CALIFORNIA ENERGY COMMISSION

California Energy Commission

FINAL PROJECT REPORT

Lead Locally Technology Demonstration Final Report

Prepared for: California Energy Commission

Prepared by: Frontier Energy

November 2022 | CEC-EPC-2017-041-DCR

California Energy Commission

Bob Hendron, Stephen Chally, James Haile, Kristin Heinemeier, Simon Pallin,
Edward Ruan, Michael Slater
Primary Author(s)

Chad Asay
Project Manager

Sonoma Clean Power Authority
431 E St,
Santa Rosa, CA 95404

Agreement Number: EPC-17-041

Jackson Thach
Commission Agreement Manager

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Jonah Steinbeck
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors wish to acknowledge the many contributions to this project made by colleagues and Lead Locally partners. First, we thank Josh McNeil, Angelo Karas, Stephen Becker, Ada Liu, Alea German, Ben White, Claudia Pingatore, Corrine Schrall, Emily Teves, Angel Garza, Samantha Bloom, Chris Bradt, and Nancy Barba from Frontier Energy for their efforts to recruit test sites, manage partners, and conduct the testing and modeling activities described in this report. In addition, we appreciate the collaboration with Lead Locally partners Mike MacFarland, Rick Chitwood, Western Cooling Efficiency Center, Aeroseal, Airscape, Insolcorp, Winwerks, Rheem, Vollrath, Hobart and Meiko to develop measure designs and installation best practices. We also thank the SCP customers who offered up their homes and businesses for this project to help the scientific community gain knowledge about emerging energy efficiency technologies. We also appreciate the support and advice provided throughout the planning, execution, and documentation of the project by Geoff Barker, Amit Kanungo, Jarred Metoyer, and Jennifer McWilliams of DNV. Finally, we thank Chad Asay, Kimberly Beltran, and Rachel Kuykendall of SCP, and Kadir Bedir, Jackson Thach, and David Hungerford of CEC for continued leadership and financial support for the project.

PREFACE

Project Overview

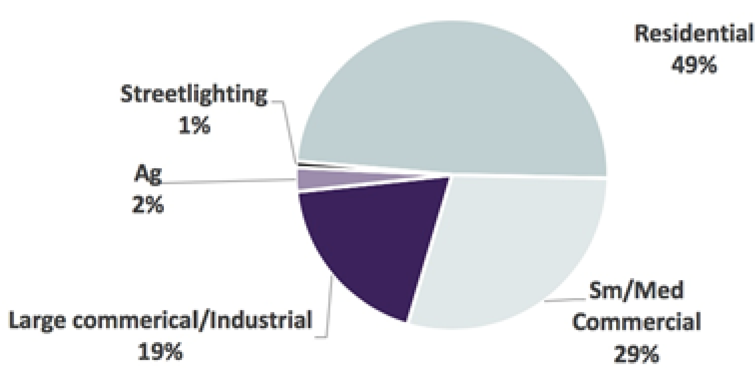
Sonoma Clean Power's (SCP) "Lead Locally" project, funded through the California Energy Commission's (CEC) GFO-17-304 aims to identify strategies and technologies that can assist with the State's goals of doubling the efficiency of existing buildings by 2030. The Project includes applied research, technology demonstration, and 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 higher risk innovative technologies that have the potential to be integrated into existing program models in the future. Technology demonstrations evaluate lower risk emerging technologies that have not yet been fully characterized in Sonoma County. Lessons learned from both the applied research and technology demonstration 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, a physical storefront where consumers can directly procure energy efficient products and services. The Advanced Energy Center 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 Lead Locally technology demonstration team was comprised of the following key partners (referenced in this document as the Team), with roles and responsibilities outlined below. Additional manufacturer and vendor partners contributed to individual technology demonstration projects.

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 technology demonstration 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.

ABSTRACT

This report documents key findings from the demonstration of seven emerging building retrofit technologies under the Lead Locally grant led by Sonoma Clean Power and funded by the California Energy Commission. These technologies have all been proven to some extent through past field test projects, but there may be uncertainty in the amount of savings potential, long term durability, cost effectiveness, and availability of qualified installers. The technologies included ducted mini-split heat pumps, grid-interactive heat pump water heaters, aerosol envelope sealing, induction cooking, phase change materials for commercial buildings, exhaust heat recovery dishmachines, and nighttime ventilation to mitigate the need for an air conditioner. Each technology was field tested in multiple test buildings in Sonoma or Mendocino County, with a total of 50 buildings evaluated. Methods of evaluation included direct submetering, utility bill analysis, modeling, durability inspections, and occupant surveys. The results indicated that many of these technologies are cost-effective based on simple payback, given the right building application. Other technologies saved energy and reduced peak demand but were too costly to be viable for the retrofit market in the near-term. In a few cases, no energy savings could be substantiated due to the mild Sonoma County climate, incorrect application, occupant behavior changes (including the effects of the COVID-19 pandemic), or measure performance issues.

Keywords: induction cooking, heat recovery, commercial dishmachines, aerosol sealing, Aeroseal, AeroBarrier, heat pump water heaters, grid-interactive, nighttime ventilation, phase change material, retrofit measures, existing homes, residential buildings, commercial buildings, electrification, energy storage, peak load reduction, Lead Locally, Advanced Energy Center, Sonoma Clean Power

Please use the following citation for this report:

Hendron, Robert; Stephen Chally; James Haile; Kristin Heinemeier; Simon Pallin; Edward Ruan, Michael Slater. 2022. *Lead Locally Technology Demonstration Final Report*. California Energy Commission. Publication Number: CEC-EPC-2017-041.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

EXECUTIVE SUMMARY

Introduction

The Lead Locally Grant, administered by Sonoma Clean Power (SCP) under funding by the California Energy Commission (CEC), utilized a multi-faceted approach to studying emerging building energy efficiency technologies with the potential to reduce electricity and gas use in residential and commercial buildings by 10% and 20% respectively, and developing new methods for accelerating their regional adoption. The program included an applied research phase to characterize the performance of several unproven technologies and determine their viability for SCP customers, a technology demonstration phase to verify the performance and costs of emerging technologies with limited previous application in Northern California, and a deployment phase to promote and incentivize more mature technologies along with the most promising retrofit measures tested during the earlier phases of the program. The overall goal was to greatly increase the number of energy efficiency and electrification projects performed in SCP service territory and expand the range of retrofit measures being implemented to include the latest proven technologies. Knowledge from this project is being published and shared with other utilities and program administrators to advance California's carbon reduction goals beyond this pilot program.

The Technology Demonstration portion of Lead Locally was led by Frontier Energy and focused on gaining performance and energy use data through field testing of select products that were commercially available and showed high savings potential yet were understudied in terms of cost and performance across a range of applications. In addition to energy savings and non-energy performance data, information was gathered regarding costs and simple payback, installation challenges, and market structures and barriers.

The subsequent portion of the Lead Locally Grant – Technology Deployment – offered incentives, financing, and customer education through the Sonoma Clean Power Advanced Energy Center. This phase of the program will be detailed in a separate forthcoming report.

An overview of the technologies demonstrated by Lead Locally is shown in Table ES-1, with more details provided in Section 1.3: Technology Overviews and in each technology section within CHAPTER 3: Technology Demonstration Projects.

Table ES-1: Overview of Demonstration Technologies

Technology	Description	Expected Electricity Savings	Other Benefits
Grid-interactive heat pump water heaters (residential and small commercial)	Tank water heaters utilizing heat pump technology with electric resistance 'backup'; potential to communicate with electric grid for load shifting purposes	60% water heating (vs electric resistance water heater)	Load shifting Hot water availability during peak hours

Phase change materials (commercial)	Materials that absorb and release heat via melting/freezing. Material can be selected based on melting point to suit particular space conditioning needs.	30% cooling, 10% heating	Load shifting Thermal comfort Gas savings
Ducted mini-split heat pump (residential)	Space heating/AC utilizing heat pump technology; a smaller, variable speed version of a ducted split system (separate indoor and outdoor units); includes whole-house supply ventilation	20-30% heating and cooling (vs standard air-source heat pump)	Peak load reduction Reduced cycling Thermal comfort Indoor air quality
Induction cooking (residential and commercial)	Rangetops that utilize electromagnetism to heat cookware instead of a flame or electric resistive elements.	10-40% cooking (vs electric resistance)	Cooking speed Safety Cleanliness Peak load reduction
Waste heat recovery for dishmachines (commercial)	Commercial dishmachines that retrieve heat from the steam exhaust via a heat exchanger and redirect to the water pre-heating compartment.	30-50% water heating	Gas savings Thermal comfort Lighter humidity load on ventilation system
Aerosol envelope sealing (residential)	Solution sprayed into a space that can plug small gaps due to its aerosol particle size and pressurized application. Different product/application used for building envelope vs. ductwork.	20% heating and cooling	Gas savings Less drafts
Nighttime ventilation (residential)	Addition to ducted space conditioning system that brings in cool outdoor air at night, pre-cooling the house before rising daytime temperatures. Can supplement existing AC systems or avoid the need for AC.	30% cooling relative to adding an AC system	Peak load reduction Indoor air quality

Research Approach

The Technology Demonstration portion of Lead Locally involved field testing of these seven technologies across 41 residential and 9 commercial test sites within Sonoma and Mendocino counties spanning 2019 to 2022. Conditions monitored before and after the technologies were installed included energy usage, thermal performance, and participant perspectives. Details on the equipment and methodology used for each technology varied depending on the needs of the project, but all technologies utilized the same general research framework to ensure meaningful data collection:

Site Selection: SCP customers were recruited through various outreach channels and asked to complete an application allowing the Lead Locally team to evaluate site testing suitability based on a range of weighted criteria detailed in a screening matrix developed for each technology. Considerations included expected energy savings, installation cost, consistency of equipment usage, data integrity, practical issues such as installation feasibility, and possibly occupant health and safety. Applicant pools were narrowed using information gathered during site visits, until the final number of participants was selected.

Baseline Data Collection: For periods ranging from 3-12 months depending on the seasonality of energy use for the technology, each site had instrumentation installed to measure data needed for ultimate data analysis.

Retrofit: The new equipment was installed at each site. All but a few simple self-installations utilized contractors that held an active Contractor's State License Board (CSLB) license appropriate for the scope of work, as well as appropriate insurance and bonding. All installers received mandatory training provided by Lead Locally or the product manufacturer.

Post-Retrofit Data Collection: For periods ranging from 3-16 months, each site had instrumentation installed to measure relevant metrics. At the end of the testing period, monitoring equipment was removed but the installed technologies remained in place.

Data Analysis: Technology performance was analyzed through a combination of direct monitoring, weather-normalized utility bill comparisons, occupant surveys, and cost-effectiveness calculations using simple payback.

Field Test Results

Brief summaries of the research findings for each of the seven technologies are provided in the following sections.

Ducted Mini-Split Heat Pumps

Overall changes in energy use between the pre-retrofit period and the post-retrofit period are summarized in Table ES-2 for overall site energy usage (kBtu) and Table ES-3 for peak electricity demand (kW). A conversion factor of 3.14 kBtu/kWh was used to convert electricity to site energy.

There is clearly significant variation in site energy savings across test sites. Some sites show negative savings for heating, cooling, or both. This may be at least partially due to changes in home occupancy and system settings due to the COVID-19 pandemic. In addition, some sites had insufficient data to assess energy savings (grey cells in the tables) due to minimal use of the cooling system or data monitoring issues. Overall, several factors complicated savings calculations such as the pandemic, the change in heating fuel from gas to electric for all but one site between pre- and post-testing periods, and the wide range of pre-retrofit cooling energy use across the test sites.

Changes in peak electricity demand (individual maximum demand regardless of time of occurrence) during the cooling season showed more consistent results. Three sites again had insufficient data, but the remaining five sites showed peak load reductions ranging from 7% to 63%. Again, it is difficult to know exactly how much effect the COVID-19 pandemic had on the results.

Table ES-2: Energy Savings for Seven Mini-Split Test Sites

Annual Energy Use Savings[b]			Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7
Heating	Pre- vs. Post-Retrofit	*kBtu*	908.2	10,801.5	3,680.2	0.0	4,813.5	4,234.3	580.4
		kWh	-910.1	-300.4	-776.0	-604.6	-1,538.1	-1,117.1	-29.3
Cooling		*kWh*	-29.2		546.3	87.7	-73.7	834.2	
		Total savings (kBtu)	-2,297		2,896	-1,764	-686	3,269	

[b] kBtu is gas savings, kWh is electricity savings

Table ES-3: Peak Cooling Demand for the Seven Test Sites Pre- and Post-retrofit

Peak Demand [kWh]	Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7
Pre-Retrofit			2.8	2.5	2.3	5.6	6.3
Post-Retrofit[a]	2.1	1.4	2.3	2.0	2.1	2.1	
Change in Demand			**17%**	**22%**	**7%**	**63%**	

[a] Post-retrofit represents data collected during 2020.

Total cost savings associated with changes to energy use across the seven test sites are summarized in Table ES-4. Savings were negative for all but one site, ranging from an annual loss of about $360 to roughly $50 in annual savings. While there are cost savings associated with avoiding the use of natural gas for heating, those savings don't appear to overcome the higher electricity bills. With an average installation cost of $26,000 ($18,600 for labor and $7,400 for materials), the resulting payback times are impractically long if they apply at all.

Table ES-4: Savings in Cost of Electricity for the Seven Test Sites and Simple Payback Time

Annual Energy Use Savings			Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7
Heating	Pre- vs. Post-Retrofit	*kBtu*	908.2	1,0801.5	3,680.2	-	4,813.5	4,234.3	580.4
		kWh	-910.1	-300.4	-776.0	-604.6	-1,538.1	-1,117.1	-29.3
Cooling		*kWh*	-29.2		546.3	87.7	-73.7	834.2	
Annual Cost Savings[a]									
Heating	Pre- vs. Post-Retrofit	*kBtu*	$11.0	$130.7	$44.5	-	$58.2	$51.2	$7.0
		kWh	$(236.6)	$(78.1)	$(201.7)	$(157.2)	$(399.9)	$(290.5)	$(7.6)
Cooling		*kWh*	$(7.6)		$142.0	$22.8	$(19.2)	$216.9	
Total			**$(233.2)**	**$52.6**	**$(15.2)**	**$(134.4)**	**$(360.8)**	**$(22.3)**	**$(0.6)**
Simple Payback[b] [years]			-	**494**	-	-	-	-	-

[a] Based on average TOU cost of electricity of $0.26/kWh and average cost of natural gas of $0.0121/kBtu in 2020 (PG&E, 2022).
[b] Average installation cost estimated at $26,000.

Unfortunately, the ducted mini-split heat pumps did not yield attractive paybacks. Several factors contributed to this result, such as:

- The start of the COVID-19 pandemic in early 2020 resulted in significant changes to home occupancy and resulting HVAC comfort needs, blurring the picture of pre- vs. post-retrofit.
- The price of natural gas is much lower than that of electricity, impacting the predicted simple payback even though HP technology is more efficient on a per-energy-unit basis.

These test sites represent retrofit applications in sites with no renewable energy. For homes with PV systems, or new construction where only the incremental HVAC costs are relevant, simple payback would likely be improved.

Feedback from test site occupants was generally quite positive as indicated on a pre- and post-retrofit survey. Input on comfort levels with the retrofit system were typically either "Very Satisfied" or "Satisfied", though some homeowners complained about noise and inconsistency in space conditioning efficacy across different rooms.

Grid-Interactive Heat Pump Water Heaters

All but one GIHPWH site enjoyed energy and cost savings from replacing their baseline water heater to a grid-interactive heat pump model, averaging 8,100 kBtu equivalents per year, or about 53% of the baseline water heater energy usage (see Table ES-5). As a portion of total home energy use, the replacement reduced average energy use from 14.2% to 9.6%. The load shifting component of the retrofit had a positive effect on cost savings because of TOU rates, but a slightly negative effect on overall energy savings.

Table ES-5: GIHPWH Energy Savings Results

Participant	Baseline Water Heater Fuel	Baseline Energy Usage (kWh/y or kBtu/y)	Replacement Energy Usage (kWh/y)	Gross Energy Savings (kBtu equiv./y)*	Energy Cost Savings ($/y)
Site 17	Gas	23,100 kBtu/y	2,032	16,200	$157
Site 18	Gas	13,900 kBtu/y	1,399	9,100	$121
Site 19	Gas	19,000 kBtu/y	2,404	10,800	$103
Site 20	Gas	16,700 kBtu/y	1,449	12,800	-$69
Site 21	Electric	4,607 kWh/y	1,858	159	$625
Site 22	Gas	10,200 kBtu/y	3,060	-200	-$104
Site 23	Gas	8,600 kBtu/y	1,027	5,100	$67
Site 24	Gas	15,500 kBtu/y	2,929	5,500	$115
Site 25	Gas	14,800 kBtu/y	2,885	4,900	$96
Average		15,300 kBtu equiv./y	7,200 kBtu equiv./y	8,100 kBtu equiv./y	$123

*1 kWh = 3.412 kBtu

The nine test sites averaged $123 in annual energy cost savings, and all but two resulted in positive cost savings.[1] When excluding the one site with an electric baseline water heater, the average savings is reduced to $61/year. Cost savings were calculated through direct energy monitoring of the water heater rather than through utility bills.

With annual average cost savings of $123 and an average purchase cost of $2500 for an 80-gallon hybrid heat pump water heater, the simple payback time for these units was projected to be 20 years. When considering the incremental cost difference between the GIHPWH and a conventional gas or conventional electric water heater (roughly $1500, including installation), the simple payback is reduced to 12 years. The sites with the longest paybacks were ones that used the laundry and dishwasher most during peak periods, and also tended to be the sites with the highest number of occupants.

The use of the GIHPWH's heat pump mode versus the energy-intensive resistive elements was also studied under this program to assess the equipment's ability to meet household needs without use of backup heating. Post-installation data showed that heat pump mode represented an average of 77% of total runtime. The most common trigger for electric heating element's activation was when a laundry washer or a dishwasher was activated after a period that had seen other hot water events such as showers. This showed that the more efficient heat pump mode, with load-shifting enabled, was viable for most of the sites' daily hot water needs.

GIHPWH load shifting via pre-heating water at non-peak hours was also explored. Though load shifting can be implemented by the utility or the manufacturer, in this study it was managed remotely by a script developed by Frontier, with a schedule designed around the electric rate structures and operating energy use profiles of each site to maximize cost savings. Post-installation data showed that peak hours from 4PM to 9PM were generally avoided.

Pre- and post-installation surveys showed that 80% of the homeowners were very satisfied with their water heaters. The largest number of negative responses concerned hot water delivery speed, which would have been driven by the existing distribution system. Noise was an issue for sites with the water heater installed indoors; for garage or outdoor installation it was not an issue. This is one factor indicating the importance of installation location, which is typically dictated by the location of the water heater being replaced due to the existing infrastructure. Another main factor is whether the location is conditioned by HVAC, as cold temperatures reduce the GIHPWH's Coefficient of Performance (COP).

Induction Cooking

Measured savings for the induction cooking demonstration sites are shown in Tables ES-6 and ES-7. In residential sites, annual savings averaged 248 kWh (848 kBtu/year) and were mainly associated with reduced cook times – 18% lower on average – per cooking event. The commercial site showed annual savings of about 3.6 therms/day equivalent (131,000 kBtu/year) due in part to the replacement of standing pilot flames with on-demand electric ignition. However, the commercial site did not demonstrate energy cost savings because of the

---

[1] Assumes $0.0150/kBtu and $0.22/kWh

higher cost per unit of electricity as opposed to gas. This is a common side effect associated with fuel switching in utility service areas where electricity is more expensive than natural gas.

Table ES-6: Residential Induction Energy Savings Data

	Baseline Energy Use (kWh/y)	Baseline Energy Cost ($/y)	Retrofit Energy Use (kWh/y)	Retrofit Energy Cost ($/y)	Energy Savings (kWh/y)	Cost Savings ($/y)
Site 28	1,377	$234	937	$160	440	$74
Site 29	2,981	$507	2,369	$400	612	$107
Site 30	2,313	$393	2,201	$374	112	$19
Site 31	1,345	$229	1,494	$253	-149	-$24
Site 32	2,014	$342	1,787	$303	227	$39
Averages	2,006	$341	1,758	$298	248	$43

Table ES-7: Energy Usage Results from Induction Cooktop Retrofit at Commercial Site

	Pilot Usage	Total Energy Use*	Daily Energy Cost ($/d)**	Annual Energy Cost[2] ($/y)
Baseline	84 kBtu/day	460 kBtu/day	$6.90	$1,750
Replacement	0	29 kWh/day	$9.86	$2,465
Savings	84 kBtu/day	360 kBtu/day equivalent	-$2.96	-$715

*1 kWh = 3.142 kBtu
** Assumed energy rates of $0.34/kWh and $1.50/100kBtu (i.e. $1.50/therm)

When incorporating costs associated with induction retrofits, the relatively low or negative energy savings across sites produced unfavorable paybacks of 70 years for residential sites and no payback for the commercial site. This reflects an optimistic payback, as there were no associated installation fees and there was already sufficient electrical capacity for the induction unit.

With such long payback periods, increased market adoption would be driven by non-financial benefits, which are numerous for induction cooking – primarily performance, safety, and environmental concerns. Ironically, though induction offers quicker cook times, the largest

2 This analysis assumes $0.015/kBtuand $0.34/kWh.

barrier is perceived performance issues due to the conflation of induction with electric resistance cooking, which has significantly higher heat up and cool down times. In commercial cooking environments, these barriers are amplified as it affects daily operations; this proved to impact recruitment for this study. From participant feedback gained via surveys, there is potential for this misperception to be corrected, as all sites reported being satisfied with the performance of their induction cooktops. The biggest complaints were related to oven capacity and the need for new cookware.

