the central fan without heating or cooling, we decided to leave fan energy out of the energy savings analysis for the purpose of analyzing field test results.

Because weather conditions were different before and after the retrofit, and data were collected for less than a full year, weather normalization was necessary to convert the HVAC energy into a form that could be compared on an equal basis. Nonlinear regression was used for this project because the relationship between energy storage in the PCM and the surrounding temperature is complex, and we did not expect energy savings to have a linear correlation with outside temperature. In the final analysis, two independent regression variables were used: degree hours (heating or cooling) and global horizontal solar radiation. The dependent variable was either daily heating energy or daily cooling energy. Correlations were developed using the Microsoft Excel statistics package. Examples for Site 52 are shown in Figure 30 for heating and Figure 31 for cooling. These examples illustrate the very rough correlation between weather and energy use, largely because of occupant behavior. Solar radiation is not included in the examples, because it is difficult to graphically represent a three-dimensional regression analysis in two dimensions. But it was used in the final weather normalization process.

Figure 30: Heating energy weather normalization for Site 52

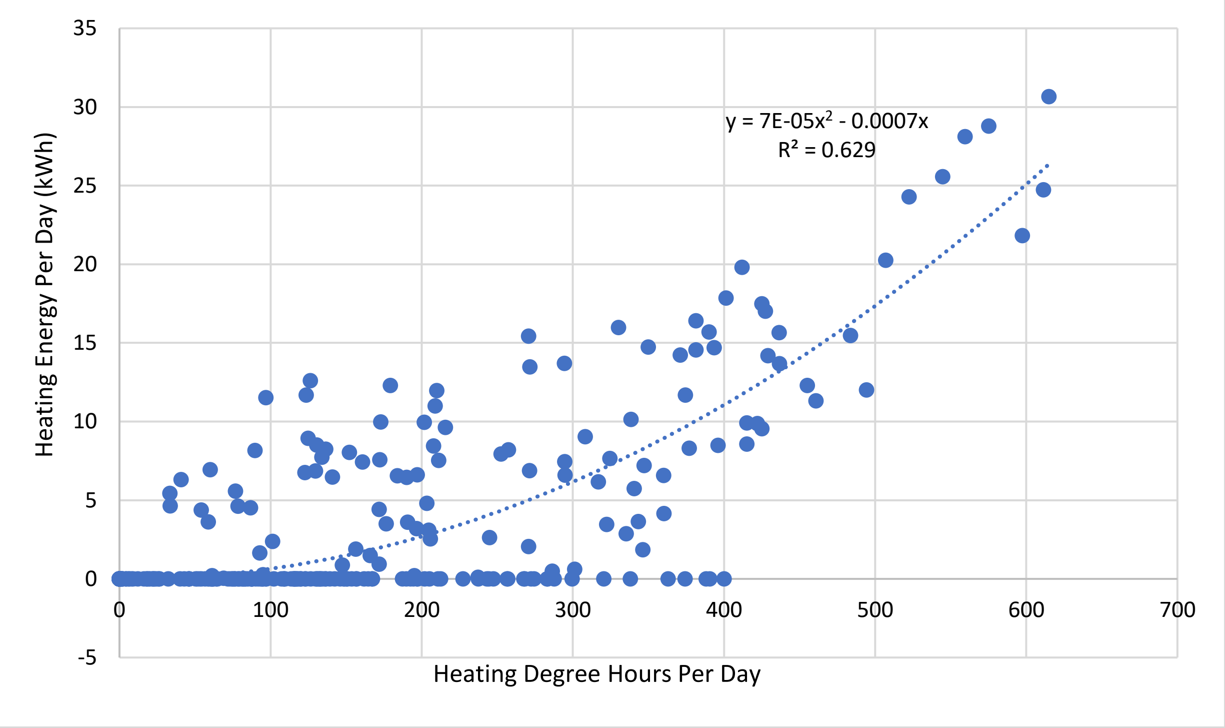
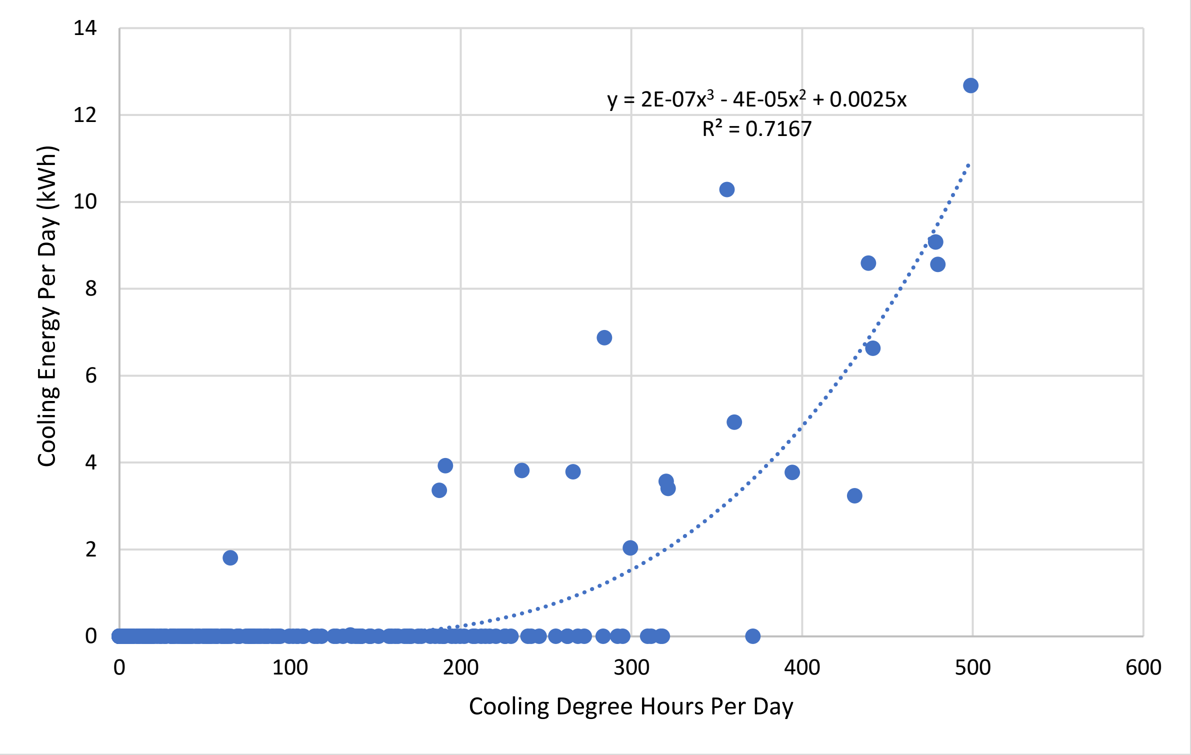


Figure 31: Cooling energy weather normalization for Site 52



Weather normalized energy use for an entire year was calculated by taking the regression equations developed for each site and applying TMY3 weather data for Santa Rosa. The heating and cooling energy for each site was then adjusted based on EnergyPlus simulation of the effects of changes to thermostat settings and occupancy levels before and after the retrofit. For example, if the cooling set point changed from 78°F before the retrofit to 76°F afterward, and the energy model predicted a 20% increase in cooling energy, a multiplier of 1.2 was applied to the pre-retrofit results to compensate for COVID-19 and other impacts on occupant behavior that we could quantify based on measured data and surveys. The results are summarized in Table 25, and estimated energy savings is shown graphically in Figure 32.

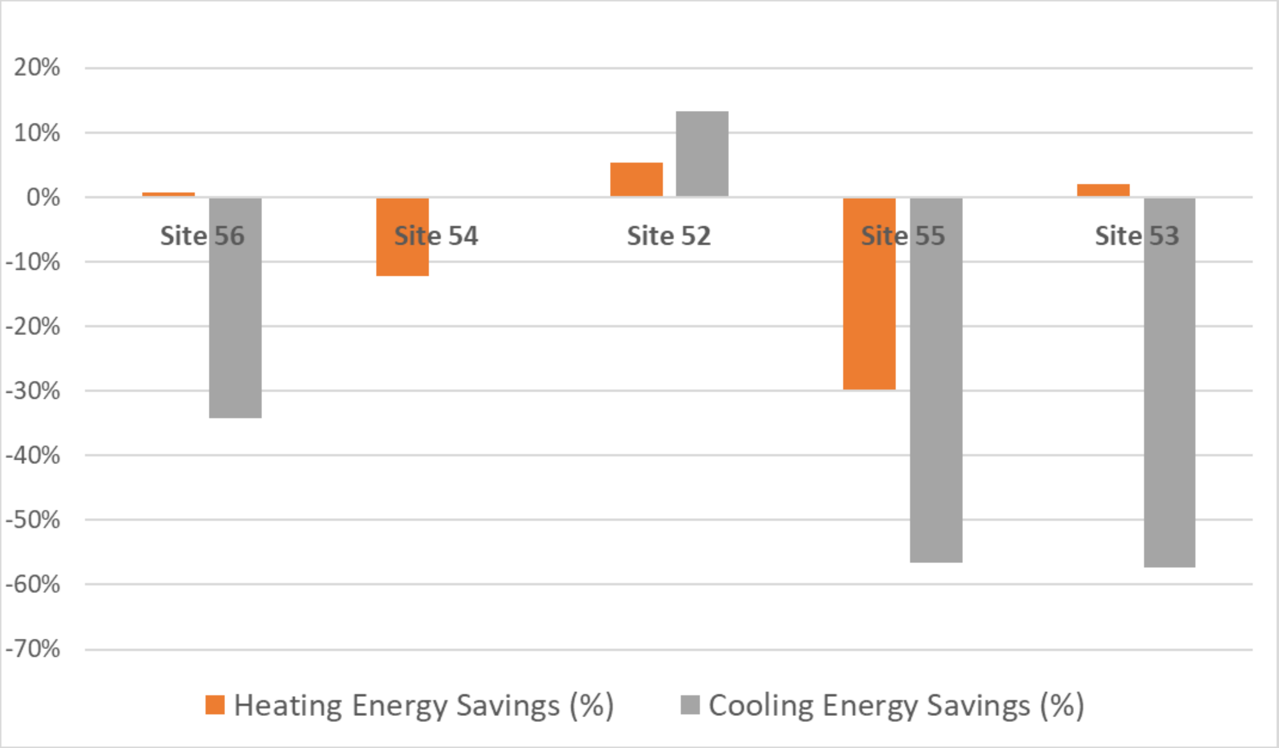
Table 25: Weather and behavior normalized heating and cooling energy use at 5 test sites based on HVAC monitoring.