Field data from participating sites replacing their gas or electric cooktop with induction shows energy savings for all but one site, but not enough to offset the higher cost of electricity when switching from a gas cooktop. Financial incentives, lower equipment costs, or the use of PV would make the economics more favorable.

Waste Heat Recovery

The two commercial sites monitored for this technology showed significant energy and cost savings as shown in Table ES-8. In both cases, energy savings were due to reduced energy load at the facility's water heater, while energy use at the dishmachine's heating elements either remained the same or increased. This was heavily affected by the fact that both sites had pre-existing electric water heaters, which were more expensive to operate and thus had higher cost savings as compared to a natural gas-powered water heater, which is the overwhelming standard in commercial foodservice facilities.

Table ES-8: Exhaust Heat Recovery Dishmachine Water and Energy Savings

Site	Data Type	Racks/ Day	Water Use (gal/ day)	Water Heater Energy (kWh/ day)	Dishwasher Energy (kWh/ day)	Net Energy Savings (kWh/ year)	Cost Savings[3] ($/ year)
Brewery	Baseline	47	73	15	38	2,920	$1,147
	Replacement	47	52	0	45		
	Savings	NA	21	15	-7		
Winery	Baseline	62	108	21	42	8,030	$2,979
	Replacement	62	74	0	41		
	Savings	NA	34	21	1		

Heat recovery undercounter dishmachines cost roughly $8,500. When applying the savings realized in this study, the simple payback time is about 3.5 years. When considering just the incremental cost of roughly $4,000, the payback is reduced to about 2 years. Labor costs were avoided in this study as installations were performed by in-house staff. In the end of useful life replacement scenario, incremental installation cost can also be neglected because the installation process for a waste heat recovery (WHR) unit is generally comparable to that of a

3 Assumes commercial electric rates of $0.34/kWh and water and sewer rates of $15 per hundred cubic feet.

conventional dishmachine. Simple paybacks associated with a typical site containing a gas water heater would likely be higher.

In select WHR dishmachines, including the undercounter units used in this study, the heat capture in combination with the machine's internal "booster" heater (standard for any high temperature dishmachine) provided enough energy to heat incoming cold water directly, precluding the need for any connection to the facility's water heating system. While this can present major advantages from a design cost perspective, it also relies on the existence (and fuel source) of the facility water heater in realized cost savings.

Qualitative considerations for this technology were gathered through participant feedback as well as the on-site experience of the field-testing team. Respondents at each site expressed overall satisfaction with the replacement and noted that the WHR unit improved the thermal comfort for kitchen staff as well as the smell within the dishwashing area. The main downside in operating these units was the increased wash cycle time of WHR models (90 seconds, compared to 60 seconds for conventional machines), needed to accommodate the heat recovery process. This was noted as a disadvantage by one of the site owners and required staff adjustment to the change. The impacts of such a change would be more pronounced for higher volume operations, posing a potentially significant barrier to widespread commercial foodservice adoption. Lastly, some WHR units are taller than analogous conventional units, which can be an insurmountable barrier for many restaurants that place their unit under a counter or otherwise have limited location options due to space constraints or location of a floor drain. These two disadvantages may be inconsequential for new construction versus the retrofit scenarios studied here.

Aerosol Envelope Sealing

Across the ten participating sites, the application of AeroBarrier showed significant reduction in air leakage. Resulting sealing improvements, shown in Table ES-9 for all sites, show the percent of measured leakage before and after aerosol application. On average, air sealing improvement averaged 83.3% for the targeted building envelope components—that is, when surfaces incompatible with aerosol sealing, such as floors, windows, and vents, were excluded. When incorporating these excluded surfaces, the average sealing improvement was reduced to 57%.

Table ES-9. AeroBarrier Improvements to the Envelope

	Targeted Envelope Only			Net Total / Whole Home		
	Baseline Leakage (ACH50[4])	Leakage after Sealing (ACH50)	Percent Sealed	Baseline Leakage (ACH50)	Leakage after Sealing (ACH50)	Percent Sealed
Site 1	13.33	0.63	95.2%	15.38	5.09	66.9%
Site 2	14.62	0.51	96.5%	12.62	4.89	61.2%
Site 3	19.45	1.23	93.7%	15.24	8.05	47.4%

4 ACH50, or air changes per hour at 50 pascals, indicates how many times an hour the air in the home is completely recycled while pressurizing or depressurizing the space to 50 Pa.

Site 4	8.65	3.40	60.7%	9.30	7.44	20.4%
Site 5	8.82	1.35	84.7%	8.82	2.53	71.3%
Site 6	7.64	1.59	79.2%	7.65	2.56	66.5%
Site 7	9.66	1.43	85.2%	9.66	2.92	69.8%
Site 8	8.44	1.88	77.7%	10.53	4.06	61.4%
Site 9	6.77	1.25	81.5%	9.44	4.60	51.3%
Site 10	6.47	1.37	78.8%	6.35	2.93	53.9%
Average	83.3%			57%		

For the three sites that also received Aeroseal duct sealing, additional sealing rates are shown in Table ES-10, resulting in a weighted average of 70% reduction in air leakage.

Table ES-10. Aeroseal Improvements

	Baseline Duct Leakage (CFM25[5])	Duct Leakage after Sealing (CFM25)	Percent Improvement
Site 2	23.9	19.1	20%
Site 5	39.4	9.3	76%
Site 10	38.8	2.7	93%

Resulting air infiltration and duct leakage rates (and other characteristics of each home) were entered into the BEopt simulation tool to estimate associated HVAC energy savings over a full year in the Sonoma County climate. The use of utility bill analysis was rejected in favor of modeling because changes in occupancy and/or building renovations that occurred around the same time the aerosol sealing was performed would have introduced uncertainty in the calculation of energy savings. Modeling results are shown in Table ES-11.

Table ES-11. Annual Aerosol Sealing Modeled Energy Savings

	Electrical Energy Savings (kWh)	Gas Energy Savings (kBtu)	Total Savings (kBtu)	Percent Total kBtu Savings
Site 1	931.4	50	3,224.8	6.5%
Site 2	59.8	10,810	11,018.0	11.7%
Site 3	49.1	8,810	8,981.5	14.9%
Site 4	7.2	2,110	2,134.6	2.9%
Site 5	-0.002	0	0.0	0.0%
Site 6	97.3	70	397.8	1.4%
Site 7	219.7	50	802.7	2.6%
Site 8	209.9	60	777.4	2.3%

5 CFM25, or cubic feet per minute at 25 Pa, represents the airflow leaking from a duct network at a pressure of 25 Pa.

Site 9	100.7	50	398.2	1.3%
Site 10	7.1	120	149.1	0.5%
Average	168.2	2,210	27.9 MMBtu	6.0%

Significant electricity savings were estimated for most sites. Minimal gas savings for many sites reflect the use of electric heat pumps for space heating. In addition, modeling results indicate that relatively little or no savings for Sites 5 and 10 could be attributed to the location of these apartment units on the middle vs top floor of the building, with an associated reduction in heat gains and losses (e.g., sun exposure, shared walls).

Cost savings, project costs, and associated simple paybacks for each site are shown in Table ES-12. To estimate cost savings, time of use rates from SCP (electricity) and PG&E's (gas) tiered rate schedule were applied to modeled savings. On average, AeroBarrier and Aeroseal (when applicable) offered $121 a year in gas and electric energy savings for the eight test sites with meaningful energy savings.[6] Project costs were taken directly from contractor invoices and averaged $2,392 per site for AeroBarrier and $3,234 per site that received Aeroseal. The bulk of the AeroBarrier costs were for labor, as the pre-work was relatively time intensive (along with aerosol application, testing and clean up, labor hours ranged from 8.4 to 10.7 hours per site). The resulting average payback periods for participating sites was 25.5 years, which is higher than desired for most homeowners without financial incentives.

Table ES-12. Aerosol Sealing Cost-Effectiveness Analysis

	Electricity Savings per Year	Gas Savings per Year	Total Savings per Year	Total Retrofit Cost	Payback Period (Years)
Site 1	$294.87	$0.48	$295.35	$3,892.00	13.2
Site 2	$18.97	$227.24	$246.22	$6,968.94	28.3
Site 3	$15.48	$172.91	$188.38	$4,209.00	22.3
Site 4	$2.19	$41.59	$43.78	$4,933.00	112.7
Site 5	$0.00	$0.00	$0.00	$4,457.33	N/A
Site 6	$29.46	$1.05	$30.50	$1,207.33	39.6
Site 7	$67.42	$0.82	$68.25	$1,207.33	17.7
Site 8	$64.33	$0.96	$65.29	$1,166.67	17.9
Site 9	$30.45	$0.86	$31.31	$1,166.67	37.3
Site 10	$1.42	$2.02	$3.45	$4,416.67	1,281.5

To inform real-world savings calculations over time, this study estimated sealant degradation over time by repeating air leakage measurements 1-1.5 years after application. The results are

[6] Sites 5 and 10 were excluded from this average due to seeing negligible savings.

summarized in Table ES-13. Of the eight[7] sites that were tested, the average degradation rate was 27%.

Table ES-13. AeroBarrier Degradation Results

	Initial Percent Reduction in Leakage (a)	Percent Reduction in Leakage after 1-1.5 Years (b)	Percent Degradation in AeroBarrier Sealing Sealing [(a-b)/a]
Site 1	67%	51%	24%
Site 3	47%	47%	1%
Site 4	61%	50%	18%
Site 5	71%	50%	30%
Site 7	70%	58%	16%
Site 8	61%	38%	38%
Site 9	51%	45%	13%
Site 10	54%	16%	71%

The nature of AeroBarrier application typically necessitates the moving or covering of items within the space. In a retrofit application, this is a minor issue when a space is unoccupied, for example during tenancy changes. In other cases, this poses a major practical barrier to use, and certainly impacted recruitment and participation within this study. In addition, the aerosol spray can damage carpet base layers, posing another practical barrier to some homes. Lastly, applying a sealant in spaces that contain gas appliances can pose indoor air quality concerns due to fuel combustion products if they are not properly ventilated.

Participant surveys were also complicated by the changes in pre- and post-retrofit conditions (tenancy and remodels), so can't be fully attributed to AeroBarrier. Still, feedback regarding comfort of occupants in sealed homes revealed overall comfort (the only quality that could be asked about) for all but one site. Many respondents reported dissatisfaction in seeing sealant particles around the house that required cleaning

Phase Change Materials

Ten test sites were targeted for this study, although several site recruiting challenges (including the COVID-19 pandemic) made it difficult to identify suitable sites. Ultimately six sites with favorable characteristics were secured, and the project team decided that this was an adequate sample size to evaluate the performance of the technology in diverse applications. A summary of the six test sites is provided in Table ES-14.

Table ES-14: PCM Technology Demonstration Sites

Site #	Building/Space Function	Score	Product	Installed Location	PCM Area	PCM Melting Point

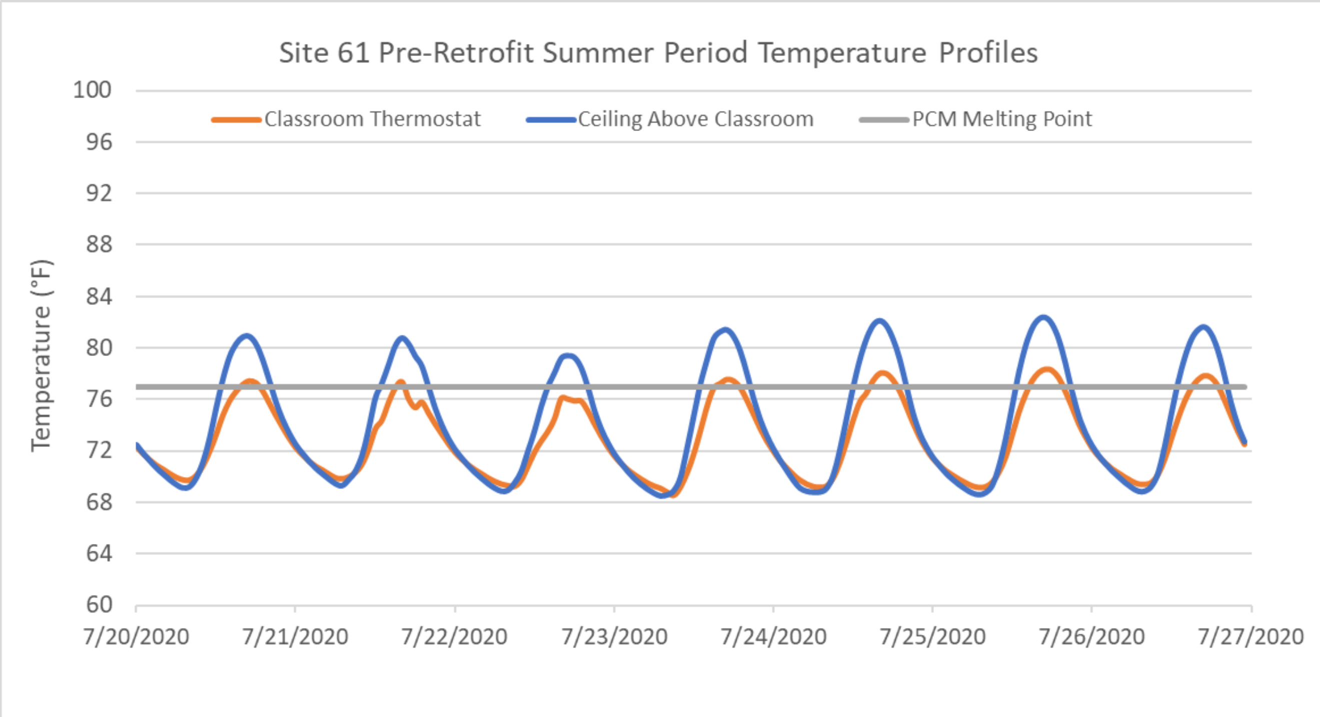
[7] Two sites were unresponsive to scheduling attempts.

11	Lecture hall	84	Templok	Drop ceiling	1,000 ft^2	75°F
57	Restaurant (Thai)	110	Templok	Drop ceiling	2,000 ft^2	72°F
58	Restaurant/wine tasting	92	Infinite R	Attic, above insulation	1,600 ft^2	77°F above kitchen, 73°F elsewhere
59	Restaurant (Pizza)	108	Templok	Drop ceiling	1,000 ft^2	75°F
60	Restaurant (Deli)	89	Templok	Drop ceiling, mechanical room above dining area	1,300 ft^2	75°F for drop ceiling, 77°F for dining area
61	Classroom/office	106	Templok	Drop ceiling	1,600 ft^2	77°F

All of the sites included drop ceiling areas for PCM installation and used the Templok material, except Site 58, which had a residential-style ceiling and used Infinite R. For many of the sites, the temperature in the drop ceiling or attic was monitored prior to purchase of the PCM, which allowed the Project Team to select melting points that best fit the application. All of the sites were self-installations, except Site 61 for which an insulation contractor was hired.

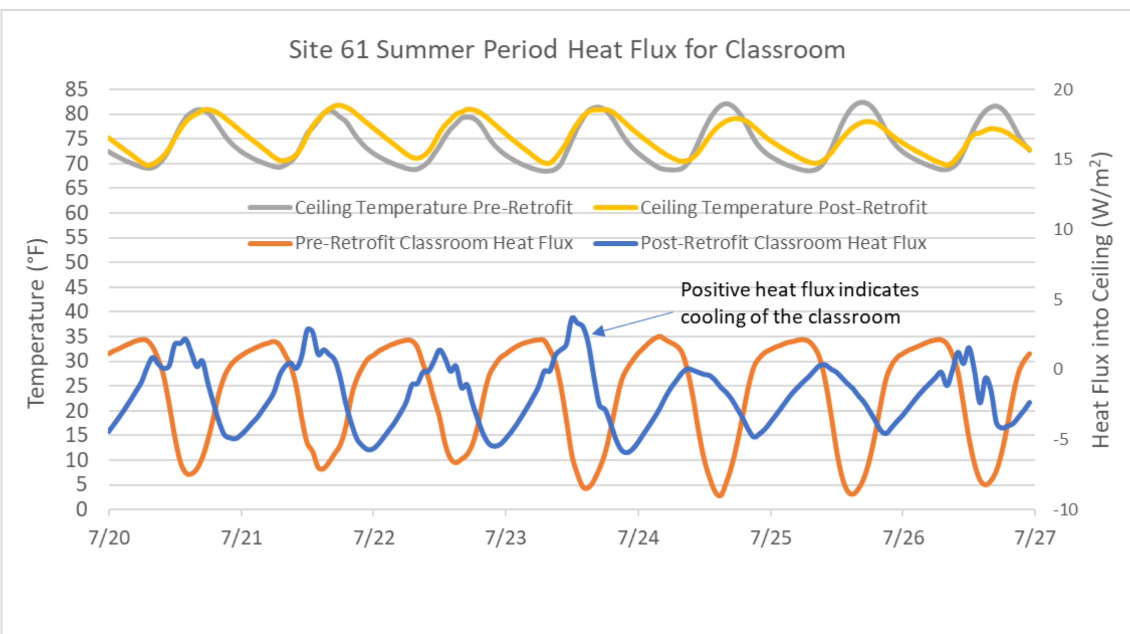
An example of the performance of PCM in drop ceilings is provided by Site 61, which was a preschool facility with no air conditioning. The PCM was installed above drop ceilings in several areas, including classrooms, offices, and a kitchenette. A relatively high melting point (77°F) Templok product was selected to help manage overheating during the summer months. Temperatures and heat flux through the ceiling were monitored in the classroom and one of the offices. The pre-retrofit summer temperature profiles in the classroom are shown in Figure ES-1. The drop ceiling area consistently reached temperatures above and below the melting point, and the PCM was expected to freeze and melt consistently during the summer. The lack of air conditioning resulted in large daily temperature swings. Pre-retrofit winter temperatures for the classroom were kept between about 55°F and 65°F all day, well below the melting point of the PCM. The preschool was not yet open at this time due to COVID-19, but even with a higher thermostat setting, it was not expected that the PCM would contribute much savings during the coldest months.

Figure ES-1: Pre-Retrofit Summer Temperature Profiles – Site 61 Classroom



Heat flux from the classroom into the drop ceiling was monitored before and after the retrofit. The results for the week of July 20 are shown in ES-2. As expected, the heat transfer reversed direction following the PCM installation, and the melting of the PCM served to cool the classroom as it warmed up during the day. The stored energy was released back into the classroom at night when there was no need for cooling. No energy savings would be expected because there was no air conditioning, but the heat flux data provided an explanation for the lower peak temperatures in the classroom during hot summer days.

Figure ES-2: Summer Heat Flux Before and After Retrofit – Site 61 Classroom



Not all test sites had a suitable base case for comparison, because the building was repurposed or because of COVID-19 impacts on building operations in 2019. A summary of the energy savings and cost-effectiveness analysis for the three test sites with a usable base case and reliable field test results is provided in Table ES-15. The long-term material cost for Site 57 was assumed to be about 60% of the actual cost, and Site 59 was assumed to be 70% of the actual cost, based on the amount of PCM that was left over after installation. The actual material costs for Site 60 seemed realistic, but the installation time was cut in half to better align with other sites and to reflect the unique installation challenges at that site. The results indicate that for sites similar to those selected for this demonstration project, the technology leads to an average of 8.9% whole-building energy savings and a simple payback period of 20 years assuming a mature market.

Table ES-15: Energy and Cost Savings Summary for PCM in Commercial Buildings

	Site 57	Site 59	Site 60	**Average**
Actual cost of measure (equipment + installation)	$5,863	$4,298	$6,080	**$5,414**
Projected long-term cost of measure (equipment + installation)	$3,758	$3,189	$5,380	**$4,109**
Annual electricity savings (Site kWh)	811	-5,389	1,261	**-1,106**
Annual gas savings (Site kBtu)	31,500	31,000	45,800	**36,100**
Annual Energy savings (Site MMBtu)	34.3	12.6	50.1	**32.3**
% energy savings (whole building)	9.2%	1.5%	15.9%	**8.9%**
Annual TOU utility bill savings ($)	$744	-$1,242	$1,108	**$203**
Simple payback (years) (actual)	7.9	No Payback	5.5	**26.6**
Simple payback (years) (projected long-term)	N/A	N/A	N/A	**20.2**

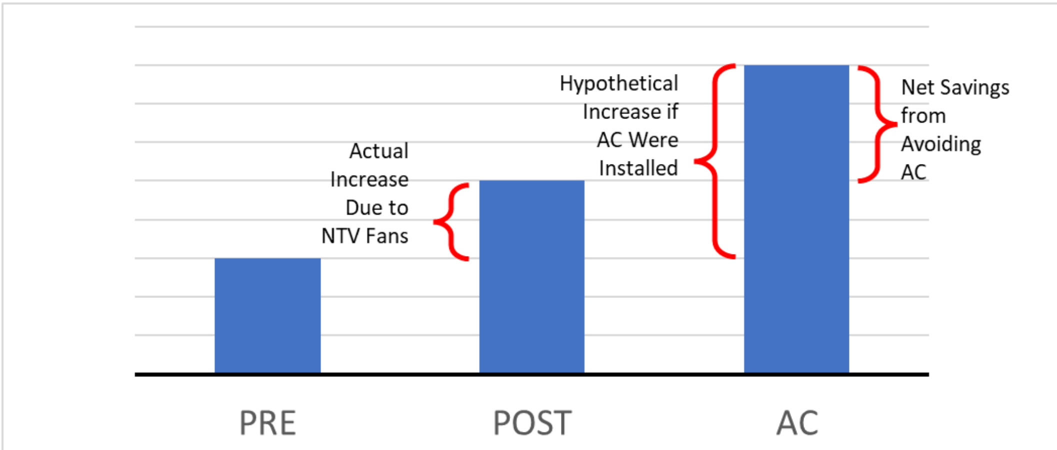
There appears to be significant energy savings for PCM installed in drop ceilings, especially if the melting point is properly aligned with the temperature of the ceiling during the cooling months. Comfort improved in certain cases according to the business owners, but it was only quantifiable when there was no air conditioning.

The Templok product appeared to be durable based on observations over a year after the retrofit. The weight of the product caused a number of concerns with business owners prior to installation, and in one case it appeared that some of the ceiling tiles had cracked or deformed due to the weight. The installation process seemed to be quick and efficient for most business owners and contractors.

Nighttime Ventilation

Three scenarios were evaluated for the nighttime ventilation (NTV) demonstration, as illustrated theoretically in Figure ES-3. Baseline or "Pre" reflects no cooling system, post-retrofit or "Post" reflects just a NTV cooling system, and "AC" reflects the hypothetical addition of a standard AC system instead of the NTV system. Of course, when comparing "Pre" and "Post" scenarios, cost and energy use would be added and the primary benefit would be enhanced comfort, but when comparing "Post" and "AC", energy savings would be significant.

Figure ES-3: Illustration of Net Impacts of Adding NTV Compared to AC



Energy savings at the test sites were modeled but informed by direct measurement of the furnace's forced air unit fan energy use (the only energy use by the NTV system aside from minimal energy use by the damper motor and actuator) and hypothetical AC use under the same conditions. Modeled results are summarized in Table ES-16, showing that a NTV system uses less energy than a standard AC cooling system – 46% less on average. When considering peak hour energy use, NTV systems offer 93% savings as the bulk of the energy use is during non-peak hours. When evaluating whole home energy use, these savings are lower but still positive.

Table ES-16: Simulated Cooling and Whole Home Energy Use and Savings as Compared to NTV

MONTH	COOLING ENERGY (kWh)					WHOLE HOME ENERGY (kWh)				
	PRE	AC	POST	SAV	SAV%	PRE	AC	POST	SAV	SAV%
1	-	-	-	-	0%	576	576	576	-	0%
2	-	-	-	-	0%	520	520	520	-	0%
3	-	-	-	-	0%	546	546	546	-	0%
4	-	-	-	-	0%	507	508	507	-	0%
5	-	41	41	1	2%	510	551	551	1	0%
6	-	130	58	72	55%	457	587	515	72	12%
7	-	122	57	65	53%	468	590	525	65	11%
8	-	167	76	91	54%	474	641	551	91	14%
9	-	68	52	16	23%	474	542	526	16	3%
10	-	-	-	-	0%	514	557	514	-	0%
11	-	-	-	-	0%	513	513	513	-	0%

12	-	-	-	-	0%	574	574	574	-	0%
TOTAL	-	528	284	244	46%	6,134	6,706	6,418	244	4%
On Peak	-	347	23	324	93%	1,924	2,298	1,947	350	15%
% On Peak	0%	66%	8%	0%		31%	34%	30%		
Off Peak	-	181	261	(80)	-44%	2,298	4,408	4,471	(63)	-1%

To translate energy savings to cost savings, modeled savings were applied to both flat and TOU rates. For the latter, energy usage results were broken down by hour. The results, shown in Table ES-17, support expectations that there is a cost penalty when using NTV (compared to no cooling system), but a larger penalty for using conventional AC.

Table ES-17: Annual Whole-Home Electricity Costs for Alternative Rate Scenarios

	ANNUAL COSTS			SAVINGS		
RATE	PRE	POST	AC	Increase for NTV (PRE-POST)	Increase for AC (PRE-AC)	Net Savings (AC-POST)
Flat (E1)	$ 1,747	$ 1,839	$ 1,934	$ (93)	$ (187)	$ 94
Time of Use (E-TOU-C)	$ 1,767	$ 1,869	$ 1,998	$ (102)	$ (231)	$ 129

Total costs for this technology averaged $4,494 per site, with $980 in materials and $3,514 in average installation costs.[8] These costs were significantly higher than the expected $2,150 average due to COVID-related market disruptions and general labor cost increases. Of course, as the technology matures in the market, costs would be expected to decrease. The average total cost of installing a conventional AC system is similar to NTV installation costs, but still higher at $4,757.[9]

Simple payback periods do not readily apply to this analysis. When considering just the installation of NTV, the increase in electricity cost renders this metric meaningless. When compared to the avoided installation of an AC system, the metric is also ill-fitting as the incremental cost of installing NTV versus AC is negative. If considering the incremental cost and savings of an NTV versus AC system, the payback would be immediate.

Homeowner satisfaction was measured in multiple ways. Indoor air temperatures were analyzed and found to be overall lower in the retrofit period than the baseline period, suggesting effective NTV cooling. As with other technologies in this study, participant surveys were also administered during the baseline and retrofit periods. In combination with feedback collected via an online 'satisfaction log' (completed at the participant's discretion), results showed that, overall, most sites were satisfied with the system. Some downsides reported by sites included comfort issues during heat waves, home cool down times, and fan unpredictability and noise (the latter was ultimately corrected by field technicians).

[8] One site (51) was excluded due to anomalous data resulting from atypical installation challenges.

[9] Based on internet research showing the installed cost of a new central AC system at about $600 per ton, plus $2,000. One ton of cooling for every 400 square feet is assumed.

Installation feedback was also gathered from the installing contractor. Though most installations went smoothly, some challenges at individual sites included insufficient attic space for the needed equipment, unexpected permitting issues, complexities in thermostat integration, and the custom wiring needed to circumvent the lack of AC within the system.

Conclusions

The seven retrofit technologies that were demonstrated under Lead Locally showed a range of performance and cost effectiveness across the 50 test sites. A summary of the average energy savings and cost-effectiveness for all technologies, assuming mature market costs and typical building applications, are presented in Table ES-18. Several demonstrated significant energy and cost savings on the path toward 10% residential and 20% commercial building energy savings, and the initial investment could be recovered within 10 years. This includes heat pump water heaters replacing electric resistance, commercial induction cooking, heat recovery dishmachines, and nighttime ventilation in lieu of air conditioning. Others achieved site energy savings that either did not translate into utility bill savings or the savings was insufficient to make the investment cost-effective within a reasonable time period (less than 10-15 years). Examples include ducted mini-splits, aerosol envelope sealing, phase change materials in drop ceilings, residential induction cooking, and HPWHs replacing gas water heaters. However, with appropriate incentives, careful choice of application (including new construction and in combination with PV systems), or end-of-life replacement, all technologies show significant promise.

This project led to many key findings, lessons learned, and area that require further research:

- Lead Locally successfully demonstrated seven emerging retrofit technologies across a broad range of applications, learning a great deal about remaining technical and market barriers that must be addressed before broad deployment is likely in Northern California.
- All technologies performed well from a technical standpoint.
- Close collaboration between SCP, Frontier, manufacturers, and installers was essential for selecting quality sites with supportive building owners, ensuring the retrofits were installed and monitored effectively, and addressing issues immediately once they were identified.
- Energy cost savings and cost-effectiveness varied significantly for different technologies and at different sites. The specific application is a very important consideration, along with the remaining useful life of existing equipment. It is important to develop guidance for building owners to determine if they are a good candidate for each technology.
- Technologies that included fuel substitution were sometimes cost-effective if the improvement in efficiency overcame the higher cost of electricity. In applications with PV, the cost-effectiveness would be greatly improved.
- COVID-19 created several challenges for the project, affecting site recruitment and reliable calculation of pre-retrofit energy usage.
- Trained contractors are readily available for some technologies (such as induction cooking and HPWHs), but other require further infrastructure development to reduce installation costs (PCM, AeroBarrier, nighttime ventilation, ducted mini splits).

- Building owners were generally very happy with the technologies installed and their experience with the Lead Locally program.
- There is a broad range of possible mini-split heat pump retrofits. Additional field studies of other options would be valuable to help determine the best design across a range of residential and small commercial applications.
- There is great potential to demonstrate cost-effective fully electric kitchens. A full in-situ field retrofit study is badly needed to prove this concept and to determine the installation costs.

Table ES-18: Generalized Site Energy Savings and Cost-Effectiveness Summary

Technology	Building type	Projected long-term cost of measure (equipment + installation)	Annual electricity savings (site kWh)	Annual gas savings (site kBtu)	Annual total energy savings (site kWh)	% energy savings (whole building kWh)	Annual TOU utility bill savings ($)	Simple payback (years) (projected long-term)
Aerosol Envelope Sealing	Residential	$3,362	168	7,300	818	6.0%	$97	34.6
Heat Recovery Dishmachines	Commercial	$4,000	5,475	0	5,039	8.0%	$2,063	2.4
Heat Pump Water Heaters (Existing Gas WH)	Residential	$4,000	-2,148	15,200	2,352	4.6%	$61	65.8
Heat Pump Water Heaters (Existing Electric WH)	Residential	$4,000	2,749	0	4,660	8.2%	$625	6.4
Induction Cooking	Residential	$3,000	248	0	249	5.0%	$43	69.8
Induction Cooking	Commercial	$5,500	-10,585	167,900	38,511	0.8%	-$700	N/A
Ducted Mini-Split Heat Pump	Residential	$26,016	-290	3,600	757	13.0%	-$53	N/A
Nighttime Ventilation (Versus AC)	Residential	-$514	244	0	244	3.6%	$129	Immediate
Phase Change Materials	Commercial	$4,109	-1,106	36,100	9,476	8.9%	$203	20.2

- It would be valuable to repeat the exhaust heat recovery study with larger dishmachines.
- From the three points of reference consisting of the initial leakage, initial post-retrofit leakage, and the leakage taken 11–19 months after the AeroBarrier installation, it was found the effectiveness of air sealing degraded 27% on average. Further research is recommended to take multiple blower door measurements from one month to three years after the retrofit to determine to what extent and how rapidly the sealant degrades.
- Lab testing of the commercial PCM technology installed in drop ceilings would be helpful for determining optimal temperatures and actual energy savings under controlled conditions.

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 is a community choice energy program providing electricity to 189,000 residential and 31,000 commercial customers in Sonoma and Mendocino Counties. This robust existing building initiative will also serve 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 technology demonstration portion of Lead Locally focused on accelerating the adoption of proven technologies in existing residential and commercial buildings through demonstration sites and innovative program strategies and channels driven through the Sonoma Clean Power Advanced Energy Center. This includes activities to demonstrate how emerging energy efficiency technologies can be installed, optimized, bundled, and promoted to effectively overcome known (and newly discovered) technical and market barriers.

This Technology Demonstration Final Report documents the activities and approaches used by the project team to demonstrate how underutilized energy efficiency technologies perform in targeted applications, and how they might be effectively deployed to maximize energy savings in California. Technology demonstration activities examined various drivers and barriers in the energy efficiency market in Sonoma and Mendocino counties and established how the data and results from the technology demonstration sites were used in the Advanced Energy Center to accelerate technology deployment.

This chapter provides an overview of the general program strategy and technologies that were evaluated during the technology demonstration stage of Lead Locally. This included limited field verification of seven market-ready technologies with some degree of performance or cost uncertainty when applied as retrofits in common building sectors in the relatively mild climates of Sonoma and Mendocino counties. Technical features are presented, along with discussion of target markets, energy savings potential, and preliminary deployment strategies. Further details on the technology demonstration plan can be found in the Technology Demonstration Program Implementation Plan (Sonoma Clean Power Authority, 2019).

1.2: Targeted Technologies

The first step in the selection of technologies for the demonstration phase of Lead Locally was to evaluate their potential relative to the priorities established through the CEC solicitation and the objectives of the proposed project:

- Commercially available
- Significant electricity savings potential that can help meet the target of 10% savings for residential buildings and 20% savings for commercial buildings
- Meaningful potential for load shifting, natural gas savings, and non-energy benefits
- Uncertain energy savings for the targeted application in the mild climates in the SCP service territory
- Uncertainty in cost of installation
- Uncertain customer acceptance based on comfort, aesthetics, or convenience
- Underutilization due to market, cost, or technology barriers that could be overcome to a large extent through Lead Locally initiatives

1.3: Technology Overviews

Brief technology descriptions are provided in the following sections, along with a summary of key technology attributes in Table 1. More comprehensive technology overviews and detailed technology demonstration plans are included in Chapter 3.

Grid-Interactive Heat Pump Water Heaters

Grid-interactive heat pump water heaters (HPWHs) communicate with their local utility and can use this connectivity to enable more advanced control strategies, primarily in the form of load shifting. Signals from the utility drive the HPWH to operate in a manner that shifts electricity use from the peak demand period by pre-heating hot water to a higher temperature in mid-afternoon when solar electricity contributes more power to the grid. This project demonstrated and verified the performance of those systems by installing grid-interactive HPWHs in houses in Sonoma Clean Power's service territory and monitoring electricity use pre and post retrofit to estimate their performance. This technology is relevant primarily to single-family residential buildings but may also be viable in multi-family residential buildings with individual water heaters or some small commercial buildings with significant water heating loads.

Phase Change Materials

PCMs are materials that absorb heat as they melt and release heat as they freeze. Unlike sensible energy storage in thermal mass, energy storage in a phase change occurs over a relatively constant temperature and requires much less volume. 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 ceilings and attics. PCMs do not contribute to the R-value of the building envelope, 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. They can also store energy and enhance the effectiveness of pre-cooling when installed in drop ceilings. For Lead Locally, two macro-encapsulated PCM products called Templok and Infinite R were studied as a method for mitigating interior temperature excursions in the drop ceiling or enhancing insulation effectiveness in attics of commercial buildings.

Ducted Mini-Split Heat Pump

A “heat pump” is a highly efficient air conditioner that can also work in reverse and provide heat during the winter. A “split” system is one that is split into two components: an “indoor unit” and an “outdoor unit.” A mini-split heat pump (MSHP) is just a smaller version that can vary the speed of its components to match the current needs of the home, using less energy in the process. A ducted mini-split typically has one indoor unit and distributes conditioned air throughout the house using compact ductwork, in contrast to a ductless mini-split which typically distributes refrigerant to multiple small indoor units, each with its own fan-coil and often with a separate thermostat. The retrofit package that was evaluated for Lead Locally included envelope improvements that reduced the required capacity of the MSHP, and integrated supply ventilation to improve indoor air quality. This technology is targeted primarily to the single-family residential market.

Induction Cooking

Natural gas and electric resistance cooktops and ranges currently share the vast majority of the residential and commercial markets in California. Electric induction cooktops offer increased efficiencies over both natural gas and coil electric resistance cooktops due to more efficient energy transfer and faster cook times. Induction cooking uses electromagnetism to heat the cookware, which must be made primarily of iron or another metal that responds to magnetic fields. Induction cooktops are market ready and have proven benefits, but there is uncertainty in market acceptance and installed energy savings for the technology. Lead Locally provided an opportunity for customer education, deployment of induction stoves, quantification of savings through installation of circuit-level monitors, and evaluation of customer acceptance of the technology through post-installation surveys. This technology was demonstrated in both residential and commercial buildings.

Waste Heat Recovery

Lead Locally examined the potential benefits and cost-effectiveness of several promising heat recovery technologies. Heat recovery ventilation (HRV) (which is a balanced system that exchanges energy between supply and exhaust air) is coming down in cost, though the technology has experienced reliability problems in the past, and energy savings tends to be lower in mild climates like Sonoma County. Drain water heat recovery (DWHR) systems work in much the same way as heat recovery ventilation where incoming cold water is pre-heated by outgoing warm drain water from showers or dishwashers. These technologies may be considered for either residential or commercial applications. For the Lead Locally technology demonstration, we selected a heat recovery dishmachine for commercial kitchens that uses energy from the exhaust flue to preheat water for dish washing.

Aerosol Envelope Sealing

The aerosol duct sealing process known as Aeroseal uses a vinyl compound suspended in a water solution, which is atomized and pumped through HVAC ducts and deposited at leakage points without coating the inside of the ducts. Responding to the need for an inexpensive, effective means of sealing building envelopes, a similar aerosol sealing process called AeroBarrier was developed. This process involves briefly pressurizing a building using a blower door, while injecting an aerosol “fog”. As the air escapes through leaks in the exterior shell of the building, the aerosolized sealant is transported to the leaks, accumulates, and seals the leakage path as pressurized air tries to escape. The AeroBarrier technology appears to be most promising for residential building applications, especially multi-family. Both duct and envelope aerosol sealing were tested in residential buildings for Lead Locally.

Nighttime Ventilation

Nighttime ventilation systems use low temperature outside air to provide cooling and can also be used to pre-cool buildings at night to offset next day air conditioner loads. Title 24 requires similar systems for rooftop package units exceeding 54,000 Btuh in non-residential buildings, but the majority of existing small rooftop package units do not include them. Nighttime ventilation has the potential to mitigate the impact of air conditioning on California’s increasing peak load by providing an alternative to air conditioners in milder climates that only rarely need them, such as much of Sonoma County. This project will evaluate the performance of a nighttime ventilation cooling system called Airscape that can be integrated with existing furnaces. This technology is targeted to residential markets.

Comparison of Selected Technologies

Important attributes and expected energy savings for the seven technologies selected for technology demonstration projects are summarized in Table 1.

Table 1: Key Attributes of Proposed Technologies Selected for Demonstration.

Technology	Expected Electricity Savings	Other Benefits	Interactions with Other Measures	Targeted SCP Customer Segments
Grid-interactive heat pump water heaters	• 60% hot water (vs electric resistance water heater)	• Load shifting • Hot water availability during peak hours	• Savings may be enhanced by tank insulation or by moving into conditioned space	• Single-family • Small restaurants
Phase change materials	• 30% cooling • 10% heating	• Load shifting • Thermal comfort • Gas savings	• Whole house fan could accelerate energy discharge to attic at night • Less cost-effective if cooling load is small	• Small food service • Small industrial • Warehouses
Ducted mini-split heat pump	• 20-30% heating and cooling (vs standard air-source heat pump)	• Peak load reduction • Reduced on/off cycling • Greater comfort	• Lower required capacity/cost when combined with load reduction • Allows integrated supply ventilation	• Single-family • Multi-family • Small office
Induction cooking	• 10-40% cooking (vs electric resistance)	• Cooking speed • Safety • Cleanliness • Peak load reduction	• May reduce kitchen ventilation hood requirements slightly	• Single-family • Commercial kitchens
Waste heat recovery for commercial dishmachines	• 30-50% hot water (for exhaust heat recovery)	• Gas savings • Thermal comfort		• Commercial kitchens
Aerosol envelope sealing	• 20% heating and cooling	• Gas savings • Less drafts	• Less cost-effective when combined with high efficiency cooling system	• Rented single-family (tenant turnover) • Multi-family (tenant turnover)
Residential nighttime ventilation	• 30% cooling relative to AC	• Peak load reduction • Indoor air quality	• Less cost-effective when combined with high efficiency cooling system	• Single-family • Small commercial

1.4: Barriers to Adoption

Each of the technologies that will be included as demonstration projects must overcome one or more barriers to widespread adoption in Northern California. Some of these barriers are technical in nature, requiring improved engineering or manufacturing processes, or greater understanding of the interactions among technologies and the influence of climatic conditions. Cost barriers can sometimes be overcome through manufacturing improvements, or by greatly increasing the scale of production so equipment and facility costs can be spread among more products. Cost barriers can also be mitigated through performance improvements where the value of greater energy savings outweighs the high cost of the technology, or through special financing mechanisms such as rebates or on-bill financing. Finally, market barriers may be present due to a dominant market share owned by an existing company (often with a patent), regulatory hurdles (energy code, safety requirements, permitting), inadequate supply infrastructure, or simply lack of awareness by contractors and potential customers. Key barriers for each technology are summarized in Table 2.

Table 2: Barriers to Adoption for Lead Locally Technologies.

Technology	Technology Barriers	Cost Barriers	Market Barriers / Knowledge Gaps
Grid-interactive heat pump water heaters	• Load shifting not customized to occupants • Impossible to predict water use with certainty	• May only be cost-effective with time-of-use rates	• Unfamiliar to homeowners • Uncertain impact on hot water availability
Phase change materials	• Performance dependent on large temperature swings	• High material cost • Uncertain economic return	• Guidance required for design and installation • Unfamiliar to business owners
Ducted mini-split heat pump	• Installed efficiency is often less than predicted • Envelope improvements often required	• High installation cost • Low cost of gas vs electricity	• Benefits can be difficult to explain to homeowners • Guidance required for design and installation
Induction cooking	• Requires iron cookware • May require electrical upgrade	• Low cost of gas vs electricity • Uncertain economic return	• General preference for gas cooking
Heat recovery dishmachines	• Less effective in mild climates	• Uncertain economic return	• Lack of infrastructure
Aerosol envelope sealing	• Can be messy • Limited evidence of effectiveness for retrofits	• Expensive equipment required • Less cost-effective in mild climates	• May require unoccupied housing unit • Unfamiliar to homeowners • Lack of infrastructure
Nighttime ventilation	• Controls unproven • May require pre-cooling	• High equipment cost	• May be negative comfort impacts • Lack of infrastructure

1.5: Objectives

The following objectives were addressed by the technology demonstration projects:

- Measure installed energy savings in a variety of targeted applications in Sonoma County.
- Determine expected cost-effectiveness of the technology.
- Characterize non-energy impacts on comfort, hot water availability, noise, etc.
- Evaluate the long-term durability of the products tested.
- Identify installation challenges and training needs for contractors.
- Establish target market sectors.