Site	Site 56	Site 54	Site 52	Site 55	Site 53	Total
Annual Weather Normalized Heating Energy (kBtu), Pre-Retrofit	25,332	9,885	7,493	27,890	7,654	78,254

Occupancy Behavior Adjustment to Match Post-Retrofit	1.13	1.00	0.92	0.87	1.19	
Annual Fully Normalized Heating Energy (kBtu), Pre-Retrofit	28,625	9,885	6,893	24,264	9,108	78,776
Annual Normalized Heating Energy (kBtu), Post-Retrofit	28,439	11,086	6,531	31,473	8,932	86,461
Heating Energy Savings (kBtu)	186	-1,201	363	-7,209	176	-7,685
Heating Energy Savings (%)	0.7%	-12.1%	5.3%	-29.7%	1.9%	-9.8%
Annual Weather Normalized Cooling Energy (kWh), Pre-Retrofit	317	N/A	52	3.6	17	390
Occupancy Behavior Adjustment to Match Post-Retrofit	1.19	2.49	1.41	1.02	1.06	
Annual Fully Normalized Cooling Energy	376	N/A	73	4	18	471

(kWh), Pre-Retrofit						
Annual Normalized Cooling Energy (kWh), Post-Retrofit	572	N/A	65	8.4	42	687
Cooling Energy Savings (kWh)	-196	N/A	9	-5	-24	-216
Cooling Energy Savings (%)	-34.2%	N/A (Unmonitored window A/C)	13.3%	-56.5%	-57.4%	-31.4%

Figure 32: Heating and cooling energy savings for 5 test sites based on HVAC measurements normalized for weather and changes to occupant behavior



Unfortunately, the results of the field test are inconclusive, though it's interesting to note that the site with PCM above the insulation (Site 52) seemed to perform the best. It is evident that the energy savings is either small compared to unquantified behavioral changes following the retrofit, or the PCM sometimes results in higher heating and cooling energy use. Intuitively, the latter seems unlikely due to the nature of PCM acting as thermal storage, not to mention the additional attic insulation that was added to all five sites. PCM can only inhibit heat transfer to and from the attic and shift it to other times of day. It cannot generate heat. Therefore, the only way PCM can cause negative savings is if the amount of beneficial heat transfer to or from the attic that is blocked by the PCM (such as the reduced free cooling during summer nights as the PCM freezes) outweighs the reduction in non-beneficial heat transfer (blocking heat from the attic during summer days as the PCM melts), in combination with how the HVAC system is used by the occupants. For example, if the cooling load is shifted from a time when the air conditioner is turned off to a time when the air conditioner is turned on, there could be negative cooling energy savings. This possibility will be examined more closely in Chapter 4: Lab Test Results.

Utility Bill Analysis

Because measurements of heating and cooling energy were performed directly, utility bill analysis was viewed as a backup method of estimating energy savings for the five test sites. Utility bills introduce additional uncertainty because space conditioning must be disaggregated from other energy end-uses, such as hot water, lighting, and appliances. Behavior effects, including COVID-19 quarantine periods, have an even greater impact on non-HVAC end uses. Although utility bill analysis was performed for completeness, it should be recognized that it provides minimal additional value for quantifying energy savings resulting from the PCM measure.

The pre-retrofit energy data could not be compared directly to the post-retrofit energy data because each year experienced different weather patterns. To weather normalize the utility bill data, a utility bill normalization tool created by Degree Days.net was utilized[1]. This tool analyzes the utility billing data relative to the actual weather data seen over the billing period, rather than using standardized weather data such as from a Typical Meteorological Year (TMY3) file. The monthly utility billing data is entered, and a local weather station is selected, then the tool calculates the degree days for that billing period and performs thousands of regressions against the data to provide the best fit lines for both gas and electricity. After the tool finishes its calculations, it provides approximately 8-10 different models found to have the best statistical fit. These models use a variety of balance point temperatures, representing the outside temperature at which there is no heating or cooling load on the house. To standardize the approach, the linear regression model using a balance point temperature of 65°F for both HDDs and CDDs was chosen for all sites.

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[1] https://www.degreedays.net/

The heating and cooling degree days calculated for the post-retrofit period of the project were used in the linear regression equation derived from the pre-retrofit data. The form of this equation is shown below in Equation 1. This approach normalizes the pre-retrofit billing data to the same weather conditions experienced during the post-retrofit period. The savings from the electric and gas utility billing data can then be determined by comparing the normalized pre- and post-retrofit data.

$$Predicted\ Monthly\ Energy = a_{Pre} \cdot HDD_{Post} + b_{pre} \cdot CDD_{post} + c_{pre} \cdot (\#\ of\ Days) \qquad (1)$$

Where a_{Pre} is the HDD coefficient derived from the linear regression process, b_{pre} is the CDD coefficient, can C_{Pre} is the constant, which is multiplied by the number of days in the month.

As an example, the weather normalized electric utility data for Site 55 is shown in Figure 33, and the weather normalized gas utility data is shown in Figure 34. Only 11 months of data were available for this analysis, with December missing because that was the month when the PCM was installed. As a result, this is not a full year comparison, but it covers several months during the heating and cooling seasons and provides an adequate data set for the purpose of calculating percent savings.

Figure 33: Weather normalized monthly utility data for electricity at Site 55

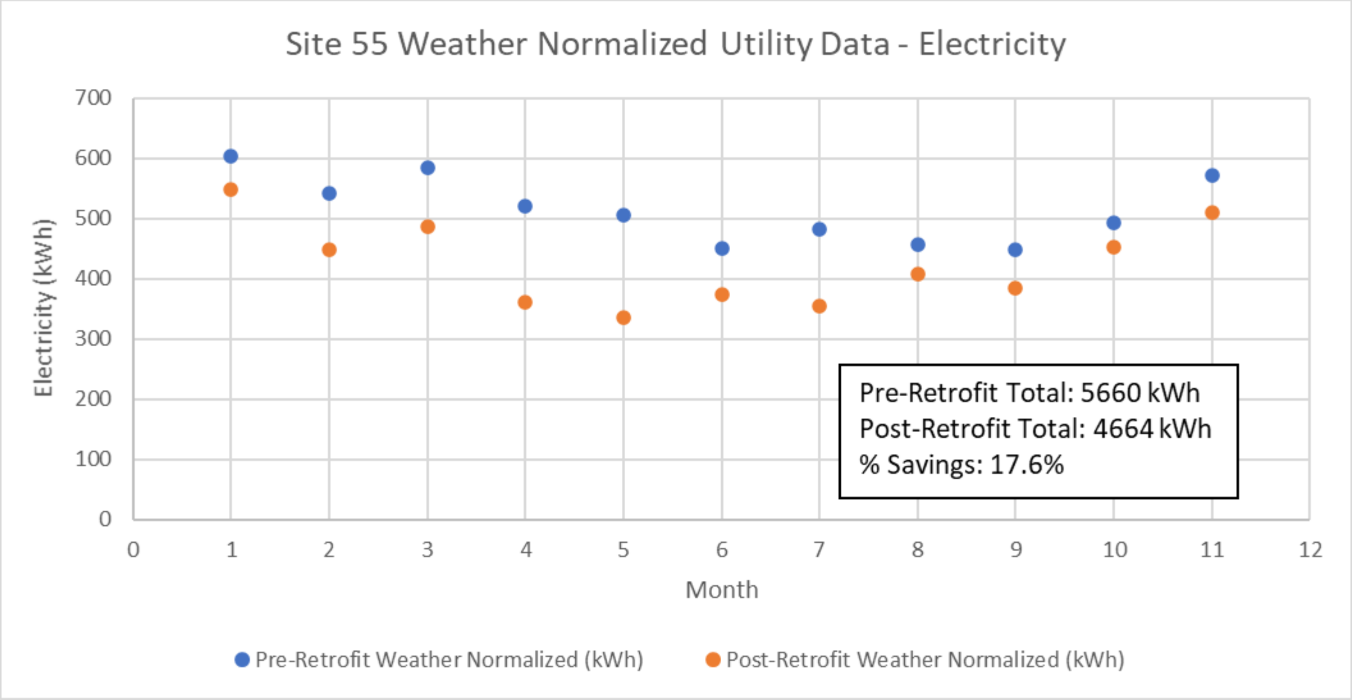
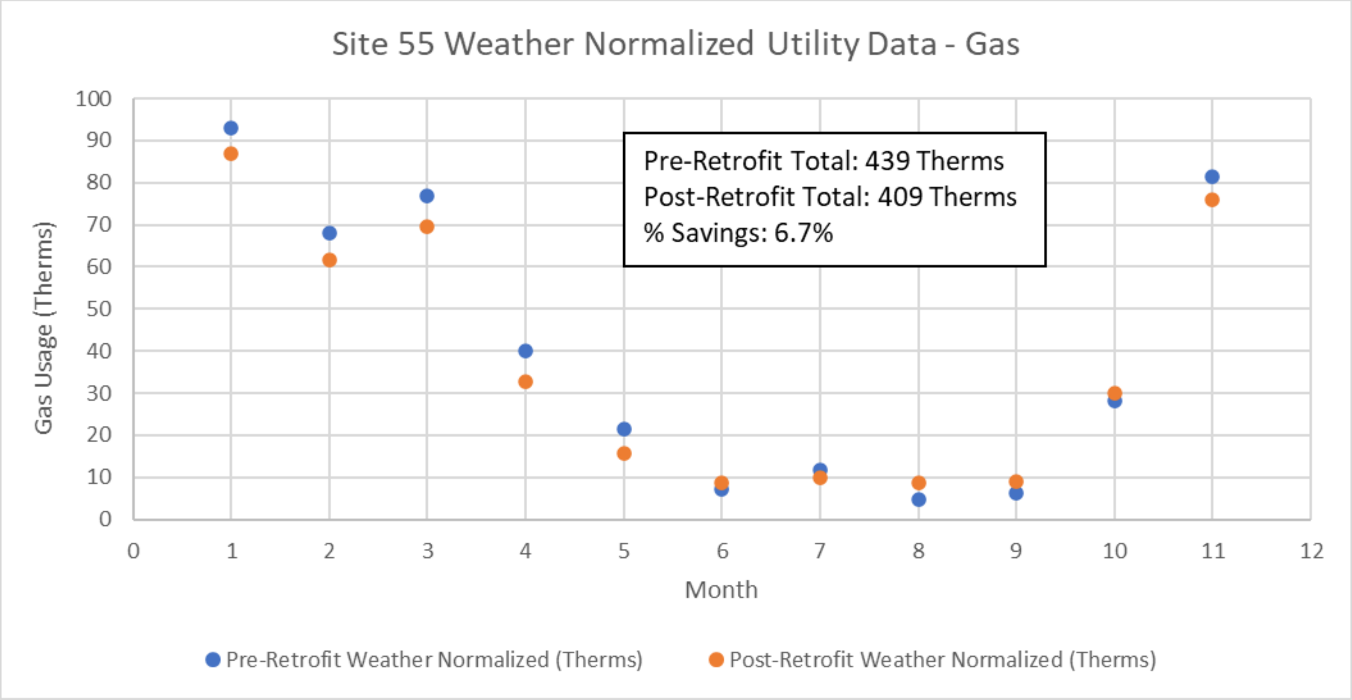