- Identify market barriers related to building codes, permitting, contractor and supplier infrastructure, and building owner perceptions.

CHAPTER 2: Technical Approach

The general technical approach for performing the seven technology demonstrations is described in the following sections. Specific adjustments for individual technologies are addressed in Chapter 3.

2.1: Strategies for Technology Demonstration

The Lead Locally team leveraged multiple strategies to advance the technology demonstration activities for Lead Locally. These strategies included:

- Site recruitment and selection activities:
    - Site-Selection Criteria – essential, important, and desired test site features and conditions, adapted for each technology
    - Customer Data – review of existing Sonoma Clean Power customer data sets related to identified site-selection criteria.
    - Customer Recruitment – outreach communications aligned with site-selection criteria and existing customer data, including interest surveys and interviews to evaluate additional site-selection criteria not included in SCP data sets
    - Site Visits and Analysis of Findings – visits to all interested and qualified sites to confirm eligibility and alignment with the needs of the technology demonstration projects.
    - Engagement with Selected Sites – confirmation of the site's program participation, including SCP customer signature on the Program Participation Agreement.
- Research and data collection activities at technology demonstration test sites as documented in Chapter 3, tailored to the research questions associated with each technology. An overview of the test sites for these technologies and the primary data collection methods is provided in Table 3:

Table 3: Overview of Technology Demonstration Test Sites.

Technology	Targeted Number of Test Sites	Actual Number of Test Sites Secured	Primary Method of Evaluation
Grid-Interactive Heat Pump Water Heaters	10 residential or commercial	9 residential (1 withdrew following baseline period)	Direct measurement, utility bills, surveys
Phase Change Materials	10 commercial	6 commercial	Temperature monitoring, utility bills, surveys
Ducted Mini-Split Heat Pumps	5 residential	7 residential	Direct measurement, utility bills, surveys
Induction Cooking	5 residential and 2 commercial	5 residential and 1 commercial (1 site was unable to complete the installation)	Direct measurement, utility bills, surveys
Waste Heat Recovery for Commercial Dishwashing	3 commercial	2 commercial (1 withdrew following baseline period)	Direct measurement, utility bills, surveys
Aerosol Envelope Sealing	10 residential sites	10 residential sites	Direct measurement, utility bills, surveys, modeling
Nighttime Ventilation	10 residential sites	10 residential sites	Direct measurement, utility bills, surveys, modeling

- Recommendation whether to pursue deployment through the Advanced Energy Center.
- Further planning, coordination with, and launch of Lead Locally and other aligned resources to overcome identified market barriers. These deployment efforts will be addressed in a future report.

2.2: Lead Locally Technologies and SCP Customers

While Lead Locally technologies evaluated through the technology demonstration process are available to all SCP customers, the associated impacts, concerns and needs will depend on the customer segment. Customer segmentation includes:

1. **Low-income customers.** Low-income customers will require access to capital or credit unavailable through existing incentive programs.

2. **Photovoltaic (PV) system and electric vehicle (EV) owners.** Customers with installed PV systems and EVSE will require information about how Lead Locally technologies may interact with these systems.
3. **Time of Use (TOU) customers.** TOU customers will need to be aware of how specific Lead Locally technologies impact their electricity costs during times of peak pricing.
4. **Propane users.** Propane users will need to know that Lead Locally technologies are functional alongside propane fueled equipment without causing any disruptions, or know the cost and greenhouse gas savings of replacing their propane appliances.
5. **Yellow-tagged property owners.** A yellow-tagged building means Cal Fire deemed the structure is safe to occupy after the 2017 wine country fires, but that it requires repairs and permits from the city. Installation of Lead Locally technologies may require additional work and financial investment.

Anticipated impacts, interactions, or concerns between customer segment and Lead Locally technologies are outlined in Table 4.

Table 4: Impacts, Interactions and Concerns Between Customer and Lead Locally Technologies

Technology	Low income CARE / FERA customers	Solar / EV customers (all on TOU rates)	TOU Customers (including Solar / EV customers)	Propane Users	Yellow tagged properties
Grid-interactive heat pump water heaters	• May be eligible for existing programs incentivizing heat pump water heater replacements if replacing electric water heater. May need financing to combat high initial installation costs.	• May reduce electric bill by shifting load from the high price late afternoon period to a lower price mid-day period	• May reduce electric bill by shifting load from the high price late afternoon period to a lower price mid-day period	• No available existing programs to help offset costs, so additional financing/funding may be needed.	• May be too expensive for homeowners without an existing electric water heater
Phase change materials	• Ineligible for incentives as a stand alone technology; if integrated into an insulation package then that package could be rebate eligible reducing overall costs	• PCM will reduce electricity demand during peak periods when TOU rates are high, and shift some of the electricity use to off-peak hours when TOU rates are low	• PCM will reduce electricity demand during peak periods when TOU rates are high, and shift some of the electricity use to off-peak hours when TOU rates are low	• PCM may reduce heating energy from propane systems	• If insulation is heavily damaged and must be replaced, including PCM under insulation will make it cheaper to install
Ducted mini-split heat pump	• May be eligible for ducted system and mini split heat pump incentives	• May reduce electricity demand during peak periods when TOU rates are high • No interaction with EV	• Little impact	• No available existing programs to help offset costs, so additional financing/funding may be needed.	• May be ideal for yellow-tagged properties where insulation and the HVAC system are heavily damaged and must be replaced
Induction cooking	• Ineligible for existing program incentives	• May reduce electricity demand during peak periods when TOU rates are high • No interaction with EV	• Little impact	• No interaction with propane heating systems	• May be a concern for yellow-tagged homes requiring kitchen counter rearrangement or new electrical lines
Waste heat recovery for commercial dishwashers	• Ineligible for existing program incentives	• May reduce electricity demand during peak periods when TOU rates are high • No interaction with EV	• May impact time TOU rates depending on water heating fuel source and usage pattern	• May lower the use of a propane heater by lowering the total CFM load	• May ease installation in the whole kitchen/scullery space if exhaust hoods are heavily damaged and need to be replaced

Aerosol envelope sealing	• May be eligible for existing programs incentivizing envelope measures	• No interaction with PV or EV	• Little impact	• Housing units using unvented propone heaters should be approached with caution	• Unoccupied housing units would make a good candidate
Nighttime ventilation	• Ineligible for existing program incentives	• No interaction with PV or EV	• No impact	• No interaction with propane heating systems	• May be less expensive if replacing heavily damaged attic

2.3: Lead Locally Technologies and Building Professionals

All contractors installing Lead Locally technologies and/or promoted through the Advanced Energy Center are required to hold an active Contractor's State License Board (CSLB) license appropriate for the scope of work. Contractors are required to document commercial general liability insurance policy or policies and appropriate bonding. The team verifies that the CSLB license number matches business name or DBA (doing business as) on record.

2.4: Field Test Approach

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 field test sites. 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 performance. The site selection criteria allowed the identification of buildings that would provide a best-case scenario for each technology 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 occupants and installers. All field test sites were selected from the SCP customer base located within Sonoma and Mendocino Counties. Specific details on the site selection process are provided in Chapter 3.

Installation

For most of the technology demonstration projects, the material costs were paid by SCP, while the building owner was expected to pay for installation costs. Due to financial hardships resulting from COVID-19, installation at a few sites was either performed by Frontier Energy or a contractor was paid by SCP. Mandatory training was provided by Lead Locally for all certified contractor installations and for self-installations (primarily PCM and induction cooking).

Utility Bill Analysis

When direct measurements of energy use associated with the retrofit were not performed directly, utility bill analysis was used for estimating energy savings. Utility bills introduce additional uncertainty because the end-use of interest (space conditioning, hot water, etc.) is not easily separable from other energy end-uses, and it must be assumed that any changes in whole-building energy use are caused by the retrofit. Behavior effects, especially COVID-19 quarantine periods, likely had a large impact on all end uses during the test period and could not be easily addressed in the analysis.

The pre-retrofit utility data could not be compared directly to the post-retrofit utility data because each year experienced different weather patterns. Unless otherwise noted in Chapter 3, a normalization tool created by Degree Days.net was utilized to weather normalize the utility bill data for each technology and test site (https://www.degreedays.net/). 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. In most cases, the linear regression model using a balance point temperature of 65°F for both HDDs and CDDs was chosen for all sites.

Unless otherwise noted, 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. The savings from the electric and gas utility billing data could then be determined by comparing the normalized pre- and post-retrofit data over the course of a full year.

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

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 7 days in the week. The Coefficient of Variation of the Root Mean Squared Error (CVRMSE) was calculated for the regression and compared to the ASHRAE Standard 14 goodness of fit criteria (<20% with less than 12 months of data, <25% with 12 months or more) (ASHRAE, 2014).

Cost-Effectiveness Analysis

Simple payback was used as the cost-effectiveness metric because it the most intuitive for stakeholders to understand. Simple payback is the initial cost of the retrofit measure divided by the annual utility bill savings. In general, a payback period of longer than 10 years would be difficult for a homeowner to accept, although a business owner may be more willing to take a long-term view if they also own the building or have a long-term lease. For this calculation, actual measure cost (material/equipment plus installation labor) was determined for each site, along with energy cost savings using SCP time-of-use rates and PG&E gas rates, unless otherwise noted. In addition to actual cost-effectiveness for the individual test sites, an estimated adjusted cost-effectiveness using mature installation costs (no prevailing wage, no learning curve, multiple trained installers) and energy cost savings for a typical building (average across test sites, modeled prototype, etc.) was calculated for the purpose of assessing each technology's readiness for further deployment through the Advanced Energy Center.

Site Close-Out

At the conclusion of the field test period, all instrumentation was removed, and the condition of each building was returned to its original state, except for the efficiency measures themselves. Any final building owner concerns were resolved at that time. Further details on the decommissioning process are provided in Chapter 3.

CHAPTER 3: Technology Demonstration Projects

The technology demonstration summaries in this section provide clear descriptions of the technologies that were evaluated through small-scale deployments at several test sites, along with key results from those test sites. Key research questions are described, along with a description of testing and modeling activities performed to address these questions.

Results for the following seven technologies are presented in subsequent sections:

- Ducted mini-split heat pumps
- Grid-interactive heat pump water heaters
- Induction cooking
- Exhaust heat recovery dishmachines
- Aerosol envelope sealing
- Phase change materials in commercial buildings
- Nighttime ventilation

In addition to these technologies, which were identified in the Lead Locally proposal, the project team considered additional technologies solicited through the Advanced Energy Center Vendor RFP or identified through conference attendance or other channels. The intention was that if it became clear that one of the proposed technologies was not technically viable, the remaining funding for that technology would be added to the budget for the most promising alternative technologies. The following technologies were considered, but ultimately rejected in favor of expanding the scope of the existing technology demonstrations through additional submetering and operational scenarios.

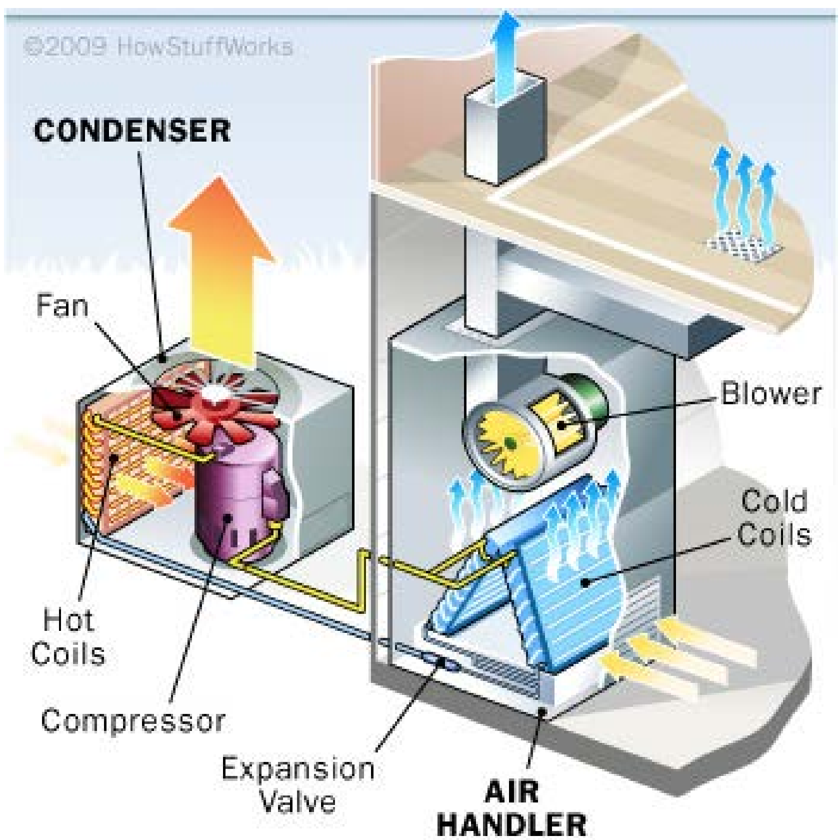
- Viking Cold defrost controller and PCM load shifting for walk-in refrigeration units
- CATALYST advanced controls for roof-top units (RTUs)
- Hank fault detection and building automation technology
- Biofiltro wastewater recovery system for commercial buildings
- Various home energy management systems

3.1: Ducted Mini-Split Heat Pump System

Introduction

A heat pump is an "air conditioner" that can also work in reverse and provide heat during cold weather. Meaning, a heat pump can either pull energy from the outdoor air to heat indoor air, or release energy to outdoor air to cool the indoor space. A "split" system (see Figure 1) typically refers to a two-component system where an outdoor unit includes a compressor, and coils to release or absorb energy from the air using a fan. The indoor unit includes the air handler and fan coils designated to condition the air running through the interior air duct system. The indoor and outdoor units are connected to each other with closed-circuit refrigerant lines running through both systems. A mini-split heat pump (MSHP) is just a more physically compact and smaller capacity version that can vary the speed of its components (compressor and fan) to match the current needs of the home and operate more efficiently.

Figure 1: Mini-Split System for Air Conditioning (credits: HowStuffWorks).



A ducted mini-split typically has a single indoor unit and distributes conditioned air throughout the house using compact ductwork, in contrast to a ductless mini-split which typically distributes refrigerant to multiple small indoor units, each with its own fan-coil (i.e. small indoor unit) and often with a separate thermostat. In this study, the MSHP system included a ducted system.

In addition to the evaluation of the MSHP system, the retrofit package for Lead Locally also included envelope improvements that reduced the required capacity of the MSHP, and integrated supply ventilation to improve indoor air quality.

The specific research questions for the field tests included:

- How do the indoor comfort and energy use provided by the retrofit systems compare to the baseline systems for each house and in aggregate?
- What are the annual cost savings and the payback period for the retrofit system, based on the energy use of the baseline system and billing data for the particular homeowner?
- What was learned about occupant behavior relative to the retrofit system? How does behavior impact performance?
- What home, climate, or occupant behavior factors led to higher savings for the retrofit systems at the test sites?

Traditional ducts in attics and crawlspaces waste as much as 30 to 50% of heating and cooling energy through leaks and thermal losses. Moving ducts into conditioned space significantly reduces these losses. Additionally, MSHP efficiency ratings tend to be much higher than those of traditional heating and cooling systems. Thermal load reduction measures translate to the likelihood of 20 to 30% heating and cooling energy savings, depending on the application. However, these energy savings may not directly translate to monetary savings on utility energy bills. Typical space heating systems burn natural gas while MSHPs use electricity, which costs more than gas per unit of energy. Nonetheless, the reductions in cooling costs may be significant enough to compensate for increased heating costs and open up the possibility of adding PV systems that can offset electric heating costs.

In addition to an expected 20 to 30% site energy reduction, the installation of the MSHP system was assumed to result in:

- Less cycling on and off by the system, thus providing better comfort and potentially less wear and tear on equipment.
- Smaller temperature swings due to a variable speed heat pump system.
- Better indoor air quality through addition of integrated supply ventilation

Methodology

The technology installed at the seven test sites consisted of a mini-split heat pump with ducts in conditioned space and integrated ventilation. For each test site, the energy usage pre- and post-retrofit is monitored and recorded. Together with the cost of installing the technology, the usage data will allow to evaluate the cost-effectiveness for each test sites.

At one of the sites, the installed equipment also included a power vent water heater. All test sites had central heating and cooling pre-retrofit, with ducts in a vented attic or crawlspace.

Traditional AC typically operates at a single speed and flow rate of the refrigerant. The installed mini-split heat pump system allows for variable speed. One of the advantages of a variable speed system is that it doesn't always run at full capacity. Thus, more efficiently handling lower internal loads and will not generate great swings in indoor air temperature. A variable speed system typically runs more often, but with adjustable capacity, the overall electricity usage is decreased. Because a variable speed system runs at varying capacity, less equipment wear and tear is expected. For the test sites, the installed outdoor unit was either manufactured by Fujitsu (AOU12RLFC or AOU18RLFC) or Mitsubishi Electric (ZUK-KA12 or ZUK-KA18). Depending on calculated design loads, the heat pumps had a cooling Btu rating of either 12,000 or 18,000 Btu/hour (1 or 1.5 tons). The installed indoor unit was a combined coil and blower system manufactured by Mitsubishi Electric (SVZ-KP12NA or SVZ-KP18NA)

At the test sites, all existing HVAC equipment and duct work were removed. A new and centrally located duct unit was installed channeling conditioned air to nearby rooms. The following were incorporated into each system design:

- Load reduction measures, including envelope sealing and new attic insulation.
- A MSHP system with a slim-duct style indoor unit.
- New ducts installed within the thermal envelope using furred or dropped ceilings, conversion of attic or crawlspace space into conditioned space, or one of several other options.
- Only one or two zones depending on loads and other site-specific issues.
- ASHRAE Standard 62.2 compliant whole-house ventilation to maintain indoor air quality.

The thermal load reduction as specified above included replacing attic insulation with R-60 blown insulation and improving the airtightness of the homes. When removing the existing attic insulation, the ceiling plane was sealed with caulk and foam at penetrations and interfaces.

Prior to the installation of the retrofit measures, a baseline period of monitoring energy usage was executed. For six months, temperature, electricity and natural gas usage data were monitored and collected. The baseline monitoring roughly started in March 2019 and ended in September the same year, thus including partial winter and summer seasons.

Key data points included the following both pre- and post-retrofit:

- Temperatures and humidity of the conditioned space.
- Outside temperature and humidity.
- Electricity and gas use for heating and cooling.
- Window and door operation.
- HVAC control settings.
- Documentation of major equipment and its usage.

Following the installation of the technology, the new HVAC system was instrumented similarly to the baseline system to quantify the reduction in HVAC energy use and to monitor occupant behavior that impacted HVAC system performance.

The cost of each retrofit was recorded in detail, including equipment, installation, maintenance, and permitting costs. Total cost was used to estimate cost-effectiveness. The homeowners were asked to complete a quarterly survey, provide access to their utility data, and allow technicians to enter the residence for data collection or repairs with reasonable notice. Retrofit costs, energy use data, and utility bills were used to estimate simple payback for the ducted MSHP technology. Occupant surveys, thermostat setting data, occupancy sensors, and window operation data were used to evaluate occupant behavior both before and after retrofits were performed.

Results and Analysis

The MSHP system was installed at seven test sites. In this report, they are referred to as test site “1” through “7”. For the purpose of identification, “1” is SCP35, “2” is SCP39, “3” is SCP36, “4” is SCP37, “5” is SCP38, “6” is SCP40, and “7” is SCP41. Each test site was a single-family home with a square footage varying from 720 up to 1,828 ft^2. All homes used natural gas for heating pre-retrofit except for Site 4, which used electricity (electric resistance).

The pre-retrofit data acquisition system was installed between March and April of 2019, recording information about energy usage, indoor and outdoor ambient temperatures, thermostat set points, etc. Six months later, the MSHP system was installed, and the data acquisition system kept collecting the very same information until the end of 2020. This allowed for an evaluation of the MSHP system and the impact on overall house energy efficiency.

Unfortunately, a comparison in performance and energy usage pre- and post-retrofit is quite problematic for the test sites. The complexity is a result of a change in energy source for heating. Pre-retrofit, six out of seven test sites use a furnace and natural gas for heating, while post-retrofit, the mini-split system uses electricity. Since, the price of natural gas is different than electricity, a side-by-side comparison is not straightforward. However, in this study, natural gas usage pre-retrofit is converted from kBtu to kWh. The influence on cost of energy will be reflected upon later in this report in a utility bill analysis.

The energy usage pre- and post-retrofit varied greatly between the residents and test sites. Pre-retrofit (between March/April through September/October), some residents basically didn’t use any energy for cooling, while others used up to 1,500 kWh during the time of data collection. Though, the heating season for 2019 was almost over, enough data was collected to make an assessment of the impact on heating demand.