Figure 34: Weather normalized monthly utility data for natural gas at Site 55



A summary of the utility bill analysis is provided in Table 26. The results suggest a mix of positive and negative energy savings for both gas and electricity, with a total of 3.9% less electricity use and 8.1% less gas use during the 11-month period. However, it must again be noted that the impact of occupant behavior is almost certainly much larger than the actual energy savings for the PCM, as suggested by the large variations in savings across different sites.

Table 26: Weather normalized utility billing data at 5 test sites (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%**

Durability

There has been no evidence of degraded thermal performance of the PCM since it was installed. However, leaks have been observed at two of the test sites since they were decommissioned at the conclusion of the test period. In addition, water has accumulated on the mats at one test site, and on the PCM mats in unopened boxes at the BSRL. Details for each situation are described below:

- Site 54
  - At least two dozen stains began appearing at the ceiling in mid-2021, about 12-18 months after PCM installation
  - All PCM was removed in December 2021. There were evident leaks in about 40% of PCM mats, almost always on the bottom
  - Many of the leaks appeared where there were scuff marks or other surface damage that may have weakened the integrity of the encapsulating material (see Figure 35). Others appeared near seams where the PCM was sealed during manufacturing.
  - Some leaks are clear, some are brown. It appears the PCM material breaks down into components after being exposed to air, or it attracts water from the air. Once leaking, the PCM remaining in the encapsulation does not freeze.

    - Lab tests were performed to determine the rate of leak penetration through the drywall. It took approximately 4 weeks before PCM applied on one surface appeared as a stain on the other. This makes it very unlikely the leaks were caused during installation. More likely there was gradual degradation leading to leaks over a year after installation. Stains in the drywall did not dry out after a month inside the laboratory. Stained locations were structurally weak and mushy.
    - A contractor is currently being hired to repair the drywall damage and clean up any residual PCM that may have leaked onto the top of the drywall.
- Site 52
    - About 25 leaking PCM mats were removed and replaced in the fall of 2021.
    - Some leaks consisted of brown material, some seemed to be clear water.
    - Leaks primarily occurred at sealing points in the material (see Figure 36), suggesting possible manufacturing flaws.
    - The site was revisited in February 2022, and no additional leaks or significant water accumulation were observed.
    - There appeared to be compression of the insulation due to the weight of the PCM, and the PCM seemed to have become wet in places due to the leaks. The site will be reinsulated after the PCM is removed.
- Site 56
    - Multiple leaks and wet spots were discovered when a contractor visited the site in February 2022.
    - The PCM was removed on March 7, 2022, and the leaks were cleaned up. On March 12, the site was revisited, and the wet spots had dried out, with no structural damage to the drywall. These spots will be sealed and repainted.
- Other test sites
    - No leaks or stains have been reported at the other 2 residential sites. A contractor is currently visiting these sites to determine if leaks are present, and the extent of possible damage.
- At BSRL
    - After 2 years, several boxes of unused PCM were opened. A large amount of water (or clear liquid) had beaded on the surfaces of the PCM and was beginning to accumulate (see Figure 37). There was no evidence of any leaks. Condensation did not seem to be a possibility, because the temperature of the PCM was the same as the surrounding air.
    - Many of the PCM mats at the lab showed evidence of degradation to the encapsulation material, but no leaks large enough to be visible. At the time this assessment was performed, the PCM was frozen, which may be the reason there were no leaks evident.

Figure 35: PCM mat with multiple leaks near scuff marks from Site 54

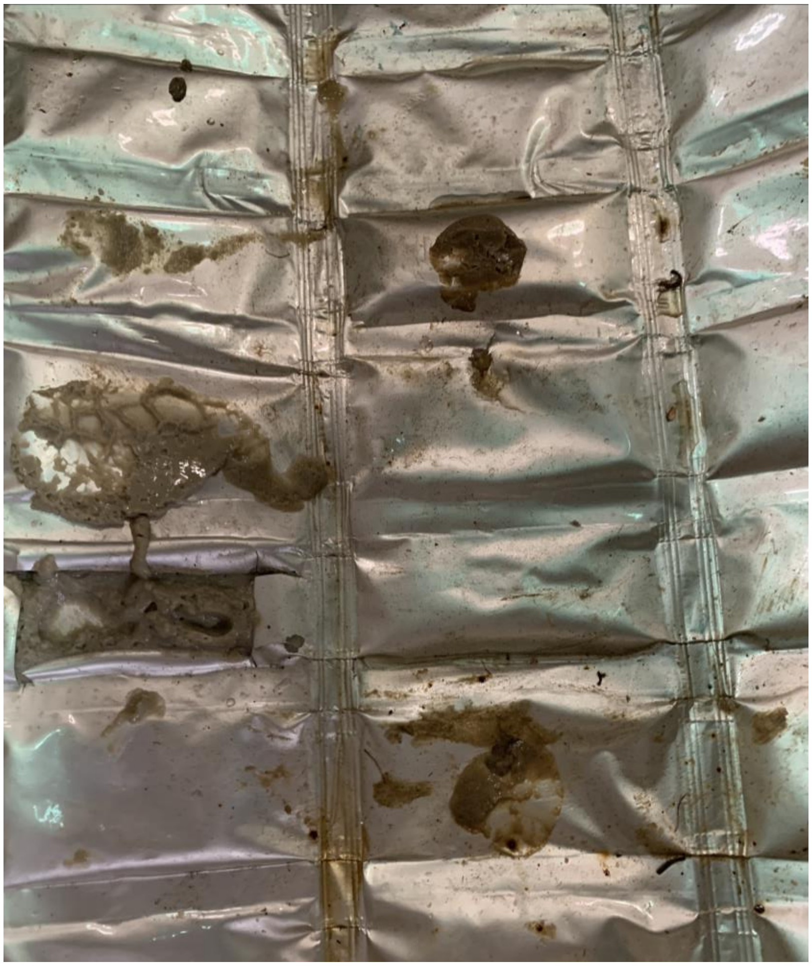


Figure 36: PCM mat with leak at seam from Site 54

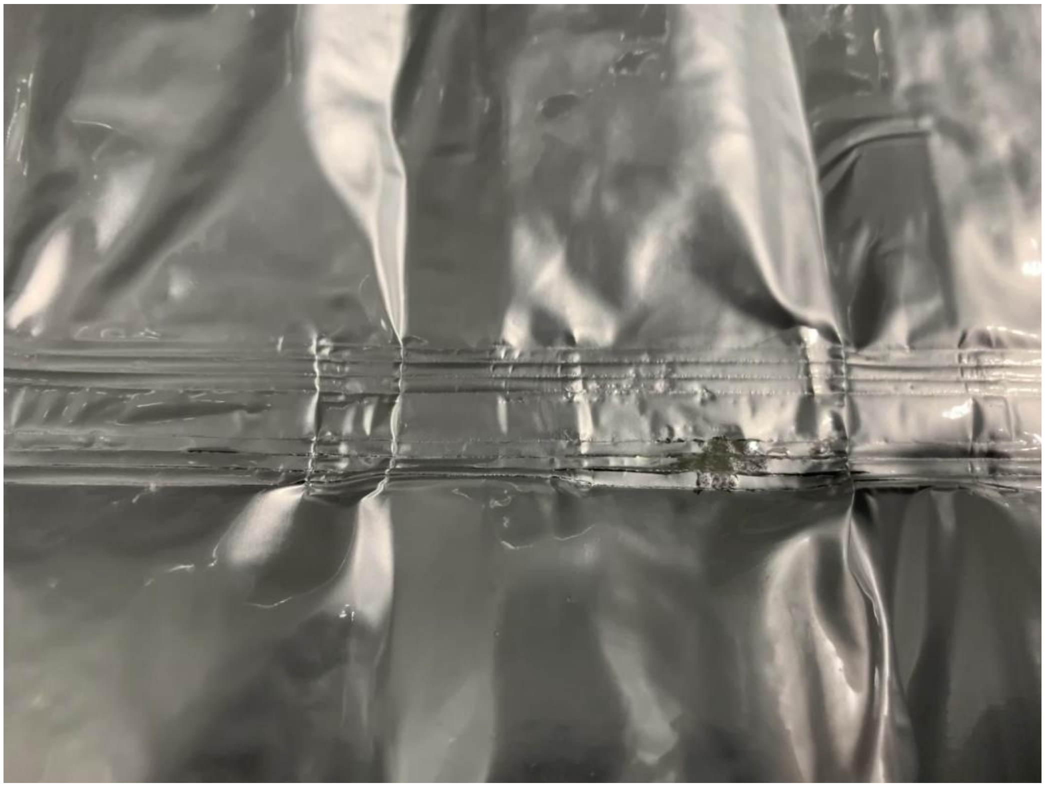


Figure 37: PCM mat with water accumulation at the BSRL

We have subsequently learned that the clear liquid was water attracted from the air by salt residue left on the surface of the PCM mats during the manufacturing process. The brown liquid was PCM leaking through a weak point in the product caused by a malfunctioning piece of equipment that was diagnosed and fixed by the factory in 2021. Additional leaks at Site 54 appear to have been caused by rough handling during installation.