The variation in outdoor climate pre- and post-retrofit is accounted for utilizing heating and cooling degree hours. In this study, degree hours are calculated assuming that heating occurs when the outdoor temperature is lower than 60°F, and cooling is needed when the outdoor temperature exceeds 65°F. Table 5 presents the calculated degree hours and heating and cooling usage pre- and post-retrofit for the seven test sites.

Table 5 also presents energy usage ratios for heating and cooling demand. The ratios are defined as normalized indicators of heating or cooling use per degree hour and are applied to evaluate reduction in use by comparing energy usage ratios before and after the MSHP system was installed. In Table 5, the reduction in use is defined as Usage Savings Ratio (kBtu/(°F·h or kWh/(°F·h) and is multiplied by the degree hours of 2020 to calculate the savings associated with the retrofit measure. All sites show savings in natural gas usage since using electricity for heating post-retrofit, except site 4 which uses electricity for heating pre-retrofit. For electricity usage, all sites show negative savings post-retrofit. These increases in energy use may have been caused by different thermostat set point temperatures pre-retrofit and changed behavior because of the COVID-19 pandemic, as further discussed later.

Some of the values in Table 5 are marked as gray, which means that data is missing or insufficient to complete the energy savings assessment as presented.

Table 5: Energy Usage, Degree Hours, Energy Usage Ratios, and Annual Energy Savings for the Seven Test Sites.

Actual Degree Hours [°F·h]			Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7	AVG
Heating	Pre-Retrofit		15,294	16,402	12,077	13,877	12,194	17,686	5,716	13,321
	Post-Retrofit[a]		46,771	46,772	53,230	51,077	54,049	51,293	43,652	49,549
Cooling	Pre-Retrofit		18,479	-	21,263	15,277	14,325	21,498	32,648	20,582
	Post-Retrofit[a]		32,414	32,415	33,332	20,208	24,816	26,054	-	28,207
Energy Use										
Heating	Pre-Retrofit	*kBtu*	297.0	3,788.0	835.0	-	1,086	1,460.0	76.0	1,257
		kWh	-	-	-	446.3	-	-	-	446
	Post-Retrofit[a]	*kWh*	910.1	300.4	776.0	2,247.4	1,538.1	1,117.1	29.3	988
Cooling	Pre-Retrofit	*kWh*	0.2	-	1,454.2	73.5	273.5	1,213.6	32.3	508
	Post-Retrofit[a]	*kWh*	29.6	137.7	1,733.3	9.5	547.5	636.6	-	516
Usage Ratio [Energy/(°F·h)]										
Heating	Pre-Retrofit	*kBtu*	0.019	0.231	0.069	-	0.089	0.083	0.013	0.084
		kWh	-	-	-	0.032	-	-	-	0.032
	Post-Retrofit[a]	*kWh*	0.019	0.006	0.015	0.044	0.028	0.022	0.001	0.019
Cooling	Pre-Retrofit	*kWh*	0.000	-	0.068	0.005	0.019	0.056	0.001	0.025
	Post-Retrofit[a]	*kWh*	0.001	0.004	0.052	0.000	0.022	0.024	-	0.017
Annual Energy Use Savings										
Heating		*kBtu*	**908**	**10,801**	**3,680**	-	**4,813**	**4,234**	**580**	**4,170**

	Pre- vs. Post-Retrofit	*kWh*	**-910**	**-300**	**-776**	**-605**	**-1,538**	**-1,117**	**-29**	**-754**
Cooling		*kWh*	**-29**	-	**546**	**88**	**-74**	**834**	-	**273**

[a] Post-retrofit *represents data collected during 2020.*
[b] kBtu *is gas savings, kWh is electricity savings*

The energy peak demand (individual maximum demands regardless of time of occurrence within a specified period) for cooling changed for several of the test sites post-retrofit. Table 6 presents maximum hourly energy usage pre- and post-retrofit. Four test sites reduced overall electricity peak demand for cooling. Unfortunately, usage data is missing for three of the seven sites to make the comparison.

Table 6: Peak Cooling Demand Usage for the Seven Test Sites Pre- and Post-Retrofit.

Peak Demand [kWh]	Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7	AVG
Pre-Retrofit	-	-	2.8	2.5	2.3	5.6	6.3	**3.9**
Post-Retrofit[a]	1.1	0.9	2.3	2.0	2.1	2.1	-	**1.8**
Change in Demand	-	-	**17%**	**22%**	**7%**	**63%**	-	**27%**

[a] Post-retrofit represents data collected during 2020.

Major variables on energy demand included human comfort levels and preferences. For the test sites, no restrictions were given on temperature range and limits for the thermostat. Thus, the homeowners were free to adjust the set point temperatures as they pleased. The thermostat set point between the test sites varied greatly, even between pre- and post-retrofit for the very same house. The change in user behavior and comfort preference for these sites may have been a result of spending more time at home in 2020 due to the COVID-19 pandemic or because of the MSHP system operating differently compared to pre-retrofit system. Table 7 presents thermostat settings and dead band for the seven MSHP test sites pre- and post-retrofit. A negative difference value means that the change to thermostat settings post-retrofit called for more heating or cooling.

Table 7: Thermostat Settings and Dead Band Pre- and Post-Retrofit for the Seven Test Sites.

Thermostat Set Point [°F]		Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7
Heating	Pre-Retrofit	68.7	64.6	64.9	62.5	67.5	71.5	61.5
	Post-Retrofit (2020)	69.2	67.3	64.4	71.5	66.4	-	60.0
	Difference	**-0.5**	**-2.7**	**0.5**	**-9.0**	**1.1**	-	**1.5**
Cooling	Pre-Retrofit	76.4	-	71.0	81.7	-	71.7	75.5
	Post-Retrofit (2020)	77.0	78.1	70.2	83.3	74.4	-	78.4
	Difference	**0.6**	-	**-0.8**	**1.7**	-	-	**2.9**
Dead band	Pre-Retrofit	7.7	-	6.1	19.2	-	0.2	14.0
	Post-Retrofit (2020)	7.8	10.8	5.8	11.8	8.1	-	18.5

The average cost to install the MSHP system consisted of labor and materials as given by Table 8. According to the breakdown in costs, about $18,600 was labor and $7,400 was material, totaling about $26,000 for the installation of the MSHP system.

Table 8: Cost of Labor and Material to Install the Mini-Split Heat Pump System.

LABOR BREAKDOWN				
DESCRIPTION		**TOTAL HRS**	**Cost Rate**	**Subtotal**
COMMISSIONING		14	150	$ 2,100.00
DRYWALL		21	150	$ 3,150.00
DUCTS		32.75	125	$ 4,093.75
ELECTRICAL		8	150	$ 1,200.00
FRAMING, FURRING, BACKING		2	150	$ 300.00
INTERIOR PROTECTION		8	150	$ 1,200.00
MECHANICAL (VENTILATION, DEHUMID)		22	150	$ 3,300.00
MISC		4	150	$ 600.00
PAINTING		8	150	$ 1,200.00
PLANNING		2	150	$ 300.00
PLUMBING		8	150	$ 1,200.00
PROJECT TOTAL				**$ 18,643.75**
EQUIPMENT AND MATERIALS BREAKDOWN				
DESCRIPTION		**UNIT**	**EXTENSION**	**EXT WITH TAX**
MITSUBISHI 1 TON SYSTEM		2,750	$ 2,750	$ 2,977
LINESET, COVER, HARDWARE		300	$ 300	$ 325
ELECTRICAL WIRING, BREAKERS, DISCONN.		150	$ 150	$ 162
PLUMBING PARTS, VENT PARTS (EXISTING)		175	$ 175	$ 189
DUCTS, ELBOWS, TRANSITIONS, MASTIC, ETC		350	$ 350	$ 379
SHEET METAL PLENUMS AND PANS		500	$ 500	$ 541
PANASONIC FANS		160	$ 320	$ 346
ECOBEE THERMOSTAT (EST)		300	$ 300	$ 325
INTERFACE MODULE (EST)		200	$ 200	$ 217
COLOR MATCHED PAINT		75	$ 75	$ 81
PERSONAL PROTECTIVE EQUIPMENT		200	$ 200	$ 217
DRYWALL, FRAMING, MUD, TAPE, ETC.		250	$ 250	$ 271
HERS VERIFICATION		450	$ 450	$ 487
PROJECT PERMIT		250	$ 250	$ 271
SHOEMAKER CANS, RETURN AIR GRILLE		50	$ 300	$ 325
ROOF AND SIDEWALL VENTS		20	$ 240	$ 260
PROJECT TOTAL				**$ 7,371.83**

TOTAL COST PER SITE	$ 26,015.58

In 2020, the average TOU price of electricity was $0.26 per kWh and the average price of gas was $0.0121 per kBtu (PG&E, 2022). Using the annual usage savings as given by Table 5, together with cost of electricity and total cost of installing the MSHP system allow to estimate a simple payback time. Table 9 presents estimated savings in cost of electricity for the seven test sites, including both heating and cooling. Naturally, cost savings is seen for natural gas usage post-retrofit. However, the cost savings for natural gas doesn't entirely compensate for increased cost in electricity for any of the test sites, except for test site 2. The total estimated costs of energy are negative for all test sites except for site 2, ranging from a loss of about $360 to roughly $50 in annual savings. Table 9 also presents payback times, in which only site 2 has a positive payback time.

Table 9: Savings in Cost of Electricity for the Seven Test Sites and Simple Payback Time.

Annual Energy Use Savings			Site 1	Site 2	Site3	Site 4	Site 5	Site 6	Site 7
Heating	Pre- vs. Post-Retrofit	*kBtu*	908.2	10,801.5	3,680.2	-	4,813.5	4,234.3	580.4
		kWh	-910.1	-300.4	-776.0	-604.6	-1,538.1	-1,117.1	-29.3
Cooling		*kWh*	-29.2		546.3	87.7	-73.7	834.2	
Annual Cost Savings[a]									
Heating	Pre- vs. Post-Retrofit	*kBtu*	$11.0	$130.7	$44.5	-	$58.2	$51.2	$7.0
		kWh	$(236.6)	$(78.1)	$(201.7)	$(157.2)	$(399.9)	$(290.5)	$(7.6)
Cooling		*kWh*	$(7.6)		$142.0	$22.8	$(19.2)	$216.9	
Total			**$(233.2)**	**$52.6**	**$(15.2)**	**$(134.4)**	**$(360.8)**	**$(22.3)**	**$(0.6)**
Simple Payback[b] [years]			**-**	**494**	**-**	**-**	**-**	**-**	**-**

[a]*Based on average cost of electricity of $0.26/kWh average and average cost of natural gas of $0.0121/kBtu in 2020* (PG&E, 2022)*.*
[b]*Average cost estimated at $26,000.*

The homeowners completed a survey about a year after the MSHP system was installed. The first part of the survey included questions related to comfort, control, and quality of equipment. The homeowners selected a number between one and five to measure satisfaction, where one represented "Very Dissatisfied" and five "Very Satisfied". Mostly, the homeowners were very satisfied or simply satisfied with the comfort levels related to temperature, feeling of drafts, perceived air quality, noise, and general comfort. Likewise, the HVAC system control was perceived as satisfactory at large. A few specific comments provided by some of the homeowners related to control were:

- "Missing option to run in "fan only" mode, and adjusting fan speed."
- "System will not run in "fan only" mode even if selected at the Ecobee thermostat."
- "Indoor air quality is easy to monitor and keep consistently great."
- "Missing humidity control."

- “Prioritization sometimes an issue (site with integrated water heater).”
- “Thermostats works as ’set it and forget it’.”

A few homeowners also requested more information on control, which was provided by Frontier Energy and their contractors after the surveys were reviewed.

Regarding indoor comfort, some homeowners complained about noise and some rooms not being conditioned/heated as effectively as others. Specific comments read:

- “Quiet delivery of conditioned air without noises from furnace or fan.”
- “Outside unit noisy.”
- “One bedroom and office are consistently warmer/colder than other areas.”
- “Return air is noisy.”
- “I feel safer with electricity than gas.”
- “Power vent from water heater made a lot of noise (site with integrated water heater).”

Comments related to performance were in general very positive.

- “We love it!”
- “System works fast at providing warm and cold air.”
- “Ecobee room sensors to detect presence work inconsistently and require battery replacement at an unreasonable rate.”
- “Less fluctuation in overall indoor temperature with the installed system. However, bathroom has no supply air from the new system, resulting in much warmer indoor air temperature during the summer and requiring space heating during the winter. Bedrooms sometime fluctuate more in temperature too.”
- “No maintenance required as of yet.”
- “Energy and cost savings with new system.”
- “Glad that increased electricity usage (because of not using gas for heating) can be offset with PV’s.”

Issues identified by homeowners were addressed to the extent possible by Frontier and Energy Docs. Finally, the survey ended with questions related to the program, support, staff, and contractors, and participating in the project. Here, the responses were mainly “very satisfied” from the homeowners.

Conclusions

The MSHP systems installed at the seven test sites resulted in very positive feedback from the homeowners, where everyone was overall very satisfied with system, performance, energy efficiency and perceived comfort.

The average cost of installing the system at the test sites was $26,000. The estimated cost savings for the test sites ranged from a loss of about $360 to roughly $50 in annual savings. For the site with positive savings, the payback time was about 500 years and naturally well beyond the service life of the installed system. However, the installation costs were paid by

Lead Locally, so the homeowners only experience the utility bill savings and any future maintenance costs.

The start of the COVID-19 pandemic in early 2020 complicated the cost-effective analysis considerably. The occupants spent more time at home, and indoor comfort preferences changed for many homeowners. The change in thermostat settings may have also been the result of a more effective system which allowed them to stay more comfortable while using the same or less energy.

Despite being perceived as a more energy efficient system by the homeowners of the test sites, the MSHP systems designed and installed for this study cannot be considered an overall success because of the lack of cost-effectiveness as a retrofit option. The two main reasons for the lack of cost-effectiveness are cost of labor and converting from natural gas to electricity. For labor, the cost was roughly $18,600, which was more than 70% of the total cost. For natural gas, the price is currently much lower than that of electricity in relation to the amount of energy used. When converting from gas to electricity, a technology must be very energy efficient to overcome the additional cost of electricity. None of the seven test sites has PV's. In applications with PV systems in place, the MSHP systems designed for this project may become cost-effective as a retrofit. Applications in new construction could also show more positive results.

3.2: Grid-Interactive HPWH (GIHPWH)

Introduction

GIHPWHs are an emerging technology which is poised for quick adoption in the residential market. These hybrid-type water heaters utilize a high-efficiency, relatively low-power heat pump in addition to standard electric resistance heating elements, which under low-to-medium hot water load conditions operate as something of a backup to the heat pump component. The heat pump works by siphoning energy from its surroundings to deposit into the water in the tank via a refrigeration cycle. The energy output of the heat pump is dependent on many factors, including how much heat is available to siphon from the surroundings (i.e., the ambient air temperature) and the size of the heat pump.

Modern hybrid HPWHs boast Uniform Energy Factor (UEF) ratings of up to 4.0 in ideal conditions, whereas conventional electric resistance water heaters typically have UEFs that range between 0.90-0.95. Natural gas storage water heaters typically have UEFs that range between 0.60-0.65. For homes that replace electric resistance water heaters with HPWHs, it is theoretically possible (based on the UEF ratings) to reduce hot water energy usage by as much as 75%. Though realistically, the HPWH effective UEFs typically are lower than the UEF ratings, as the heaters often operate in less favorable air and water temperature conditions and with larger hot water draws that call for activation of the electric resistance elements.

A resistance element is activated at times when the heat pump cannot handle the hot water load. This is problematic because more energy is needed to produce the same volume of hot water, and subsequently the operating cost of the water heater rises. This can be especially expensive in electric service areas with time of use pricing when the resistance element is engaged during peak hours. GIHPWHs work to reduce the electric resistance component, both overall and especially during on-peak hours, through load-shifting. The grid interaction can allow a utility or manufacturer to directly control the energy performance of a water heater and implement different energy-saving schemes on that basis through a Wi-Fi connection via limiting the amount of electric resistance heat. The user can also directly control the water heater's outlet set point temperature and mode (i.e. energy-saving, performance, travel, etc.). Energy-saving mode would maximize the heat pump component and limit the amount of electric resistance heat, where the performance mode would not limit electric resistance heat to provide a higher volume of hot water or to provide hot water more quickly than energy-saving mode. Other modes like travel can be implemented to limit all water heater action while users are travelling.

Upon receiving a grid signal, these water heaters can pre-condition the tank water temperature before the beginning of TOU on-peak hours and shift as much of the load possible from the relatively inefficient resistance element to the much more efficient heat pump. During the peak period, the resistance element activation is blocked (unless manually bypassed by the user).

The recovery capacity (i.e. first hour rating) of the heat pump component for these residential HPWHs (requiring 30-amp, 240-volt supplies) is in the order of 20% of the total, including the resistive heat. To compensate for the lower available input energy when in heat-pump-only mode, the load shift strategy can incorporate a larger storage tank for added volume capacity, a thermostatic mixing valve to allow the pre-conditioned tank temperature to be driven higher (e.g., 145°F) while maintaining a safe mixed outlet temperature (e.g., 120°F), thereby increasing effective capacity, or a combination of both a larger tank and increased storage temperature.

The specific research questions for the field tests included the following:

- What are the specific energy savings associated with GIHPWHs?
- Can GIHPWHs efficiently handle different water usage profiles?
- What are the annual cost savings and payback period for the GIHPWH?
- Can peak pricing be avoided?
- What can be learned about occupant hot water usage behavior?

Methodology

This technology was evaluated at nine single-family homes in the SCP service territory via a baseline monitoring and replacement monitoring in-situ field study. The baseline water heater at each site was monitored for a minimum of two months with the following data points being recorded every 30 seconds for storage tank-type water heaters and every 5 seconds for tankless water heaters:

- Incoming water flow rate via a pulse-output single-jet water meter

- Incoming cold water and outlet hot water temperatures via type-T thermocouples affixed to the pipe surface with heat-sink compound and covered with pipe insulation
- Gas energy consumption either by gas on/off status monitored with a thermocouple inserted into the flue or gas flow via a diaphragm-type gas meter
- Electrical energy consumption with a WattNode or MILUR 107 energy meter
- Data logger: Campbell Scientific CR310 and a Cell modem

The baseline monitoring was used to determine the average daily and annual energy use of the existing water heaters and to determine their average operating energy and load profiles. The profiles were to determine the required capacity of the replacement heater to accommodate a load shifting schedule and to estimate the annual utility cost of water heaters, including electrical peak pricing (in one case).

The post-retrofit monitoring included a similar measurement plan but was extended to one year data sets, which were compared to the baseline to determine energy and cost savings per replacement. Also, focus was placed on whether the electric heating element or only the heat pump was active to determine the effectiveness of dual-mode control, that shifts the load from the resistive element to the heat pump where possible., and the effectiveness of the control to divert electric consumption during the peak to cheaper time-of-use periods. The average simple payback time was calculated based on the calculated energy savings and the incremental cost difference between similar-sized conventional water heaters and the HPWHs. The installation costs were assumed to be similar between a HPWH and a conventional electric water heater. Although, labor costs incurred within this study were considerably greater because of the added complexity of the contractor navigating the demonstration project requirements.

The installed retrofit units were Rheem ProTerra and Ruud Ultra hybrid HPWHs equipped with the Rheem EcoNet WiFi interface. Seven of the nine sites received 80-gal units. Site 17 received a 65-gal unit, and site 25 received a 50-gal unit (to reduce the cost to the homeowners), as it was determined from the baseline data that these households had relatively low hot water demand.

Figure 2: Installed GIHPWH with Thermostatic Mixing Valve

Thermostatic mixing valves were required on all the GIHPWH retrofits, which allowed the storage tanks to be held at a higher temperature during the pre-conditioning load-up time. This facilitated a higher effective storage capacity before and during peak demand operation time. Rheem had integrated its onboard application programming interface for SCP's GridSavvy program, a WiFi-connected demand response load-shedding program for residential EV chargers, smart thermostats, and HPWHs, and had worked with Olivine, the GridSavvy DR implementor, which pushes the load shed signals during critical event days. Although it was originally planned to use SCP's GridSavvy program implementor, Olivine, to send daily load shifting signals to these heaters, this plan could not be accommodated, though fortunately Frontier engineers were able to collaborate with Rheem to access the API and program a script to send the daily control signal directly. (This precluded using GIHPWH model offerings from other manufacturers besides Rheem/Ruud.)

Results and Analysis

Table 10 shows the gross energy and cost savings at each site included in the study. Generally, baseline water heating accounted for a significant portion of the total energy use at each site, between 10 and 30% of a home's total energy use, with an average of 14.2%. This number fell to 9.6% in the replacement period. This analysis was performed without regard to the number of heating degree days but was normalized to the hot water consumption. This was generally done because of the relative, though not complete, independence of residential water heaters to weather conditions. Thermal efficiency and energy demand for water heaters depend on the average temperature of the incoming cold water supply, which varies slightly based on average weather, but is generally seasonally consistent within a few degrees in Northern California. Heat pump effectiveness is dependent on the temperature of the surrounding air since the surrounding air is the source of heat, but the dependence on outdoor weather conditions depends on where the heat pump's evaporator is installed. If the evaporator is installed in a conditioned space, the heat pump is much less dependent on weather conditions than if the evaporator is installed outdoors.