Frontier Energy made a decision in consultation with SCP to remove all of the Infinite R material from all five residential sites, even though at this point three of the homeowners do not see any evidence of leaks. Regardless of energy savings potential, the potential for leaks and water damage prevented us from pursuing further deployment of this technology in residential attic applications. Insolcorp is currently producing a new product with PCM encapsulated in a more rigid package, which has been tested under Lead Locally in commercial drop ceiling applications and has shown no signs of leakage so far.

CHAPTER 4:
Lab Test Results

The laboratory tests conducted at the BSRL were performed in accordance with the approach described in Section 2.1. This section presents the key results from the lab tests.

4.1: Lab Test Matrix

The lab test matrix is provided in Table 27. All tests were successfully completed.

Table 27. Lab Test Schedule

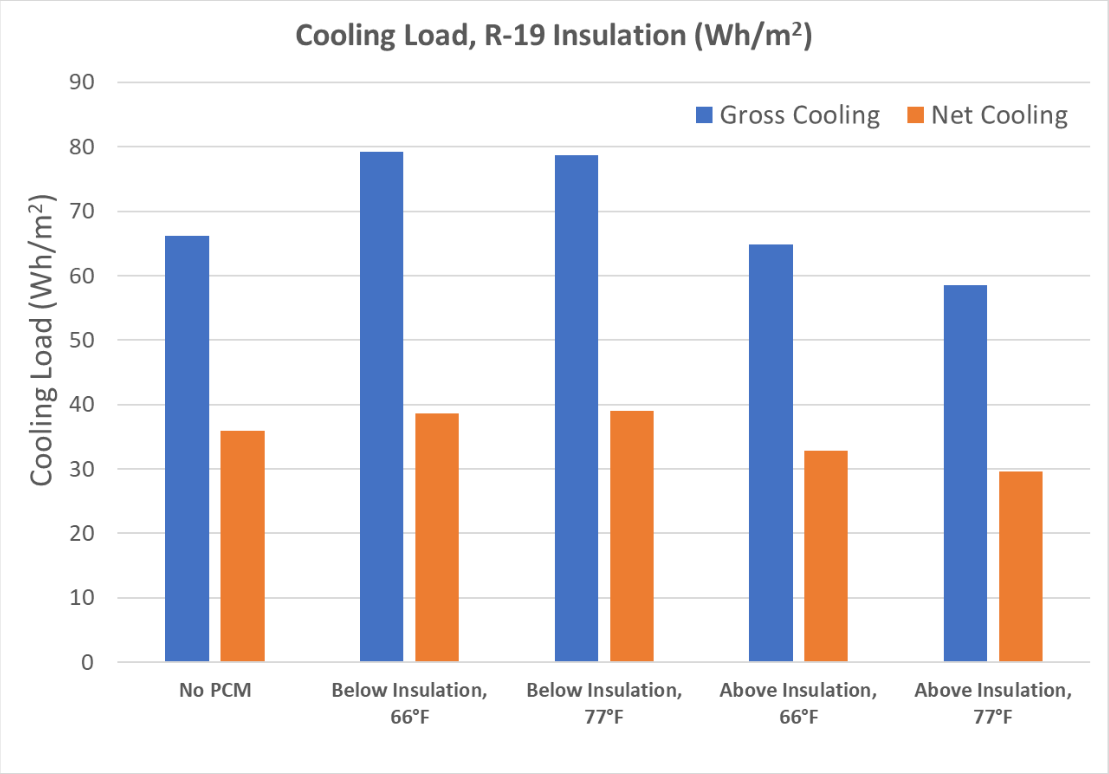
Test	Melting Point (°F)	Indoor Temperature Schedule	Insulation	Season	PCM Orientation
1	66°F	Title 24 Schedule	R-19	Cooling	Below Insulation
2	66°F	Title 24 Schedule	R-19	Heating	Below Insulation
3	77°F	Title 24 Schedule	R-19	Cooling	Below Insulation
4	77°F	Title 24 Schedule	R-19	Heating	Below Insulation
5	77°F	Constant Temperature	R-19	Cooling	Below Insulation
6	77°F	Constant Temperature	R-19	Heating	Below Insulation
7	77°F	Constant Temperature	R-38	Cooling	Above Insulation
8	77°F	Constant Temperature	R-38	Heating	Above Insulation
9	66°F	Title 24 Schedule	R-19	Cooling	Above Insulation
10	66°F	Title 24 Schedule	R-19	Heating	Above Insulation
11	77°F	Title 24 Schedule	R-19	Cooling	Above Insulation
12	77°F	Title 24 Schedule	R-19	Heating	Above Insulation
13	77°F	Title 24 Schedule	R-38	Cooling	Above Insulation
14	77°F	Title 24 Schedule	R-38	Heating	Above Insulation
15	Baseline	Title 24 Schedule	R-19	Cooling	No PCM
16	Baseline	Title 24 Schedule	R-19	Heating	No PCM
17	Baseline	Title 24 Schedule	R-38	Cooling	No PCM
18	Baseline	Title 24 Schedule	R-38	Heating	No PCM
19	Baseline	Constant Temperature	R-19	Cooling	No PCM
20	Baseline	Constant Temperature	R-19	Heating	No PCM
21	Baseline	Constant Temperature	R-38	Cooling	No PCM
22	Baseline	Constant Temperature	R-38	Heating	No PCM
23	77°F (Not Simulated)	Title 24 Schedule	R-38	Cooling	Above Insulation

4.2: Lab Test Energy Savings Results

The change in cooling load for two melting points and two PCM configurations are shown in Figure 38. Both gross cooling and net cooling are presented. We define gross cooling as the total cooling load during hours when a cooling load is present, while net cooling subtracts the free cooling that occurs overnight when the attic temperature is below the interior (technically a "heating load", even though the furnace would not operate). Both numbers can be important, and modeling is ultimately required to determine the net effect of the attic on cooling energy, with and without PCM.

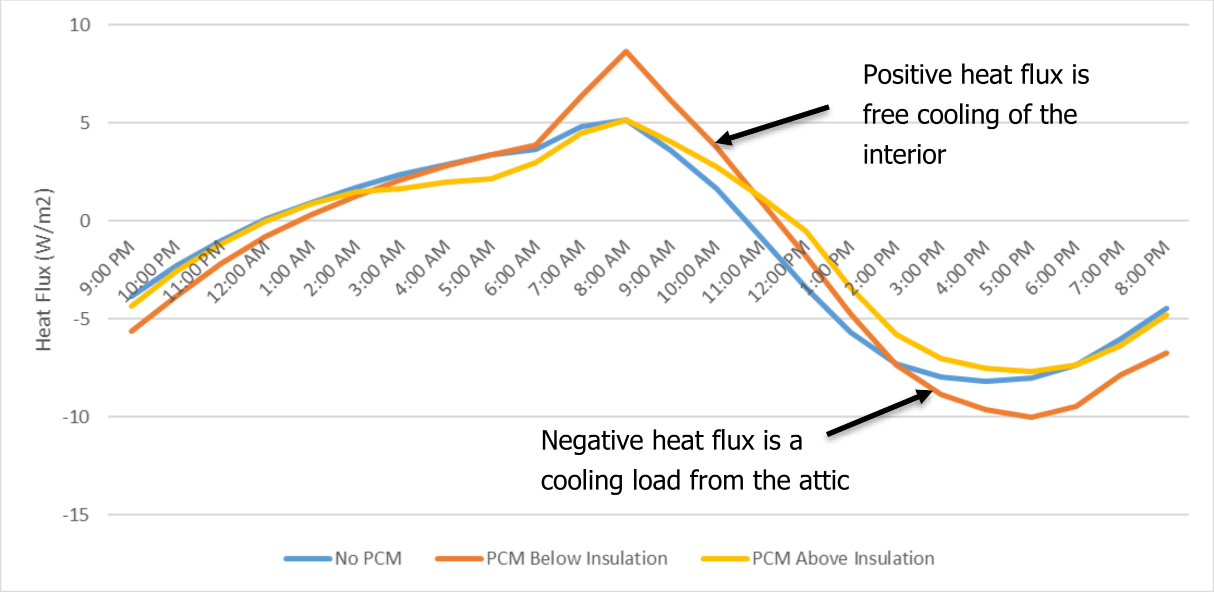
The results were unexpected, but not inconsistent with the field test results discussed earlier. With PCM above the insulation, a modest decrease in cooling load was measured, and the 77°F melting point PCM performed better than 66°F. However, with PCM below the insulation, the gross and net cooling loads went up compared to the baseline case of no PCM. It remains a possibility that the heat flux sensors used for the lab tests, which were higher quality sensors than those used in the field tests, do not provide accurate readings when placed against PCM material that is changing shape while it freezes and melts. But we must also consider the growing evidence that the PCM can actually have a negative impact on cooling energy use. These tests were conducted for one day with one set of assumptions about attic temperatures and interior set points, and it is difficult draw conclusions about cooling load impacts for the entire summer without modeling, which will be discussed in Chapter 5.