Table 10: GIHPWH Energy Savings Results

Participant	Baseline Water Heater (gas or electric)	Baseline Energy Usage (kWh/y or kBtu/y)	Replacement Energy Usage (kWh/y)	Gross Energy Savings (kBtuequiv./ y)	Cost Savings ($/y)
Site 17	Gas	23,100 kBtu/y	2,032	16,200	$157
Site 18	Gas	13,900 kBtu/y	1,399	9,100	$121
Site 19	Gas	19,000 kBtu/y	2,404	10,800	$103
Site 20	Gas	16,700 kBtu/y	1,449	12,800	$125
Site 21	Electric	460,700 kBtu/y	1,858	15,900	$625
Site 22	Gas	10,200 kBtu/y	3,060	-200	-$104
Site 23	Gas	8,600 kBtu/y	1,027	5,100	$67
Site 24	Gas	15,500 kBtu/y	2,929	5,500	$115
Site 25	Gas	148 kBtu/y	2,885	49	$96
Average		15,300 kBtuequiv./y	7,200 kBtuequiv./y	8,100 kBtuequiv./y	$123

The data analysis for both the baseline and replacement periods at each site used data from a year of monitoring. The results in Table 10 represent the documented energy usage from each period. It was confirmed by comparing summer and winter data from the same site during the same study phase that the overall energy usage as well as total hot water demand was not largely seasonally dependent, although there was significantly higher hot water demand (~15%) during the weekends.

The replacement saved an average of 8,100 kBtu equivalents per year, or about 53% of the baseline water heater energy usage. The highest cost saving was seen at the site with the electric baseline water heater, though a couple of sites had negative cost savings. Overall, the expected value of cost savings was calculated to be $123 per year assuming $0.015/kBtu and $0.22/kWh, but the cost savings given fuel switching from a gas water heater to the electric heat pump were only $61. The electric resistance to hybrid electric heat pump conversion saved the site $625/year. Cost savings were calculated through direct energy monitoring of the water heater rather than through utility bills, to better track the energy savings directly linked to the water heater.

Researchers found that following the replacement phase, the water heaters were in heat pump mode for an average of 77% of their total runtime. The most common event outside of normal operation (i.e. the electric heating element needed to run during some water heater activities such as purging) that triggered the need for the electric heating element's activation was when a clothes washer or a dishwasher was activated after a period that had seen other hot water events such as showers. The HPWHs were generally successful at not running during peak hours from 4PM to 9PM. In the year-long nine site retrofit study, there were only 34 recorded instances of the water heater running its electric resistance unit during peak periods. Researchers speculate based on incoming cold water flow rates that most of these periods were due to the activation of a laundry machine's fill cycle. The dishwasher was not found to be a significant driver of either hot water consumption or peak demand electric resistance cycling. This is because most dishwashers use less than 5 gallons per cycle, and dishwasher cycles are long enough where the heat pump unit can generally recharge the tank sufficiently. Overall, when taking demand surge pricing into account, the transition from a gas water heater to a hybrid electric heat pump water heater saved $58/year.

The retail cost of an 80-gallon hybrid heat pump water heater is about $2500. Given the average yearly project site savings of $123, the simple payback time for these units is 20 years. However, the incremental cost difference between the GIHPWH and a conventional gas or conventional electric water heater is roughly $1500 and would have a similar installation cost, which would yield a simple payback time of 12 years.

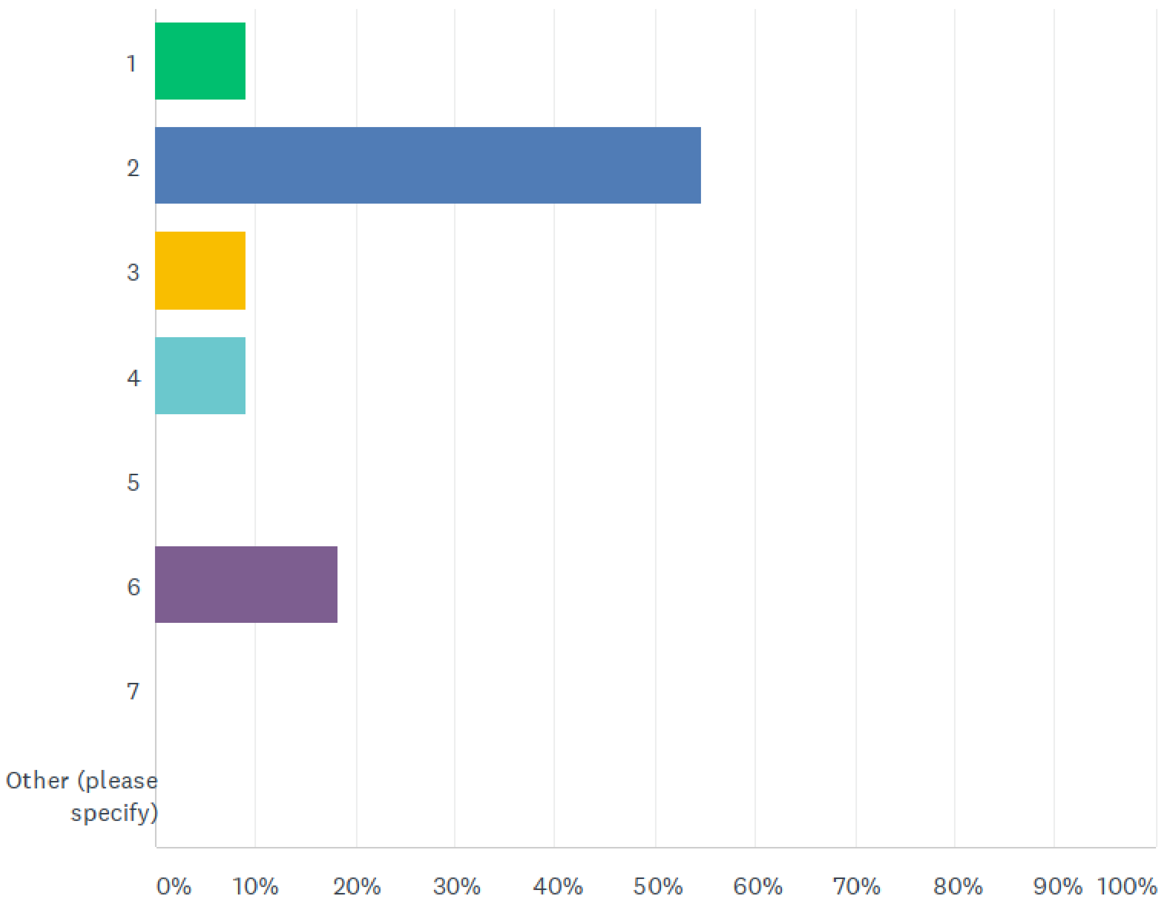
The results of the pre-monitoring survey showed some of the occupants' usage patterns. It also showed that most people don't really think about their water heaters much, with most questions about satisfaction being answered in the neutral (see Table 12). Most residents were generally pleased with the ease of use, noise level and maintenance requirements of their water heaters, which is unsurprising given their usual locations far away from actual living spaces. The largest number of negative responses came with the hot water delivery speed. This is something that replacing a water heater would generally not address and actually points to dissatisfaction with the hot water delivery piping between the water heater and the shower.

Table 11: Responses to GIHPWH Pre-Monitoring Survey Q1-6

	1 (VERY DISSATISFIED)	2	3 (NEUTRAL)	4	5 (VERY SATISFIED)	N/A	TOTAL	WEIGHTED AVERAGE
1. Hot water delivery temperature	0.00% 0	18.18% 2	27.27% 3	18.18% 2	36.36% 4	0.00% 0	11	3.73
2. Hot water delivery speed	9.09% 1	18.18% 2	54.55% 6	9.09% 1	9.09% 1	0.00% 0	11	2.91
3. Ability to keep up with household hot water needs	9.09% 1	9.09% 1	18.18% 2	27.27% 3	36.36% 4	0.00% 0	11	3.73
4. Ease of use	0.00% 0	9.09% 1	36.36% 4	18.18% 2	36.36% 4	0.00% 0	11	3.82
5. Noise level	0.00% 0	0.00% 0	27.27% 3	9.09% 1	54.55% 6	9.09% 1	11	4.30
6. Maintenance requirements	0.00% 0	9.09% 1	27.27% 3	9.09% 1	45.45% 5	9.09% 1	11	4.00

The most important data point the survey yielded was the number of people who lived in each household (see Figure 3) because it accurately predicted hot water demand in this study. Most of the survey respondents lived in 2-member households, and unsurprisingly, the homes with the largest hot water demands were the homes that had the largest number of occupants. By and large, the majority of respondents took their showers in the morning (90.9%) and in the evening during peak hours from 4 PM to 9 PM (54.6%). 50% of participants ran loads of dishes during peak demand hours, and 54.6% of participants ran loads of hot water laundry during peak demand hours.

Figure 3: Responses to GIHPWH Pre-Monitoring Survey "How many people live in your household?"



The homeowner satisfaction survey showed that 80% of the homeowners were very satisfied with their water heaters, giving a 4 or a 5 rating to each of the six satisfaction questions. The most common problem with the GIHPWH from a satisfaction standpoint was the amount of noise the heat pump made for indoor installations. There were two respondents who were dissatisfied with the noise, and one comment which showed that the customer would not have installed the GIHPWH if they had previously known the noise level. The satisfaction survey also showed that no people moved in or moved out between the baseline and replacement phases, and that the perceived time of use of hot water did not change.

Conclusions

The most important takeaway for homeowners with a heat pump water heater was to refrain from running the laundry machine on a hot water setting during peak demand pricing times, but the study showed that these water heaters were by and large successful. GIHPWHs are clearly a viable technology for the residential market because they show positive cost savings even when replacing gas water heaters, and the grid interaction component coupled with demand-pricing-informed occupant water usage behavior can successfully minimize the consequences of demand peak pricing. The sites which had the worst paybacks were the sites which ran the largest number of loads of laundry or dishes during peak periods, and also tended to be the sites with the highest number of occupants. This suggests that the storage tank size of 80 gallons might be insufficient for households with more than 5 members.

One pressing issue for this technology is the choice of location for installation. Generally, as a retrofit technology, the location of a water heater is difficult to change. However, placing a HPWH in a cold garage or in an unheated room is known to lessen its COP, so new construction contractors and designers need to be aware that placing HPWHs in conditioned spaces or in rooms known to get very hot will improve their performance. Alternately, evaporator inlet and/or outlet ducting can be installed to improve temperature conditions.

HPWHs share a barrier with all electric technologies poised to replace many gas appliances in that they can involve significant upgrades to a building's electrical system, including upgrading the utility service capacity and installing a new circuit breaker panel. During this project's participant screening process, only homes with adequate reserve electrical capacity were chosen. This may be an even greater concern for larger HPWHs or for commercial or multifamily residential buildings with more limited electrical service.

The most important benefit of HPWHs in general is that they are a viable replacement technology for gas water heaters and can be used in a cost-effective way that can offset the increased cost associated with using electricity instead of relatively cheaper gas. The grid interaction was shown to reduce the operating costs of HPWHs significantly, so modern water heaters boast significant savings. GIHPWhs can also be used as thermal storage for excess solar electric energy, which could reduce the necessary capacity and first costs of battery storage systems.

3.3: Induction Cooking

Introduction

Induction cooktops are an emerging technology in both the residential market and the commercial foodservice market. They are a replacement for gas and electric stovetops for residences and a replacement for gas and electric ranges for commercial sites. Induction cooktops work by generating a magnetic field by use of an induction coil. Any ferromagnetic piece of cookware placed on the cooktop will get hot nearly instantaneously as a result. Induction cooktops have much better thermal response times than electric resistance coil cooktops. Resistance coil cooktops take much longer than gas cooktops to reach their peak cooking temperatures and take much longer to cool down. This phenomenon is one of the main reasons that people prefer gas stoves to electric stoves in their homes. The induction stovetop has thermal response times similar to gas ranges and has the added benefit of being cooler to the touch than conventional rangetops unless engaged and in contact with the heating vessel. Induction stovetops have been very slow to adoption in both the residential and commercial markets because of perceived issues with all electric stovetops.

The purpose of this study was to document the energy savings associated with replacing existing gas or electric ranges in residential and commercial buildings with induction cooktops and to document the resulting energy savings. Another goal was to document user experiences with induction cooktops and introduce induction as a viable electric alternative to gas cooking.

Methodology

This project was designed to demonstrate and quantify energy savings for a transition from conventional ranges to induction ranges. An important aspect of this project was to survey both commercial and residential test sites at the end of the project. This survey was designed to answer the following:

- What kinds of training measures will need to be implemented for commercial customers?
- How did commercial menus or residential cooking habits change as a result of this project?
- What additional barriers to widespread market adoption exist? How can we overcome them?

Field testing constituted the bulk of this project. To accurately assess the field readiness of this technology, one commercial site and five residential sites were identified for a retrofit. The combined range/oven configuration was the prioritized configuration considered for this project to augment existing commercial field data. Residential sites needed to fulfill three main criteria: existence of an electric stovetop, at least two people living in the home year-round, and customers with eating habits that rely on cooking using their oven and stovetop. Sites ideally used their stovetops frequently and consistently throughout each week. For residential customers, this meant using their stovetop to prepare at least five meals per week. The submetering data could be used to make a rough estimate of the number of meals cooked, so the data could be normalized to a per meal basis if a customer's eating habits changed during the project. These criteria were determined through an initial phone/e-mail survey and site survey. Commercial sites just needed to have a single range/oven that the business owners were willing to change out for an induction cooker, and the chefs and line cooks needed to be excited about the project and ready to make a change. For commercial sites, the customer willingness to participate and handle a change of a major piece of equipment was paramount for the overall project success.

Figure 4: Replacement Residential Induction Range

For residential sites, the electricity consumption of the existing range was directly measured for at least three months to determine an energy baseline. An appropriate replacement range was chosen based on a combination of existing lab data and the willingness of each manufacturer to participate by donating equipment. When necessary, cookware was replaced with magnetic options designed for use on induction range tops. Energy savings was determined by continuing monitoring for at least three months after replacement. The customer’s utility bills were analyzed to determine how much of an impact the replacement had on the home’s overall energy consumption, including possible effects on HVAC, range hood, and microwave use.

For commercial sites, the same experiment was performed. Commercial sites were likely to need more support with the transition to using induction ranges. Menus and cooking procedures may have needed to be slightly modified to accommodate the new technology. Cooking times are typically shorter with induction ranges, and these ranges boast faster water boil times. This could lead to burnt food if handled incorrectly. Part of the training process included an analysis of the baseline menu and range cooking procedures and suggestions on how to modify these procedures, as well as a live training of the cook staff on how these procedures changed. The replacement phase could have been extended on a site-by-site basis if there was a period of growing pains after replacement.

Energy savings was calculated at the residential and commercial sites by directly comparing the energy consumption in the pre- and post-retrofit monitoring periods.

Results and Analysis

One commercial site was monitored for this project, a full-service restaurant (FSR) (Site 34) which originally had a gas 6-hob range connected to a convection oven. Table 12 details the energy consumption results from the FSR.

Table 12: Energy Usage Results from Induction Cooktop Retrofit at FSR Site

	Pilot Usage	Total Energy Use	Energy Cost ($/d)	Annualized Energy Cost ($/y)
Baseline	84 kBtu/day	460 kBtu/day	$6.90	$1,750
Replacement	0	29 kWh/day	$9.86	$2,465

The baseline unit had 7 standing pilot lights: one for the oven, and one for each hob. This resulted in an energy usage of 84 kBtu per day which would have been avoided by any more efficient range oven with electric ignition. The total energy use was only 460 kBtu per day, so this represented a very small portion of the site's overall energy usage (~1%). This is a general feature of commercial ranges in that range tops are usually only used for finishing foods (e.g., searing a steak after it has come out of the oven) or for warming soups. Most of the bulk cooking usually occurs in convection ovens, combination ovens, steamers, on a griddle/grill/char broiler, or in a fryer or pasta cooker. This site was large enough to have a standalone soup cooker and a tilt skillet, so the baseline unit was only used for finishing. Overall, this site ended up saving the equivalent of 360 kBtu per day. This was partially due to the elimination of pilot usage and partially due to the higher efficiency of the induction stovetop. Because of the higher cost of electricity however, the estimated annual energy cost gain was $700. This analysis assumes $0.015/kBtu and $0.34/kWh.

There was no installation fee (the site luckily had a plug available for the induction unit so there was no need to hire an electrician to create a standalone subpanel) so the total cost of replacement was limited to the retail and delivery fees, which totaled $5500. There is no simple payback on this installation because energy cost savings were negative. The return on investment for mid-life replacements are not favorable for this technology, but for replace-on-burnout and new construction situations, induction stovetops are a necessary part of an all-electric zero net carbon kitchen.

For the residential portion of this project, five single family homes with electric cooktops were retrofitted with an induction stovetop with similar monitoring times to the commercial study. Site 28 had a baseline recessed cooktop in an island counter which was replaced with an induction recessed cooktop, but all other sites had standalone cooktop/stove combinations which were replaced with equivalent induction units. Table 13 details the energy usage and cost data from this project.

Table 13: Residential Induction Energy Savings Data

	Baseline Energy Use (kWh/y)	Baseline Energy Cost ($/y)	Retrofit Energy Use (kWh/y)	Retrofit Energy Cost ($/y)
Site 28	1,377	$234	937	$160
Site 29	2,981	$507	2,369	$400
Site 30	2,313	$393	2,201	$374
Site 31	1,345	$229	1,494	$253
Site 32	2,014	$342	1,787	$303
Averages	2,006	$341	1,758	$298

Ultimately, the induction stovetops saved an average of $43 per year when replacing the electric stovetops in this study. The induction stovetops were used for an average of 18% less time per cooking event than the baseline electric resistance stovetops, which accounted for the electric savings.

The homeowner satisfaction surveys for this technology were only completed by 3 of the residential sites and the commercial site. Anecdotally, the sites that have completed their surveys report being satisfied with the performance of their induction cooktops. However, all sites completed the pre-installation survey, which showed that sites were neither satisfied or dissatisfied with their ranges.

The post installation survey showed that the respondents were satisfied with their ranges. The biggest complaints were oven capacity and the need for new cookware. It also showed that all three respondents spent significantly more time at home starting in March of 2020 due to COVID-19. The commercial site survey showed that the commercial customer was totally satisfied with their new range.

Conclusions

There were significant energy savings at the commercial site, but the commercial site was unable to overcome the higher cost of fuel after the fuel switching occurred, so they experienced a higher energy bill. Generally, stovetops in residences don’t see enough energy usage for the incremental efficiency gains from switching from gas to induction to be able to offset the increased cost of electricity, so this technology may not present homeowners with the ability to save money on their energy bills when fuel switching is necessary. However, when a site is switching from an electric stovetop to an induction stovetop, positive energy savings can be achieved. With that said, induction stovetops are a way for people to have a similar cooking experience to gas ranges through an electric technology that presents fewer health concerns related to fossil fuel combustion.

Induction stovetops are widely available for both the commercial and residential markets, and as California transitions to a more electric-heavy energy economy through decarbonization, they are a convenient replacement for gas ranges. They are sometimes as easy to install as gas ranges: the standalone units are easy to install as long as there is space on the existing breaker, and countertop-embedded units require running wire from a breaker as opposed to running gas pipe from the building's main. The most significant barrier to widespread adoption is public education. The narrative around electric stovetops is still dominated by peoples' negative experiences with resistance coils, and there is a significant need for programs like induction cooktop lending to help influence public perception. Most people still think gas ranges offer a superior cooking experience to any electric products and need to have the visceral experience of cooking with induction before California can expect to see significant market transformation.

3.4: Waste Heat Recovery

Introduction

Exhaust heat recovery dishmachines are appliances for the commercial foodservice industry which are used to wash cookware and dishware. They are much more efficient than conventional high-temperature-rinse dishmachines because they use a heat exchanger or a heat pump to recycle energy that is typically wasted through the production of steam in the washing process into the incoming cold water for the next rinse cycle. Dishmachines are typically fed by the building water heater and usually represent around 75% of a full-service restaurant's hot water load. One major benefit to using an exhaust heat recovery dishmachine is that these models can be fed with cold water, which means that they can be removed from the building's hot water system entirely. This can result in many design benefits to retrofit and new construction situations including reduced water heater sizes, pipe sizes, recirculation losses and better hot water delivery performance.

Undercounter and door-type exhaust heat recovery dishmachines have the added benefit of needing much less ventilation because they produce so much less steam. There are additional energy savings available for sites which decommission a dishroom's exhaust hood and fan as a result of replacing a conventional dishmachine with a heat recovery model. Heat recovery dishmachines are also associated with a much more thermally comfortable working environment in the dishroom, which can reduce the incidence of heat stroke and help retain employees for longer.

The goal of this study was to document the energy savings of undercounter and door-type exhaust heat recovery dishmachines in various commercial foodservice facility settings.

Methodology

This project was designed to demonstrate and quantify energy savings for a transition from conventional undercounter and door-type dishmachines to exhaust heat recovery models. This was accomplished by monitoring water and energy usage of two commercial dishmachines for at least one month each, then retrofitting with exhaust heat recovery models and continuing monitoring. Energy consumption was normalized to a per-rack-washed basis, and energy savings was reported consistent with the average number of dishes washed per day. The important data points monitored were:

- Hot water inlet temperature
- Cold water temperature
- Inlet flow rate
- Rinse temperature
- Electric energy consumption

Pre-retrofit energy use at the water heater was calculated consistent with the hot water used by the dishmachine. The energy demand on the water heater was calculated as the energy necessary to heat the volumetric water demand from the monitored cold water temperature to the water heater's nominal setpoint. The out-of-wall hot water delivery efficiency was assumed to be 70%.