Figure 38: Cooling load reduction for alternate melting points and installation configurations using R-19 insulation and Title 24 thermostat settings



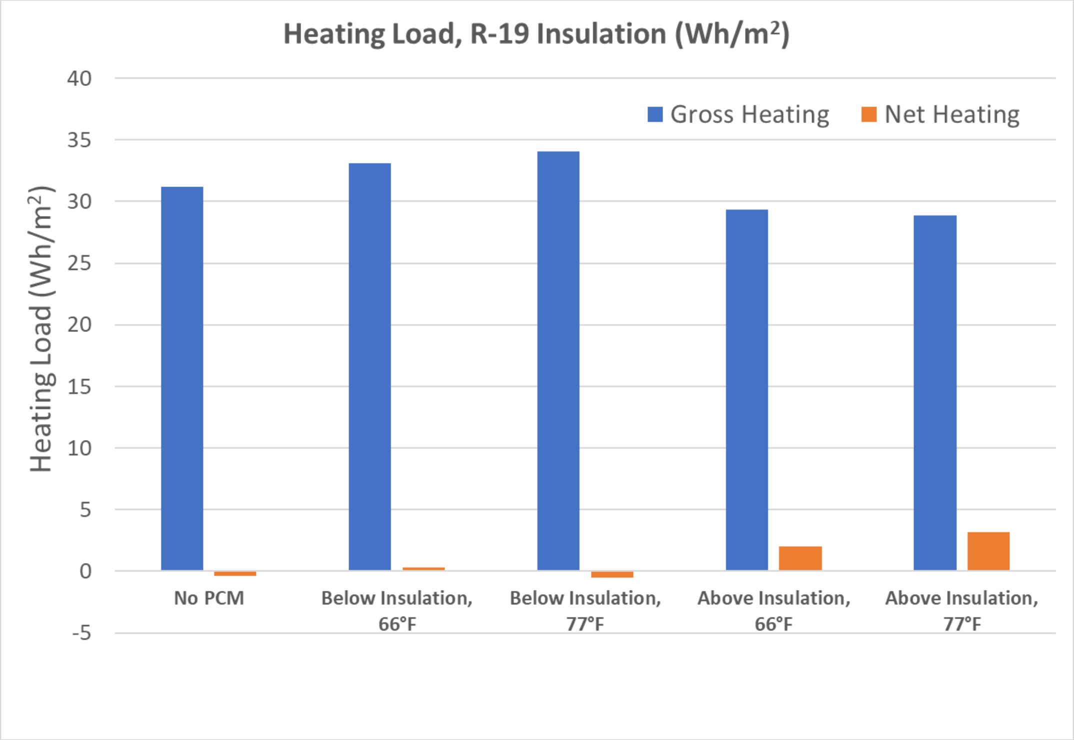
Heat flux measurements during this series of tests shed additional light on the results, as shown in Figure 39. Our sign convention is that heat flux upward into the attic from conditioned space is positive, meaning cooling loads are negative. The heat flux data indicate that a small delay in heat transfer results from the melting and freezing of the PCM, but this delay is not very large. In addition, the peak loads are not dampened by the PCM, they are merely shifted and sometimes amplified as attic and interior temperatures change.

Figure 39: Heat flux measurements with and without PCM during cooling season with Title 24 thermostat settings



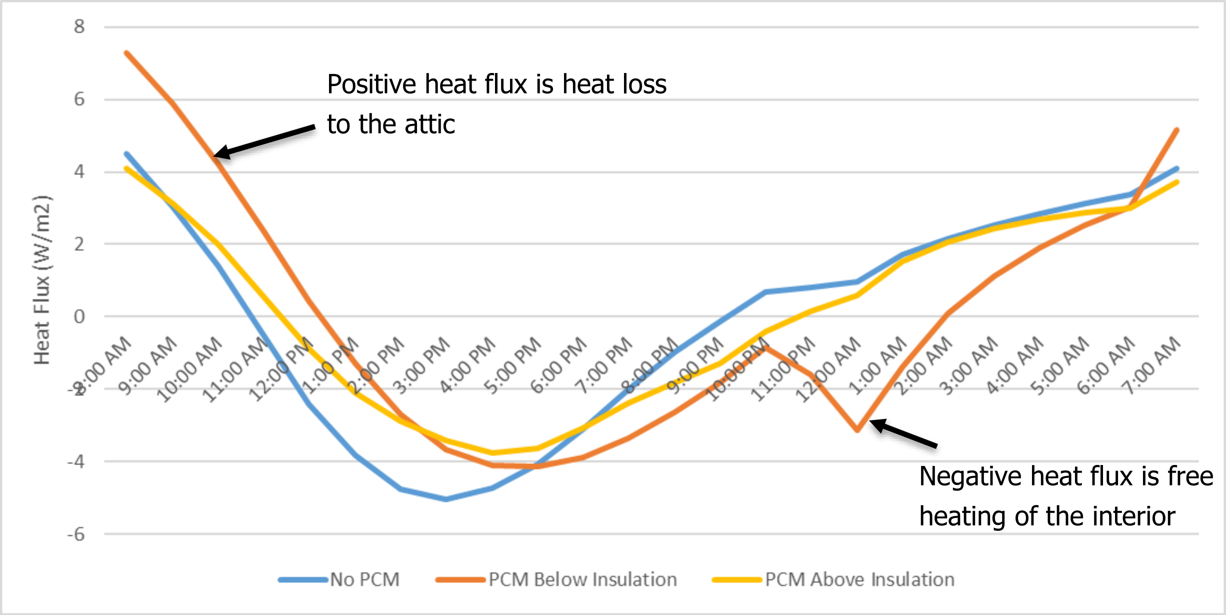
Gross and net heating loads for the typical winter day are shown in Figure 40. In this case, gross heating loads are reduced when PCM is installed above the insulation and increase when PCM is below the insulation. However, net heating loads are worse in both cases where PCM is added. The 66°F melting point appears to perform a little better than 77°F in heating mode.

Figure 40: Heating load reduction for alternate melting points and installation configurations using R-19 insulation and Title 24 thermostat settings



Heat flux measurements for the winter day are shown in Figure 41. The data indicate some shifting of heat loads, and more dampening of free heating energy from the attic than dampening of actual heat load overnight. For PCM under the insulation the peak heating load is significantly higher than without PCM and shows greater sensitivity to the reduction in thermostat setting at 10pm, at which point it begins to freeze rapidly (heating the interior at a time when it's not very beneficial).

Figure 41: Heat flux measurements with and without PCM during heating season with Title 24 thermostat settings



The effect of higher insulation levels on cooling energy savings is shown in Figure 42. Overall cooling loads are reduced, as would be expected. The effect of PCM installed above the insulation is about the same, but energy savings and cost-effectiveness for PCM would be lower for houses with higher attic R-values. The pattern is similar for heating loads with different insulation levels, as shown in Figure 43. It’s interesting to note that adding attic insulation alone has a negative effect on net heat load, given the sunny and mild weather in Santa Rosa.

Figure 42: Cooling load reduction for alternate insulation levels with 77°F melting point PCM above the insulation and Title 24 thermostat settings

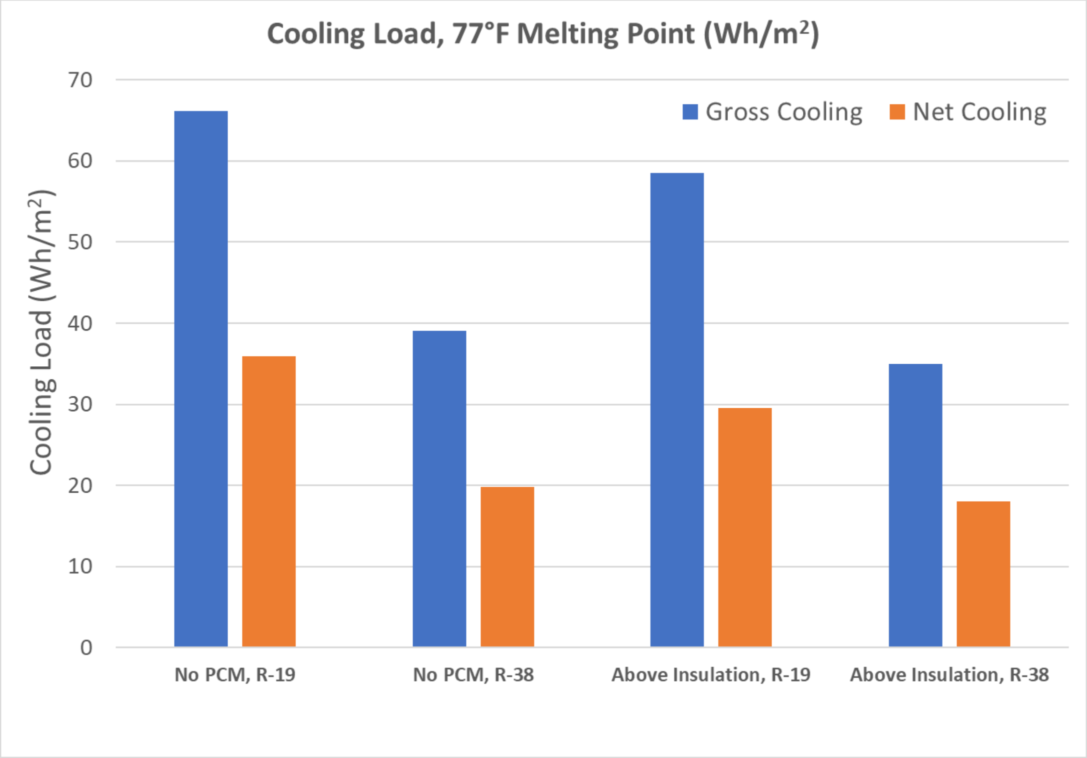
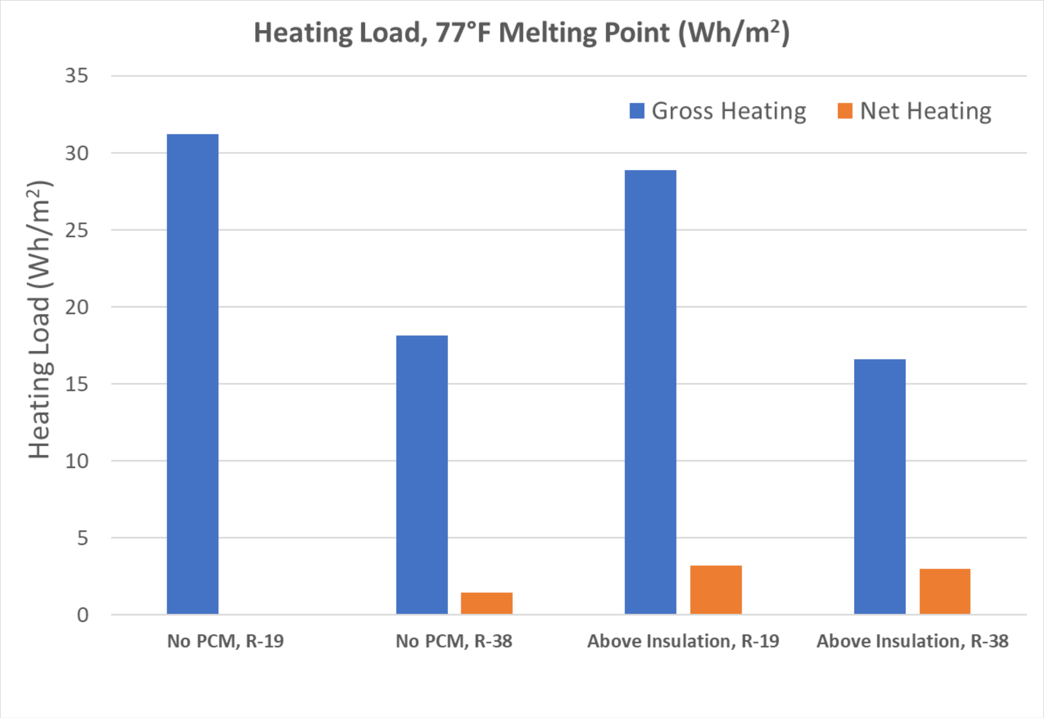


Figure 43: Heating load reduction for alternate insulation levels with 77°F melting point PCM above the insulation and Title 24 thermostat settings



The effect of thermostat settings on cooling loads with and without PCM is shown in Figure 44. Cooling loads increase with a constant setting compared to the setup/setback profile from Title 24, but the effect of PCM installed above the insulation is not much different either way. Results are similar for heating loads, as shown in Figure 45.

Figure 44: Cooling load reduction for alternate thermostat settings with 77°F melting point PCM above R-38 insulation

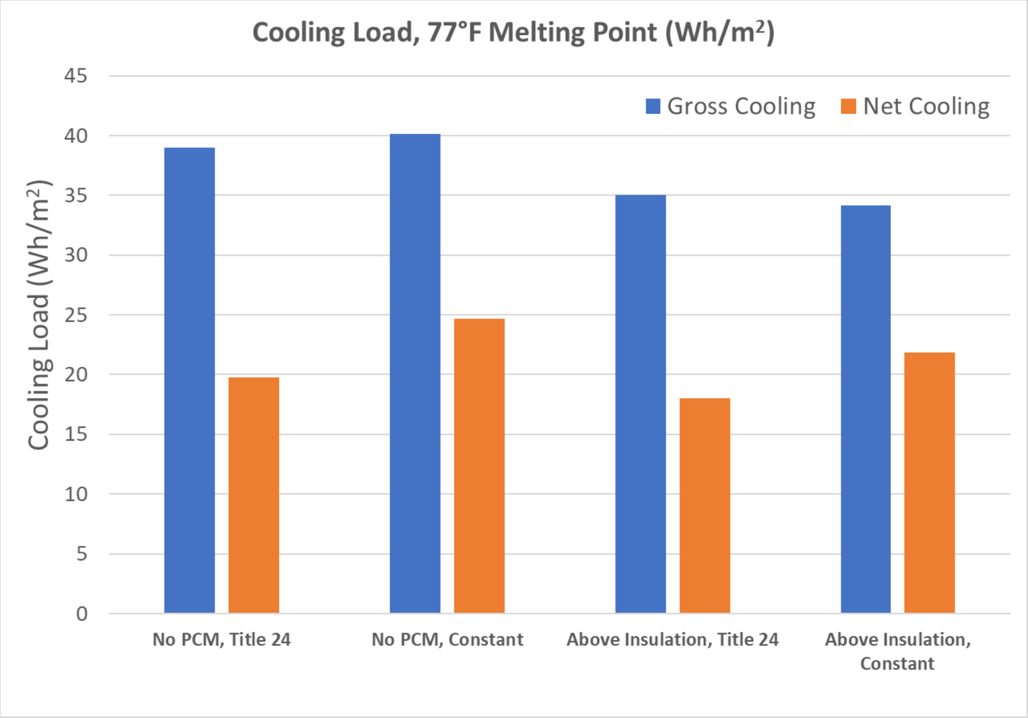
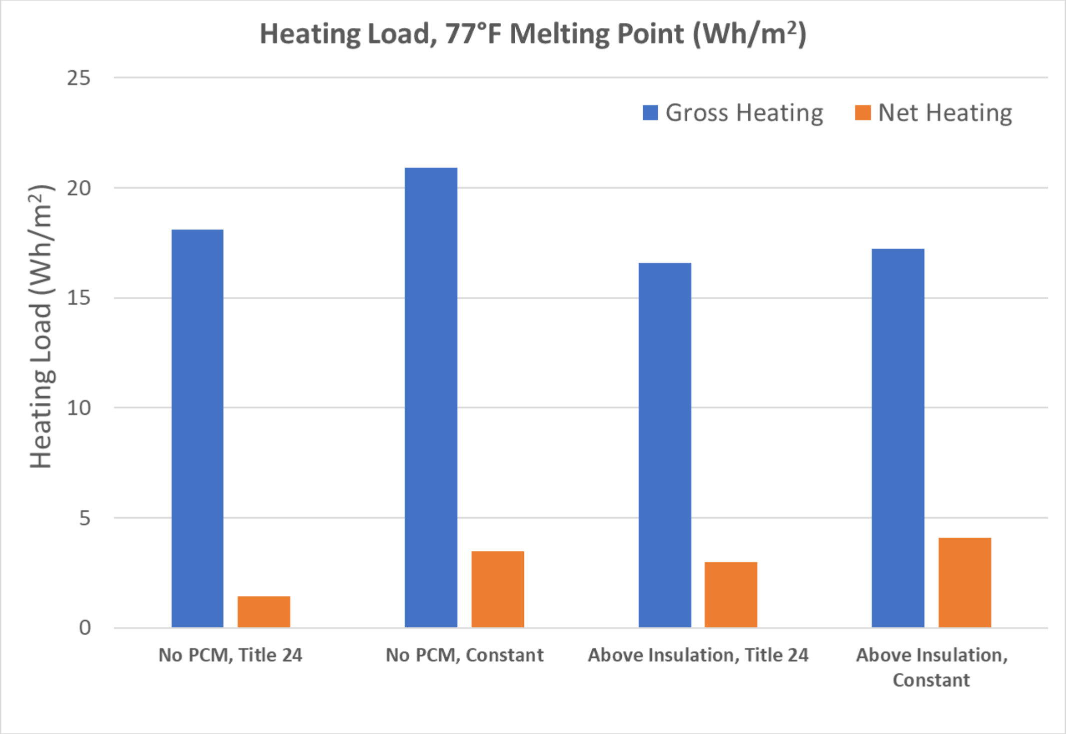
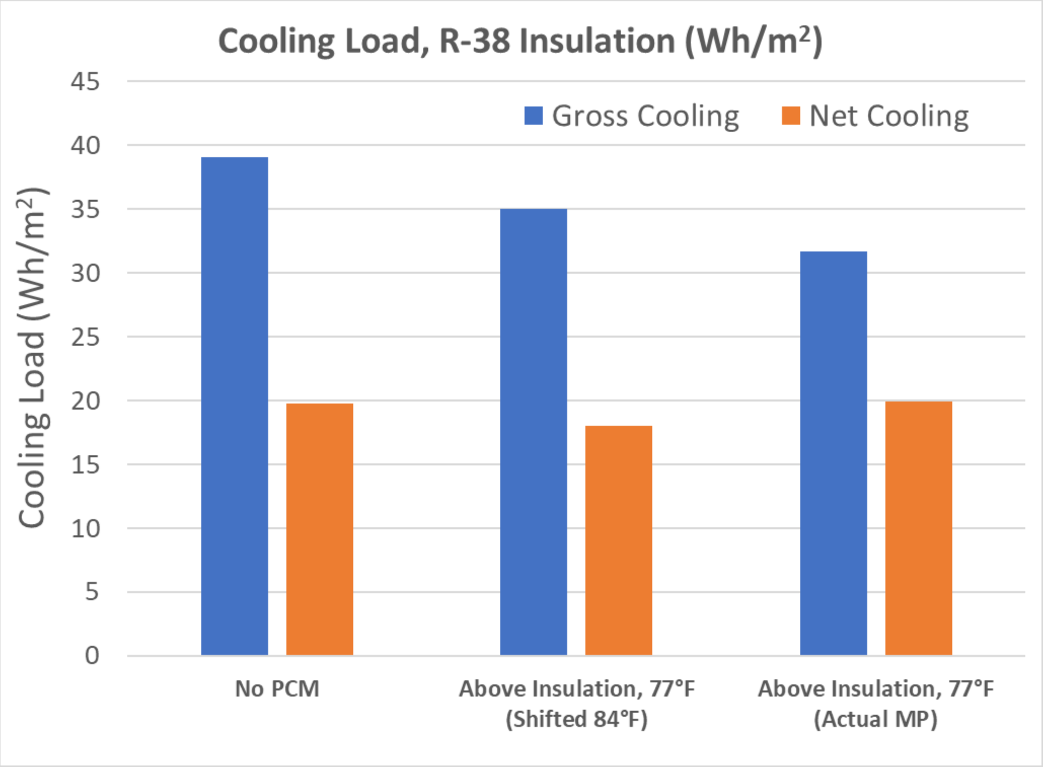


Figure 45: Heating load reduction for alternate thermostat settings with 77°F melting point PCM above R-38 insulation



As a check on our test method of shifting attic and interior temperatures in the test chambers to approximate changing PCM melting points, we ran a test using 77°F melting point PCM instead of the 84°F PCM that was used for all other tests. The results are shown in Figure 46. It appears that there is a fairly significant difference in performance for the two materials, with greater savings in gross cooling and less savings in net cooling for the PCM with 77°F melting point. The chemical compositions vary for Infinite R materials with different melting points, and consequently affect the thermal performance to some extent. However, for the purpose of assessing the effect of PCM melting point alone, the lab test approach we selected is more useful for drawing general conclusions about melting point, in addition to being more practical.