Cost effectiveness was determined by comparing the operating utility savings to the total installed cost of an exhaust heat recovery dishmachine, and also by comparing savings to the incremental cost difference between an exhaust heat recovery dishmachine and an equivalent conventional dishmachine at the time of equipment replacement.

Results and Analysis

Table 14 details the results from the monitoring study. The two sites chosen were a brewery (Site 14) and a winery (Site 16), both of which were open five days per week for in-house service. Both of these sites had other significant energy consuming equipment onsite, so the baseline dishwashers represented a small fraction of their energy footprint. The brewery had a 20-barrel capacity set of brewing equipment, so the dishwasher was less than 1% of the load. This is not typical of all commercial foodservice facilities where the dishwasher can represent up to 10% of the total energy usage. The baseline dishwashers were also fed by electric resistance water heaters, which significantly increased the cost savings when switching to the more efficient heat recovery models. The winery had a 120 gallon tank-type water heater rated at 95% thermal efficiency and the brewery had a tankless water heater rated at 96% thermal efficiency. Generally, many commercial foodservice facilities will depend on natural-gas fed tank-type water heaters, so the savings from these sites was higher than they would be for more conventional CFS sites. Both sites had undercounter dishwashers and ran between 40 and 60 racks of dishes per day. The throughput and selection of undercounter dishwashers is common for these site types.

Figure 5: Existing Undercounter Dishmachines

The models chosen for the exhaust heat recovery dishmachine were cold-feed-only models, meaning they could be removed from the hot water system entirely. The water heater energy was entirely displaced to the dishwasher. For conventional dishwashers, hot water enters the machine around 140°F and is heated to the final rinse temperature of 180°F with a booster heater. The heat recovery machines heated water from the supply water temperature of 65°F to the final rinse temperature (180°F) directly. This led to the dishmachine at the brewery using more energy at the dishwasher's heating element but having significant savings at the building water heater. The retrofit dishmachine at the winery was a very efficient glasswasher with heat recovery and used the same amount of energy at the dishwasher as the baseline machine but saved additional energy at the water heater. Overall, the heat recovery machines saved a significant amount of energy at both sites. Utility bills were not used because the commercial sites were significantly impacted by COVID-19. There were extreme differences in throughput that skewed the total energy usage such that the energy savings needed to be calculated on a per-rack-washed basis to compare the pre and post-retrofit periods.

Table 14: Exhaust Heat Recovery Dishmachine Water and Energy Savings

Site	Racks /Day	Water Use (gal/d)	Water Heater Energy (kWh/day)	Dishwasher Energy (kWh/day)	Net Annual Energy Savings (kWh/y)	Cost Savings ($/y)
Brewery Baseline	47	73	15	38		
Brewery Replacement	47	52	0	45		
Brewery Savings		21	15	-7	2,080	$817
Winery Baseline	62	108	21	42		
Winery Replacement	62	74	0	41		
Winery Savings		34	21	1	5,720	$2117

Based on commercial electric rates of $0.34/kWh and water and sewer rates of $15 per hundred cubic feet (equivalent to 748.15 gallons: an HCF is a standard unit for water utility billing) the annual cost savings were $817 at the brewery and $2,117 at the winery. The incremental cost difference between an undercounter heat recovery dishmachine and a conventional undercounter dishmachine is about $4,000, so the average site in this study had an end-of-life replacement simple payback time about 2 years. The cost of an exhaust heat recovery undercounter dishmachine is $8,500, so a mid-life retrofit has a simple payback time about 3.5 years. These results are atypical of the average commercial foodservice facility because most CFS sites have gas water heaters which significantly lessen the cost savings associated with exhaust heat recovery. If the sites in this study had gas-fired water heaters and achieved similar energy savings, the cost savings would have been $250 at the brewery and $475 at the winery. In most cases, heat recovery dishmachines should be considered a fuel substitution technology.

Undercounter dishmachines are fairly easy to install compared to other commercial dishmachines, and there is no incremental cost difference for labor between installing a machine with or without exhaust heat recovery. One issue that researchers faced when selecting retrofit units was the height of the machines, which can be problematic when the dishmachine is literally placed under a counter. It is necessary for undercounter dishmachines to drain into a floor drain, so their location within an existing foodservice facility is not easily changeable. In addition, most existing facilities do not have the ability to change their counter heights, so some tall undercounter models are poor choices for some retrofits. Some heat recovery models also have larger depths, so this could present a problem where the dishmachine sticks out from under a counter into a bar area. This is not a concern at sites like the winery which run their undercounter dishmachines in the back-of-house and have no front-of-house dishwashing option.

The sites were surveyed, and the surveys help to describe the overall satisfaction with the baseline and replacement machines, rating overall happiness as 4's and 5's on a 1-5 scale. Generally, both sites were happy with the replacement, although the winery site observed that the heat recovery machine had a somewhat longer wash cycle time, and this took staff some getting used to. Because this site had such low throughput however, the increased time was tolerable. Both sites commented that the heat recovery machine improved the thermal comfort and smell of the space where they were installed. This was more important at the brewery, where the machine was located in the front of house, so a detergent/chlorine smell was thought to detract from drink sales at the bar. This site did not comment on the increased wash cycle length.

Conclusions

Exhaust heat recovery dishmachines have the potential to save significant amounts of energy in commercial foodservice facilities. For undercounter and door-type models, the barriers to wide-spread adoption in the CFS industry are the significant up-front cost of dishmachines, which generally keeps old conventional-efficiency machines working in facilities well past their intended working lifetimes, and the additional time per wash cycle. There are also physical equipment size constraints; both because of undercounter dishmachines requiring a maximum counter height they can fit under and because door-type machines need stainless steel loading and unloading tables which fit to their dimensions. Most dishmachines require increasing the wash cycle time from 60 to 90 seconds to accommodate the heat recovery unit. This time is crucial because it allows the machine to capture the heat that would otherwise be wasted by increasing the time when steam is in contact with the heat exchanger. The technology could also be perceived as presenting a significant change to the workflow of a working scullery. For sites like the two monitored in this study which are washing far fewer racks of dishes than the dishwasher could theoretically handle in a day, this typically is not much of an issue, but it can present some throughput problems for higher volume facilities or facilities which have rush periods. Retrofitting an existing facility with an exhaust heat recovery dishmachine can lead to staff unhappiness with having to accommodate a different workflow. While staff training was not a major goal of this study, staff training will be necessary for any retrofits to explain why the change is being made and how to best accommodate the new machine. This is typically less of an issue for new construction because the back-of-house workflow would have to accommodate the speed of the dishmachine from the beginning of the site's operation.

For a typical restaurant, the dishwasher can represent up to 75% of the total hot water load, which means that it's one of the main drivers of the hot water system design. There may not be real-world cost savings associated with installing a cold-feed only dishmachine at a site with a gas water heater because most of the energy savings from a cold-feed only dishmachine would be realized at the water heater. However, this retrofit scheme does present an opportunity to significantly downsize a hot water system in terms of pipe length and diameter as well as the size of the water heater. Upgrading to an exhaust heat recovery dishmachine is therefore paramount to upgrading a gas water heating system to an electric heat pump water heating system because it will reduce the hot water load on the water heater enough so that commercially available heat pumps can keep up with demand. This has the potential to create a cost-effective fully-electric kitchen because the commercial heat pump's typical COP around 3.25 can offset the increased cost of using electricity versus gas. This also has the potential to dramatically reduce the amount of energy used by the typical CFS facility's hot water system without reducing functionality. A full in-situ field retrofit study is badly needed to prove this concept and to determine the costs of making these kinds of changes.

It would be valuable to repeat the exhaust heat recovery study with larger dishmachines. At the time of writing, there are no commercially available cold-feed only rack conveyor or flight-type dishmachines. The larger heat recovery dishmachines currently on the market only use hot water for the tank fill used in the washing phase which usually totals less than 25% of the total water use; the water used in the rinse phase is from the cold-feed. The energy savings from heat recovery on these larger machines would be significantly higher than the savings from the smaller undercounter machines and because throughput is set by the conveyor speed, they will have less of a throughput issue. More research is needed to determine the expected ROI and energy savings from this type of retrofit.

3.5: Aerosol Envelope Sealing

Introduction

A process for sealing ducts using an injected aerosol was developed by Dr. Mark Modera in 1994 at Lawrence Berkeley National Laboratory and is now owned by Lead Locally partner Aeroseal[10]. The technology uses a vinyl compound suspended in a water solution to act as a vapor barrier inside duct systems to seal leaks as well as preventing moisture from entering. Once atomized, the sealant is pumped through HVAC ducts and deposited at the leakage points. It does this without coating the inside of the ducts. Responding to the need for an inexpensive, effective means of sealing building envelopes, the UC Davis Western Cooling Efficiency Center (WCEC) began experimenting in 2014 with a similar aerosol sealing process for building envelopes, now called AeroBarrier[11]. The AeroBarrier sealant is a water based acrylic compound designed not to be a vapor barrier, unlike Aeroseal, to prevent the trapping of moisture in-between walls or other interstitial spaces within a home.

Features

The AeroBarrier process involves briefly pressurizing a building while injecting an aerosol "fog" (as shown in Figure 6). As the air escapes through leaks in the exterior shell of the building, the aerosolized sealant is transported to the leaks, accumulates, and seals the leakage path as pressurized air exits the building shell. Existing blower door equipment is used to facilitate the

---

10 https://aeroseal.com/aeroseal-history/

11 http://aerobarrier.net/

sealing process as well as to provide real-time feedback and a permanent record of the sealing that is occurring. Because belongings and furnishings must be covered up or removed during sealant application, rental housing is the most appealing target market because application is more convenient and takes less time during tenant turnover when the unit is vacant and devoid of furnishings. With appropriate preparation work, however, it can also be done in occupied homes.

Figure 6: Aerosolized Sealant Released into the Interior of a Building

Photo credit: AeroBarrier

Following successful laboratory tests, the building envelope sealing technology was tested in multiple existing apartments in Queens, NY, where it reduced air leakage by at least 80% in less than two hours (Harrington & Modera, 2012). A subsequent test of six California production homes showed leakage reductions of 62% to 80% (1.8 to 5 ACH50) in less than 90 minutes (U.S. Department of Energy, 2016). In that study, WCEC estimated that a single-family home can be sealed for a materials cost of less than $500 (plus labor), much lower than the cost of traditional sealing methods that would achieve the same outcome.

Objectives

The objective of the Aerosol sealing 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. These questions are summarized below:

- What is the typical absolute and percent reduction in air infiltration for existing homes?
- Will the envelope sealing bring the house to tightness levels requiring mechanical ventilation according to Title 24 or ASHRAE 62.2?
- Can the sealant be readily removed after it is deposited in undesired locations?
- How much preparation and clean-up time is required?
- Does the sealant lose its effectiveness over time?

Methodology

Ten field test sites were selected to be used with AeroBarrier and Aeroseal (where the HVAC system is ducted). In the site selection process, the AeroBarrier site selection criteria were given more weight than Aeroseal criteria because Aeroseal has been in the retrofit market for many years and the performance has been well documented. AeroBarrier on the other hand is just being introduced to the market and was the main focus of this project. The primary AeroBarrier site selection criteria were whether the site was occupied and if the site had little to no carpeting. Unoccupied sites were given precedence because everything in the home needs to be removed (if possible), excluding large mechanical equipment such as washing machines, refrigerators, and dryers, prior to the sealing. Sealing an occupied home requires hiring a mover to transfer all belongings to an offsite location and putting the occupants up in a hotel for one to two nights, which is costly and inconvenient. This could also lead to occupants' possessions being misplaced or damaged in the relocation process, which could lead to further complications. Sites with little to no carpet were of high value because of the unknown possibility of the AeroBarrier sealant finding a pathway beneath the plastic floor covering and damaging the carpet. While assessing this technology in residential homes, sites with hardwood, tile, or linoleum flooring were targeted so any leaks could be cleaned up easily. All the criteria used to select sites for this technology are presented in Table 15.

Table 15. Technology Demonstration Site Selection Criteria for Aerosol Sealing in Residential Buildings

Criterion	Criterion Value	Criterion Weight (1-10)
Owned by current occupants?	Yes	1
Occupied?	No	Essential
Rental Property?	Yes	10
Employees of Energy Industry?	No	2
Occupants will remain for 2 years?	Yes	5
Will the site be unoccupied and/or empty within the next year?	Yes	10
Building Owner Enthusiastic?	Yes	8
Building Type	Single-family, Multifamily	1
Major Renovations in next 2 years?	Yes	10
Does the site have carpet?	No	10
What percent carpet is the house?	<20%	10
What type of flooring if not carpet?	Hardwood, tile, etc.	8
Does the homeowner plan or want to replace carpet within the next year?	Yes	10
Sq. feet of retrofit space	<2,500	5
Practical Installation Challenges?	No	10
Located Near Other Sites?	Yes	4

Features Similar to Other Sites?	Yes	2
Does the site allow easy access for movers?	Yes	8
Central Cooling?	Yes	3
Central Heating?	Yes	7
Electric heating?	Yes	4
HVAC Duct Location	Attic or crawlspace	3
Operational year long?	Yes	8
Does the Site Have Constant Mechanical Ventilation?	Yes	10
Does the Site Have Gas Appliances	No	10

Pre- and Post-Installation Monitoring Approach

Prioritizing homes that were unoccupied during the AeroBarrier sealing led to the selection of sites that were undergoing a tenant changeover or a renovation. This made any utility bill or long-term monitoring approach unfruitful. Therefore, the only measured data used to determine the effectiveness of the aerosol sealants were the initial and final envelope and duct leakages. These results provide the percent reduction in air infiltration that was used in models of each of the sites using BEopt simulation tool to determine energy savings. In addition to measuring the building leakage before and after the AeroBarrier and Aeroseal upgrades, the leakage rate was measured approximately a year after the retrofit to determine if the effectiveness of the sealant degraded over time.

Non-Measure Improvements Made in Addition to Aerosol Sealing

In addition to the AeroBarrier and Aeroseal upgrades, two of the sites received new water heaters and six others underwent a total renovation at the time of the sealing. Site 1 had a notable concern with a laundry room add-on that had a gas water heater with no combustion air ventilation. If the leaky laundry room was tightened, these harmful gases would build-up in the home and could cause health and safety hazards. This site was highly desired however, since it had no carpet and was soon to be unoccupied, making it an ideal test site. It was decided to proceed with the site and to offer to fund a heat pump water heater upgrade to eliminate any combustion gases or to fully fund a contractor to install combustion air ventilation. The homeowner opted for the HPWH upgrade where a Rheem PROPH50 T2 RH350 DCB 50-gallon HPWH was installed.

At another site, the AeroBarrier damaged the combustion water heater during the sealing process. The flue was taped off, but the AeroBarrier sealant still found a way into the combustion chamber and clogged the water heater. This was an oversight where the contractor did not realize the combustion chamber would have a pressure differential that would attract the aerosol sealant, which was a lesson learned when using AeroBarrier in retrofit applications. To remedy the situation, the AeroBarrier contractor helped fund the replacement of a new water heater for the site.

Six of the sites were apartments at an ADA facility that was undergoing a renovation during the AeroBarrier install. This remodel included: a new HVAC system, continuous bathroom ventilation, an upgraded water heater, new kitchen hood and appliances, new flooring, upgraded light fixtures, etc. These apartments were the only sites that had the same occupants pre- and post- AeroBarrier. However, because of all the renovations, active monitoring and utility bills still would not provide much insight into the cost and energy savings for the aerosol sealing itself.

Methods of Calculating Energy Savings

To calculate energy savings, BEopt was used to model homes in Santa Rosa to determine the estimated energy use and utility bill costs based on Sonoma Clean Power's time of use electricity rate schedule and PG&E's tiered gas rate schedule. Floor area, pre- and post-retrofit building leakage, pre- and post-retrofit duct leakage (when applicable), HVAC system type, and number of bedrooms and bathrooms were used as inputs. A cooling setpoint of 76°F and a heating setpoint of 71°F were used for the models.

The exact buildings for the ten sites were not modeled nor calibrated, a similar vintage home was used to generate a generic model for each site to estimate these savings. Three prototype models were used to generate a model of each site. These protypes are described below in Table 16.

Table 16. Santa Rosa Model Prototypes

Building Component Efficiency Feature: Envelope	Pre-1978	1978-1991	1992-2010
Exterior Walls	2x4 16"oc wood frame, R-5	2x4 16"oc wood frame, R-11	2x4 16"oc wood frame, R-13
Foundation Type & Insulation	Uninsulated slab	Uninsulated slab	Uninsulated slab
Ceiling Insulation & Attic Type	Vented attic, R-11 @ ceiling level	Vented attic, R-19 @ ceiling level	Vented attic, R-30 @ ceiling level
Roofing Material & Color	Asphalt shingles, default values (0.10 reflectance, 0.85 emittance)	Asphalt shingles, dark	Asphalt shingles, dark
Radiant Barrier	No	No	No
Window Type: U-factor / SHGC	Metal, single pane: 1.16 / 0.76	Metal, dual pane: 0.79 / 0.70	Vinyl, dual pane Low-E: 0.55 / 0.40

Methods Used to Determine Costs & Cost Effectiveness

To determine cost effectiveness, the total cost to seal the site with AeroBarrier and Aeroseal (when applicable) were divided by the cost savings determined from BEopt to determine the simple payback period, which is the time it will take for the upgrades to pay for themselves. Sites with a payback period longer than 30 years will be considered not cost-effective.

Results and Analysis

Site Characteristics

Out of the ten sites chosen, AeroBarrier was used on all ten test sites and Aeroseal was used on three. Many of the sites did not have duct systems or had ducts in such poor condition that Aeroseal was not applicable. Four of the sites were single-family homes, the six remaining were ADA multi-family apartment units. The site characteristics are listed in Table 17.

Table 17. Aerosol Sealant Demonstration Sites

	Building Type	Floor Area	Bedrooms	Bathrooms	Stories
Site 1	Single-Family	1,648 ft^2	3	2	1
Site 2	Single-Family	1,198 ft^2	2	1	1
Site 3	Single-Family	1,162 ft^2	3	2	1
Site 4	Single-Family	1,346 ft^2	4	3	2
Site 5	Multi-Family	720 ft^2	2	1	1
Site 6	Multi-Family	630 ft^2	1	1	1
Site 7	Multi-Family	630 ft^2	1	1	1
Site 8	Multi-Family	630 ft^2	2	1	1
Site 9	Multi-Family	630 ft^2	1	1	1
Site 10	Multi-Family	590 ft^2	1	1	1

The AeroBarrier was highly effective when tightening the envelope. On average for all ten sites, 83.3% of the envelope leakage was sealed. However, this improvement only reflects the reduction in air leakage to the area exposed to the AeroBarrier sealant. This does not include areas such as flooring, windows, vents, exhaust ports, etc. that were taped off to protect the home from the sealing process. The results for these improvements are provided in Table 18. The values listed are characterized in air changes per hour at 50 pascals (ACH50), which indicates how many times an hour the air in the home is completely recycled while pressurizing or depressurizing the space to 50 Pa. ACH50 is the common metric when looking at home infiltration.

Table 18. AeroBarrier Improvements to the Envelope

	Baseline Envelope Leakage (ACH50)	Envelope Leakage after Sealing (ACH50)	Percent Sealed
Site 1	13.33	0.63	95.2%
Site 2	14.62	0.51	96.5%
Site 3	19.45	1.23	93.7%
Site 4	8.65	3.40	60.7%
Site 5	8.82	1.35	84.7%
Site 6	7.64	1.59	79.2%
Site 7	9.66	1.43	85.2%
Site 8	8.44	1.88	77.7%

Site 9	6.77	1.25	81.5%
Site 10	6.47	1.37	78.8%

The whole building leakage was measured prior to any protective plastic and tape being installed on the flooring, windows, registers, and other openings, excluding exhaust ports to the exterior, and after it was removed to further assess the improvements seen from AeroBarrier. With these surfaces and openings exposed, the reduction in envelope leakage on average was found to be 57%. The savings were much less prominent due to a variety of factors, such as hardwood flooring exposed to a crawlspace or leaky window frames that could not be sealed using AeroBarrier. The net improvements to the homes are presented in Table 19.