Figure 46: Cooling load reduction for actual 77°F melting point PCM compared to shifted 84°F melting point PCM above R-38 insulation



CHAPTER 5: Modeling Results

Building simulation models were used for several purposes in support of this project:

- Selecting the preferred melting point and position of the PCM relative to the insulation for field test applications
- Quantifying the impact of COVID-19 and other occupant behavior changes before and after the retrofits at the field test sites
- Generalizing cost-effectiveness analysis to determine if the technology should be encouraged or incentivized for SCP customers through the AEC

Analysis supporting PCM selection and position was discussed in Section 2.2. Pre and post retrofit behavior changes were addressed in Section 3.3, along with their impact on energy savings at the field test sites. The following sections focus on the calibration of our energy models and estimation of energy savings and cost-effectiveness for the technology in Sonoma County.

5.1: Model Overview

Frontier created an EnergyPlus model representing a typical existing home in Sonoma County. Because there are many possible house designs, we selected the attributes that we felt were most common in the existing housing stock in Sonoma County, supported by the modeling efforts performed for the Optimal Retrofit Strategy activities under Lead Locally. The characteristics of the simulated house we selected are summarized in Table 28. The only differences between the pre and post retrofit models were the attic insulation R-values and the presence of PCM.

Table 28. Characteristics of modeled house used for cost-effectiveness analysis

Characteristic	Pre Retrofit Model	Post Retrofit Model
Orientation	East Facing	East Facing
Size	1400 ft^2, single story	1400 ft^2, single story
Foundation	Vented crawlspace	Vented crawlspace
Roof Material	Asphalt Shingles	Asphalt Shingles
Windows	Clear Single Pane, 2-ft eaves	Clear Single Pane, 2-ft eaves
Leakage	10 ACH50	10 ACH50
Cooling	SEER 17 A/C	SEER 17 A/C
Heating	Gas Furnace 78% AFUE	Gas Furnace 78% AFUE

Ducts	30% leakage, R-2.1 insulation, located in unconditioned attic	30% leakage, R-2.1 insulation, located in unconditioned attic
Walls	R-12	R-12
Floor	80% carpeting	80% carpeting
Water Heater	50-gal gas water heater	50-gal gas water heater
Attic Insulation	R-18	R-20
Occupants	3	3
PCM Related Objects	No	Yes

The PCM was modeled using the customizable finite element algorithm within EnergyPlus. Manufacturers data for enthalpy as a function of PCM temperature were used as inputs. None of our measured data contradict the published data related to PCM thermal properties, which are difficult to quantify except under very controlled conditions.

5.2: Model Calibration

To improve the accuracy of the model, we used data collected from Site 53 to help guide the model calibration process. Site 53 had the most reliable and consistent data set, although it is difficult to say how representative the specific features of that house may be. At a minimum, the calibration process helps ensure that the results are realistic, given the challenges related to modeling vented attics and PCM performance accurately.

The following information from the field test monitoring results and occupant surveys was used in support of model calibration:

- Attic temperature
- PCM temperature
- Indoor temperature
- Outdoor temperature, relative humidity, and solar radiation
- Thermostat settings
- Occupancy levels

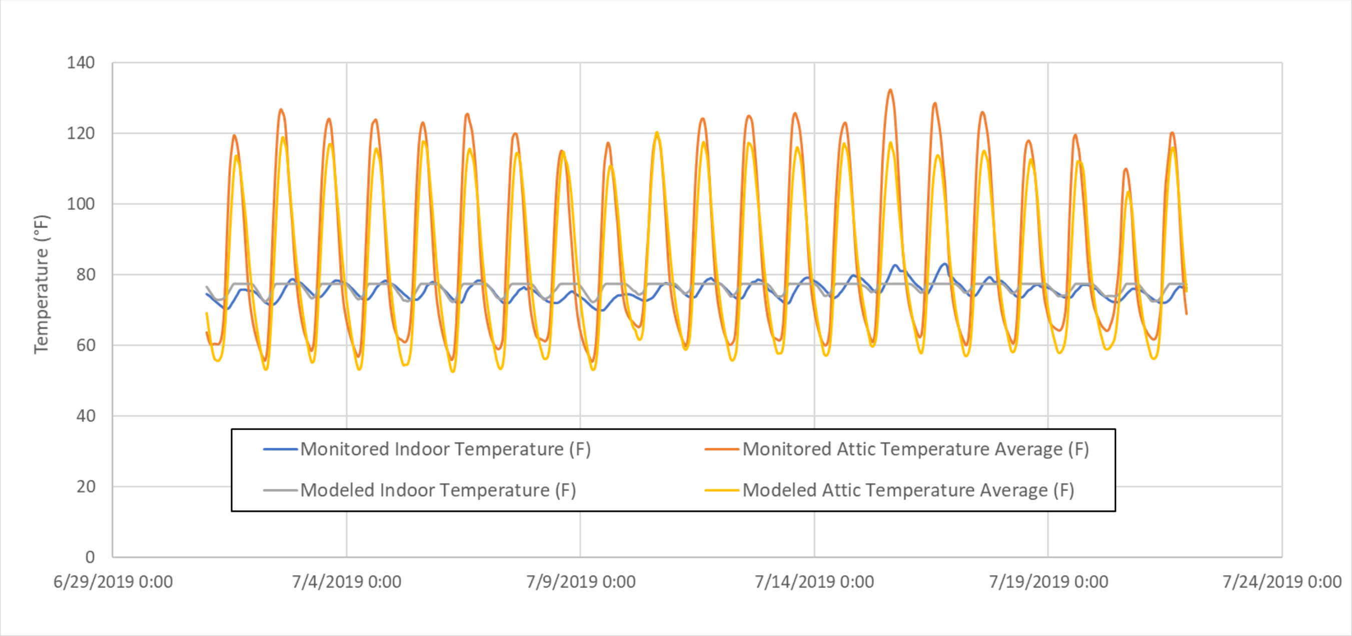
The following house attributes in the model were adjusted relative to the original model (described in Section 2.2) to improve the correlation of modeled data with field measurements:

- House furnishings thermal capacitance
- Wall insulation
- Attic ventilation rate
- Roof emissivity
- Attic insulation level

- Occupancy level
- Occupancy schedule
- Thermostat set point schedule

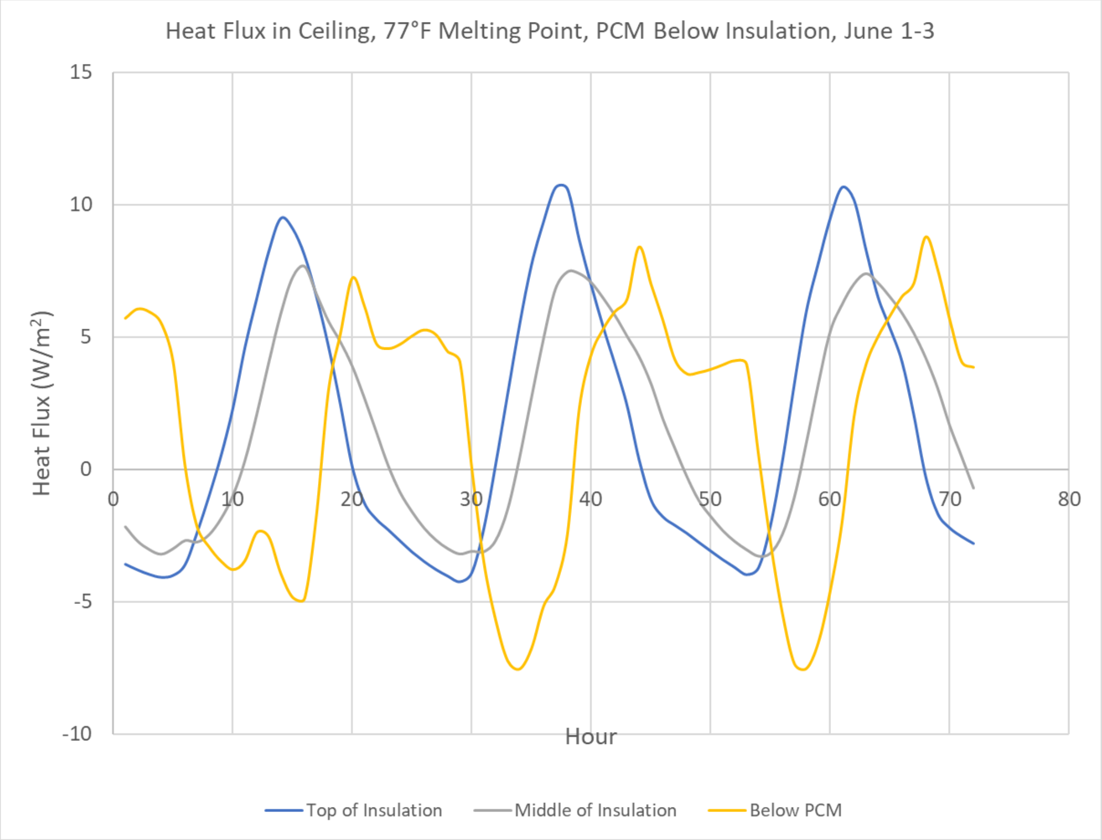
The calibration process focused on entering known specifications and operating conditions from Site 53, and matching key temperatures in the house, especially attic and indoor temperatures. We did not attempt to match heat fluxes or energy use, because this would bias the modeling results. An example of the final calibration results comparing pre-retrofit summer attic and indoor temperatures in the model to actual attic and indoor temperatures at Site 53 is shown in Figure 47. Additional comparisons were performed for winter periods, and with the PCM installed. It is impossible to match all the performance characteristics of a house through model calibration, even when detailed drawings are available, short-term testing of air and duct leakage are performed, and spot measurements of equipment efficiency are made. But the model can at least be improved by making sure the results are reasonably consistent with the actual conditions of the house.

Figure 47: Model calibration results for pre-retrofit summer period



Heat flux predictions from the model were also examined to verify that they were consistent with measured data. As shown in Figure 48, the modeled heat flux under the PCM during a warm period in early June was generally in the opposite direction as above the PCM, indicating melting and freezing activity similar to what was observed in the field tests.

Figure 48: Modeled heat flux in ceiling assembly during early summer period



5.3: Generalized Results for SCP Service Territory

Annual electricity and natural gas savings were calculated using the final calibrated model and 2019 actual weather data for Santa Rosa. 2021 Sonoma Clean Power time-of-use rate schedules were used to calculate energy cost savings for electricity. 2021 PG&E rate schedules were used for natural gas cost savings. Electricity savings is summarized for two PCM configurations and two melting points in Table 29. Natural gas savings for the same cases is shown in Table 30, and total savings is shown in Table 31.

Table 29. Modeled electricity use and utility cost savings for PCM

Case	Base Elec kWh	Base Elec Utility Bill	PCM Elec kWh	PCM Elec Utility Bill	Elec kWh Savings	Elec 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 30. Modeled 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 Therms Savings	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

Table 31. Modeled 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

5.4: Generalized Results for Other Northern California Locations

The models used for the analysis of PCM in Santa Rosa were modified for analysis of PCM in a hotter California climate (Fresno) and a colder climate (Truckee). No changes were made except the weather files used in the modeling. The results for Fresno are shown in Table 32 to Table 34, and the results for Truckee are shown in Table 35 to Table 37. The results suggest that the total energy savings for PCM is slightly to moderately negative in both of these locations, indicating that the mild Santa Rosa climate may be the best application of the technology.

Table 32. Modeled electricity use and utility cost savings for PCM in Fresno

Case	Base Elec kWh	Base Elec Utility Bill	PCM Elec kWh	PCM Elec Utility Bill	Elec kWh Savings	Elec Utility Bill Savings
PCM above insulation, 73°F melting point	11139	$3,804	11123	$3,800	16	$4
PCM below insulation, 73°F melting point	11139	$3,804	11146	$3,809	-7	-$4
PCM above insulation, 77°F melting point	11139	$3,804	11116	$3,797	24	$7
PCM below insulation, 77°F melting point	11139	$3,804	11139	$3,806	1	-$1

Table 33. Modeled natural gas use and utility cost savings for PCM in Fresno

Case	Base Gas Therms	Base Gas Utility Bill	PCM Gas Therms	PCM Gas Utility Bill	Gas Therms Savings	Gas Utility Bill Savings
PCM above insulation, 73°F melting point	317	$493	327	$510	-10	-$17
PCM below insulation, 73°F melting point	317	$493	326	$509	-9	-$15
PCM above insulation, 77°F melting point	317	$493	327	$510	-10	-$17
PCM below insulation, 77°F melting point	317	$493	327	$510	-10	-$16

Table 34. Modeled total utility cost savings for PCM in Fresno

Case	Base Total Utility Bill	PCM Total Utility Bill	Total Utility Bill Savings

PCM above insulation, 73°F melting point	$4,298	$4,310	-$13
PCM below insulation, 73°F melting point	$4,298	$4,317	-$19
PCM above insulation, 77°F melting point	$4,298	$4,308	-$10
PCM below insulation, 77°F melting point	$4,298	$4,316	-$18

Table 35. Modeled electricity use and utility cost savings for PCM in Truckee

Case	Base Elec kWh	Base Elec Utility Bill	PCM Elec kWh	PCM Elec Utility Bill	Elec kWh Savings	Elec Utility Bill Savings
PCM above insulation, 73°F melting point	6902	$2,131	6915	$2,135	-13	-$4
PCM below insulation, 73°F melting point	6902	$2,131	6914	$2,135	-12	-$4
PCM above insulation, 77°F melting point	6902	$2,131	6914	$2,135	-12	-$4
PCM below insulation, 77°F melting point	6902	$2,131	6865	$2,115	37	$16

Table 36. Modeled natural gas use and utility cost savings for PCM in Truckee

Case	Base Gas Therms	Base Gas Utility Bill	PCM Gas Therms	PCM Gas Utility Bill	Gas Therms Savings	Gas Utility Bill Savings
PCM above insulation, 73°F melting point	622	$1,102	662	$1,185	-39	-$83
PCM below insulation, 73°F melting point	622	$1,102	660	$1,182	-38	-$80
PCM above insulation, 77°F melting point	622	$1,102	662	$1,185	-39	-$83

PCM below insulation, 77°F melting point	622	$1,102	662	$1,185	-39	-$82

Table 37. Modeled total utility cost savings for PCM in Truckee

Case	Base Total Utility Bill	PCM Total Utility Bill	Total Utility Bill Savings
PCM above insulation, 73°F melting point	$3,233	$3,321	-$87
PCM below insulation, 73°F melting point	$3,233	$3,317	-$83
PCM above insulation, 77°F melting point	$3,233	$3,320	-$87
PCM below insulation, 77°F melting point	$3,233	$3,300	-$66

5.5: Cost-Effectiveness Analysis

The material and installation costs for the five test sites are summarized in Table 38. Actual costs included a number of items that are not likely to be part of the 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. A multiplier of 75% was applied to material costs, and 60% was applied to installation costs. These are engineering estimates, based on our experience with this project. The predicted average price per house is $6,341.

Table 38. Average installation and material costs for PCM

	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,	$4,210	$4,010	$5,153	$3,979	$4,127	$4,296

prevailing wage, learning curve) (60%)						
Total Projected Cost at Deployment	**$6,685**	**$6,413**	**$7,289**	**$5,017**	**$6,299**	**$6,341**

The best scenario for utility bill savings based on the modeling described in the previous section was $16/year, although it's certainly possible that many applications with more favorable weather conditions and a more optimized design could experience higher savings. Unfortunately, our best estimate of simple payback is $6341/$16, or 396 years.

CHAPTER 6:
Conclusions and Recommendations

6.1: Technology Readiness

Key findings regarding the energy performance and technology readiness of PCM in residential attics include the following:

- Field testing, lab testing, and energy modeling all indicate that the energy savings potential is small in the mild Sonoma County climate and may even be negative in some applications.
- 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 saving standpoint in the unique Sonoma County climate, though it would still reduce peak loads.
- PCM appears to have more potential for reducing cooling energy use than heating energy use.
- The PCM partially shifts heating and cooling loads forward an hour or two, but not enough to reduce peak summer cooling loads.
- Lab testing indicates that PCM above the insulation performs better than PCM below the insulation, while energy modeling predicts the opposite.
- A melting point of 77°F appears to be near the optimum value for the Sonoma County climate.
- Modeling in hotter and colder climates suggest lower energy savings than the mild Santa Rosa climate.
- Higher attic insulation levels and thermostat setup/setback reduce heat transfer from the attic, but do not change the relative effectiveness of PCM in a meaningful way.
- PCM leakage and water accumulation observed at the end of field testing present manufacturing and durability concerns for the Infinite R product.
- Trained installers for PCM in residential attic applications are not yet readily available, because this project was the first such application to our knowledge.
- Permitting requirements are ambiguous for PCM installation, because it is not categorized as insulation and building departments are not familiar with the technology.
- At this time, the 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 the Advanced Energy Center.

6.2: Lessons Learned

This applied research project presented a number of implementation challenges throughout the process. The following are some of the key lessons learned and other observations from the project:

- Although site recruitment went very smoothly and the homeowner partners had excellent attitudes about the project, they were generally very energy conscious when setting their thermostats and turning on their air conditioners. This resulted in limited potential for energy savings from the PCM retrofit, especially in the summer months.
- The onset of the COVID-19 pandemic occurred shortly after the PCM retrofits were installed at the field test sites and caused great difficulty for comparing pre- and post-retrofit energy use on an equal basis.
- The rapid temperature changes required for the simulated attic in the BSRL test chamber was very difficult to achieve in practice. Originally the temperatures were to be controlled by radiant panels, but eventually a fan coil was used to increase the rate of heat transfer. This approach was not ideal, because it required air circulation that could have increased the heat transfer rate from the attic to the interior space beyond what is likely to occur in a real attic.
- The foil heat flux sensors used for the field tests provided highly questionable readings, partly due to issues with the third-party signal conversion, and partly because of difficulty maintaining good contact with the freezing and melting PCM mats. The disc heat flux sensors used for lab testing seemed to perform much better.
- A substantial amount of field test data was lost because Frontier did not maintain control over the raw data and signal conversions. Responsibility was given to a third-party provider that offered a convenient interface for plotting field test results in real time, but apparent financial issues led to staff turnover, lack of responsiveness, and ultimately the loss of some of the raw data.
- Leaking PCM mats in the attics of at least two of the five test sites have left a significant liability issue for the project partners. For any future projects of this type, greater quality control requirements are needed to ensure that the product is free of residue and pinhole sized leaks before being installed.
- Frontier modelers had difficulty matching modeled attic temperatures to field test data, especially after the PCM retrofit. Buffer spaces like attics are notoriously challenging to model accurately due to complex heat transfer mechanisms involving radiation, natural convection, thermal storage, and mass transfer through ventilation grilles and duct leakage.

6.3: Areas for Further Research

Several ideas for future research on residential attic PCM retrofits became apparent as we executed the project:

- Modeling and/or lab testing of a wider range of PCM melting points and weather conditions are needed to establish the optimum melting point for applications in Northern California beyond Sonoma County.

- The thermodynamic mechanisms related to PCM are complex, and greater research is need on both embedded PCM and macro-encapsulated PCM to better identify beneficial applications for both new construction and retrofits.
- Extended durability testing under realistic temperature cycling should be performed on macro-encapsulated PCM products.
- Further validation of attic energy modeling assumptions and algorithms may be necessary to provide higher confidence in the ability of building simulation software to predict energy savings for attic energy efficiency measures.
- Heat flux sensors may need additional calibration and installation guidance when used in PCM applications where the material may shift as it melts and freezes.

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