Table 19. AeroBarrier Improvements to the Homes

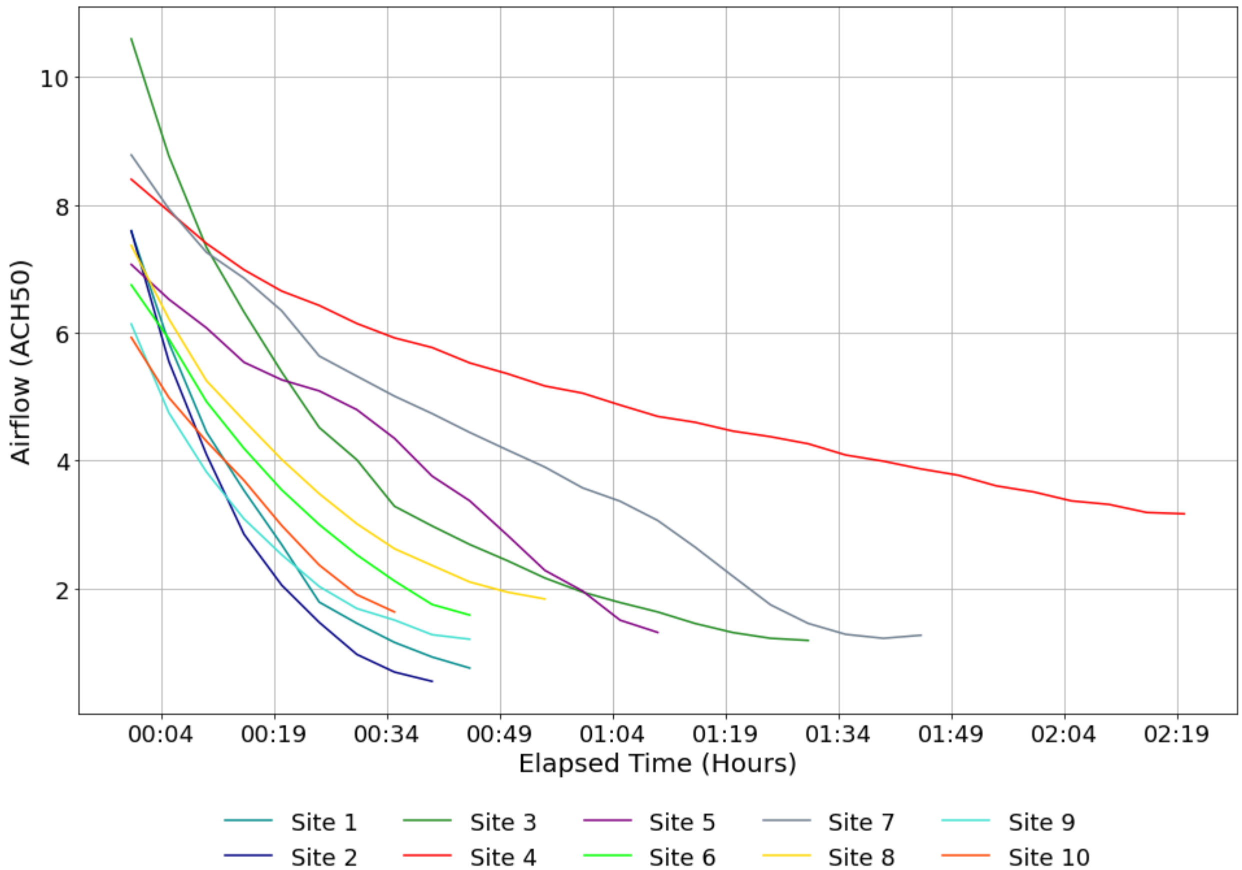
	Baseline Total Leakage (ACH50)	Total Leakage after Sealing (ACH50)	Percent Envelope Sealed
Site 1	15.38	5.09	66.9%
Site 2	12.62	4.89	61.2%
Site 3	15.24	8.05	47.4%
Site 4	9.30	7.44	20.4%
Site 5	8.82	2.53	71.3%
Site 6	7.65	2.56	66.5%
Site 7	9.66	2.92	69.8%
Site 8	10.53	4.06	61.4%
Site 9	9.44	4.60	51.3%
Site 10	6.35	2.93	53.9%

Site 4 saw the smallest improvement to the building's leakage; this can likely be associated with a leaky fireplace flue and the fact that the home was undergoing renovations that included several sources of leaks, such as a hole in the shower tile that opened to the interstitial space between the house and outer walls. This site also required ducts to be replaced due to holes caused by rodents that were too severe for Aeroseal to address.

AeroBarrier Runtime

Another important consideration of the AeroBarrier technology is how long the prep-work, sealing time, and clean-up takes. On average, it took roughly 6-8 hours to prepare each site, which includes removing left over items, such as window shades, light bulbs, outlet covers, etc., then covering flooring, door frames, windows, and other surfaces with plastic and/or tape. The average time to seal the ten sites was 59 minutes. Once the sealing was finished, the contractor reported the site clean-up roughly lasted an hour (depending on the mess left over). This entailed throwing away all tape and plastic, then cleaning any splotches left over from the sealant using a cleaning solution and a rag. The total average time it took to use AeroBarrier on a home was 9.2 hours, ranging between 8.4 hours and 10.7 hours. The sealing curves for all ten sites are presented in Figure 7.

Figure 7. AeroBarrier Sealing Curves



Aeroseal

The results from the Aeroseal improvements for the three applicable sites is presented in Table 20, where the technology was able to seal 70% of the duct leakage. The results are presented in CFM25 (cubic feet per minute at 25 Pa). CFM25 is the standard measurement when discussing duct leakage and represents the airflow leaking from a duct network at a pressure of 25 Pa.

Table 20. Aeroseal Improvements

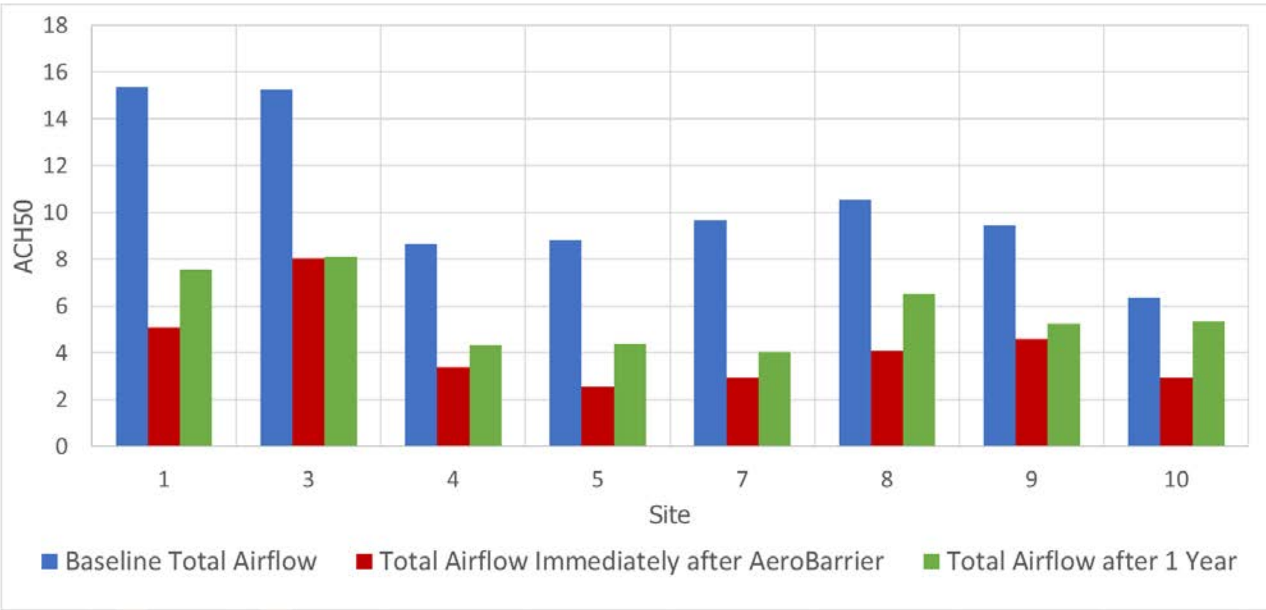
	Baseline Duct Leakage (CFM25)	Duct Leakage after Sealing (CFM25)	Percent Improvement
Site 2	23.9	19.1	20%
Site 5	39.4	9.3	76%
Site 10	38.8	2.7	93%

Site 2 showed the least improvement of the three, this is due to how tight the duct network was prior to the Aeroseal process. The ducts at this site were too damaged as is to effectively use Aeroseal, so the contractor had to manually seal holes larger than 5/8" in diameter prior to air sealing to allow the sealant to effectively seal smaller holes.

AeroBarrier Degradation

According to lab testing performed by a third-party lab on behalf of Aeroseal, the AeroBarrier sealant is expected to last at least 50 years (Aeroseal, LLC, n.d.). However, it is unknown if the sealant degrades during this period of time or if the tests performed in that study translate to real life conditions. To assess if the sealant degrades over time, eight of the ten sites were visited 11–19 months after the initial sealing to perform an additional post-retrofit blower door test. The results from the initial testing compared to the results after roughly a year are presented in Figure 8. Sites 2 and 6 were not included in this comparison because site visits could not be scheduled with the occupants.

Figure 8. AeroBarrier Degradation



With an additional datapoint taken roughly a year after the AeroBarrier sealing process, the change in ACH50 over time relative to the baseline leakage was used to determine how much the sealant degraded during this time period. The data are presented in Table 21.

Table 21. AeroBarrier Degradation Results

	Initial Percent Reduction in Leakage (a)	Final Percent Reduction in Leakage after 1 Year (b)	Percent Degradation in AeroBarrier Sealing [(a-b)/a]
Site 1	67%	51%	24%
Site 3	47%	47%	1%
Site 4	61%	50%	18%
Site 5	71%	50%	30%

Site 7	70%	58%	16%
Site 8	61%	38%	38%
Site 9	51%	45%	13%
Site 10	54%	16%	71%

After calculating the total average leakage based on the eight applicable sites, the total degradation on average seen over a range of 11-19 months was 27%. However, since only two post-retrofit measurements were taken during this period, it cannot be said if this degradation happened slowly over time or abruptly within the first month or two after the sealing. To better understand how the AeroBarrier material degrades over time, multiple data points should be taken over the course of at least a year to determine the long-term life of this product. Nonetheless, after seeing that 27% of the savings are lost over several months, it is concerning that this degradation may continue in the coming years causing the calculation of payback period for this technology to be less than fully reliable.

Results of Homeowner Satisfaction Survey

An initial post-retrofit survey was sent to Sites 1-4, and an additional survey was sent approximately a year after the retrofit to all ten sites. An initial survey was not sent to Sites 5-10 because these sites just underwent a total renovation and any initial improvements to the sites could not be attributed to the aerosol sealing. The surveys aimed to target occupant comfort over time to determine if any noticeable difference could be seen to evaluate degradation. Since all ten test sites either had an occupant changeover or a complete renovation, no baseline comparison could be made to quantify comfort due to the AeroBarrier upgrade specifically. In addition, due to the occupant changeover, the initial survey and the survey sent a year later often had different occupants who responded.

From all the occupants that responded for each site, the ratings for comfort from both surveys remained consistent, even with multiple survey takers for several of the sites. The only site that identified poor comfort was Site 1. No additional feedback was included in the new tenant’s survey, but this can likely be attributed to the hardwood flooring that was very leaky and could not be sealed. The site also did not have a ducted HVAC system. There was a ductless mini split system mounted in the main room which may also have affected how well the heating and cooling supply air was distributed throughout the house.

While no determination could be made about occupant perceptions of sealant degradation, a lot of the occupants noticed that there were sealant particles around the house once they moved in. They found residue on door latches, around electrical outlets, on the linoleum flooring in the kitchen and bathrooms, and in strike holes in door jambs that needed to be scraped out before the door could shut properly. One of the sites mentioned that after 4-months of living at the site, they were still occasionally finding new spots with AeroBarrier residue to clean. While only one homeowner provided a detailed description of sealant residue problems, the owners of the other single-family homes responded with ratings from medium to very high when asked if there was an abundance of sealant particulates left over after the sealing. The apartment occupants did not find any residue, but that is to be expected due to the AeroBarrier being installed during a renovation. The apartments likely had a thorough cleaning prior to the occupants moving back in.

Nonetheless, this issue is a concern for the AeroBarrier upgrade. Even though the sealant can be cleaned with a rag and cleaning spray, cleaning should not be left up to the occupants. Although it was reported that roughly an hour of cleaning went into these sites, it is recommended that contractors spend even more time to find a majority of the sealant left over so if the occupants find any residue, it would not be time consuming to clean.

Utility Bill Data

For completeness, the utility bill data was collected and analyzed even though changes in occupancy would make this analysis of limited value. The utility bill data for a majority of the ten sites were received for January 1st, 2018 – February 28th, 2022. The electrical data for Site 1 was not available until late 2021 (during the post-retrofit period) due to no prior occupants having SCP's utility service.

To determine the savings, degreedays.net was used to normalize the pre- and post-retrofit data. The curve fit equations determined from the normalized post-retrofit data using a balance point temperature of 65°F for both the heating and cooling degree days was chosen to standardize the electrical and gas energy with the heating and cooling degree days seen during the baseline period. The time period chosen for the baseline period was January 1st, 2019 – December 31st, 2019 for all sites, except for Site 2. Site 2 saw sparse energy use during 2019 – mid 2020, likely due to the site being unoccupied, thus the 2018 year was used for the baseline data instead. The annual normalized electricity and gas energy savings are presented in Table 22 and Table 23 respectively. The average electrical energy savings found was -19.2% and the savings seen in gas energy was 47.6%. In combination, the energy savings from both electricity and gas was 32.9% or 113 MMBtu. However, this cannot be attributed directly to the AeroBarrier and Aeroseal upgrades. Sites 1-4 all saw tenant changeovers after the AeroBarrier install date, and it is uncertain how many tenants lived at each of these sites as far back as 2018. When comparing the 2018/2019 baseline energy data to the post-retrofit data, any savings or increased energy use could largely be due to occupant behavior. In addition, Sites 5-10 upgraded their pre-existing gas equipment to mini splits or PTAC units and HPWHs, decreasing the gas energy use substantially and increasing the electricity use, which can be seen in the tables below. The gas data for the apartment buildings were all on one master meter as well, so the individual apartments could not be separated. Thus, for these sites, the energy was divided by the number of apartment units in each building for an approximation.

Table 22. Aerosol Sealing Utility Bill Savings - Electricity

	Pre-Retrofit Weather Normalized Electrical Energy (kWh)	Post-Retrofit Weather Normalized Electrical Energy (kWh)	Weather Normalized Electrical Energy Savings (%)
Site 1	0	0	0

Site 2	5,014	3,636	27.5%
Site 3	3,586	4,952	-38.1%
Site 4	278	284	-2.3%
Site 5	2,697	2,074	23.1%
Site 6	1,619	1,258	22.3%
Site 7	3,336	4,333	-29.9%
Site 8	1,642	2,745	-67.1%
Site 9	2,177	4,654	-113.8%
Site 10	1,831	2,510	-37.1%

Table 23. Aerosol Sealing Utility Bill Savings - Gas

	Pre-Retrofit Weather Normalized Gas Energy (kBtu)	Post-Retrofit Weather Normalized Gas Energy (kBtu)	Weather Normalized Gas Energy Savings (%)
Site 1	18,890	6,911	63.4%
Site 2	18,328	3,8617	-110.7%
Site 3	38,998	20,666	47.0%
Site 4	0	0	0%
Site 5	33,234	15,183	54.3%
Site 6	33,234	14,874	55.2%
Site 7	33,234	14,874	55.2%
Site 8	30,654	9,754	68.2%
Site 9	30,654	9,754	68.2%
Site 10	30,654	9,685	68.4%

The Coefficient of Variation of the Root Mean Squared Error (CVRMSE) calculated from utility data during the baseline period are presented in Table 24. ASHRAE Standard 14 determines that CVRMSE values less than 20% are considered adequate. Due to standardizing the post-retrofit utility data to the baseline timeframe, only the baseline CVRMSE data was closely examined when determining which sites had acceptable variations between both time periods.

The CVRMSE values calculated using the electrical billing data were unacceptable for all sites, except for Site 4. The CVRMSE results calculated from the gas utility bills were unacceptable for only Sites 1-4. Although, as mentioned above, all sites were expected to have high levels of uncertainty when comparing the billing periods due to selecting sites that were unoccupied prior to installing the AeroBarrier and/or selecting sites that were undergoing a building renovation. Even though Site 4 saw acceptable variation within the electrical data and Sites 5-10 had acceptable CVRMSE values for the gas utility bill data, there is still a lot of noise not represented in this comparison due to the tenant changeover and/or the other building upgrades in addition to the AeroBarrier and Aeroseal. These results confirm that the utility bill data could not be used when calculating the effectiveness of the aerosol sealants, therefore modeling is needed to further analyze the improvements of these technologies.

Table 24. Aerosol Sealing Utility Bill CVRMSE Data

	Baseline Electric Data	Baseline Gas Data
Site 1	-	102.79%
Site 2	29.46%	107.03%
Site 3	40.81%	47.42%
Site 4	5.87%	-
Site 5	41.99%	16.50%
Site 6	38.69%	16.50%
Site 7	23.89%	16.50%
Site 8	21.60%	15.14%
Site 9	53.98%	15.14%
Site 10	24.09%	15.14%

Modeling Data

From the modeling results provided by BEopt, monthly energy use was estimated for each of the sites using the baseline leakage and using the improved envelope and duct leakages measured immediately after the retrofit. The electrical and gas savings for each site are reported in Table 25. The gas savings for Sites 1 and Sites 5-10 were all very minimal due to these sites relying on electrical mini splits and/or fan coils for heating and cooling. The average gas and electricity savings found for the ten test sites were 2,210 kBtu/year and 168.2 kWh/year respectively. For the sites that had natural gas furnaces, the average savings were 7,250 kBtu/year. The total average energy savings when including both gas and electricity was 27.9 MMBtu/year or 6.0% of whole-house energy use per year.

Table 25. Aerosol Sealing Modeled Energy Savings

	Electrical Energy Savings (kWh)	Gas Energy Savings (kBtu)	Total Savings (kBtu)	Percent Total kBtu Savings
Site 1	931.4	47	3,224.8	6.5%
Site 2	59.8	10814	11,018.0	11.7%
Site 3	49.1	8814	8,981.5	14.9%
Site 4	7.2	2110	2,134.6	2.9%
Site 5	-0.002	0	0.0	0.0%
Site 6	97.3	66	397.8	1.4%
Site 7	219.7	53	802.7	2.6%
Site 8	209.9	61	777.4	2.3%

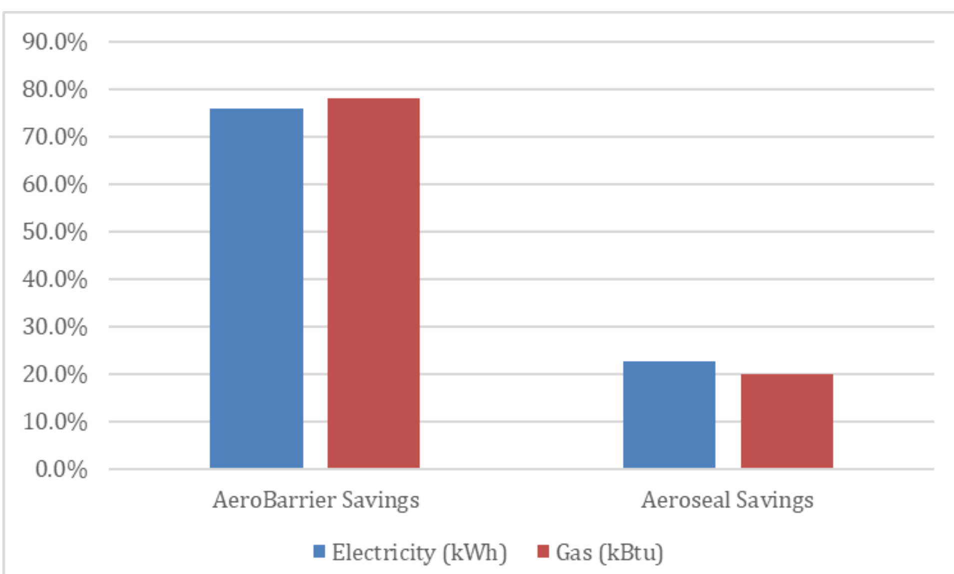
Site 9	100.7	55	398.2	1.3%
Site 10	7.1	125	149.1	0.5%

Sites 5 and 10 saw very little to no savings in comparison with the other sites. This is attributed to the location of these apartment units within the building. Sites 5 and 10 were located on the second floor of a three-story building, while all the other apartment units modeled were located on the third floor. The modeling results show that these corner unit apartments that only have two exterior walls, tend to heat up far quicker than the other apartments due to the lack of infiltration. This indicates the energy savings from using AeroBarrier on these middle floor apartment units may be canceled out from solar and internal gains on the units that become trapped once the unit's infiltration, which was previously providing "free cooling" during windy days or conditioned air from neighboring apartments, was removed. However, it could be expected that these occupants would be opening windows to cool their apartment units down rather than utilizing their HVAC unit to maintain their desired set point.

To confirm the two apartment units are likely to have miniscule energy savings due to apartment unit location, the two apartment units were also modeled on the top floor of the building as well to compare the savings. Site 5's electrical energy savings went from -0.002 kWh per year to 159.5 kWh per year, and Site 10's electrical energy savings went from 7.1 kWh per year to 194.8 kWh per year which would be much more consistent with the other sites.

In addition to comparing the total energy savings, Aeroseal and AeroBarrier were analyzed separately for Site 2 to determine which technology offered more energy savings. Figure 9 presents the energy savings for Site 2 separately where 76.9% of the total savings resulted from AeroBarrier.

Figure 9. Site 2 AeroBarrier and Aeroseal Energy Savings



Cost-Effectiveness

The energy data from the modeling was used with time of use rates from SCP (electricity) and PG&E's (gas) tiered rate schedule to determine the estimated utility costs for the baseline and post-retrofit periods without the other renovations and changes in occupancy reflected in actual utility bills. Retrofit costs were based on the actual costs charged by the AeroBarrier and Aeroseal contractors for the project, which is believed to be consistent with what a homeowner or landlord would be charged for similar work. The total savings from this analysis are presented in Table 26.

Table 26. Aerosol Sealing Cost-Effectiveness

	Electricity Savings per Year	Gas Savings per Year	Total Savings per Year	Total Retrofit Cost	Payback Period (Years)
Site 1	$294.87	$0.48	$295.35	$3,892.00	13.2
Site 2	$18.97	$227.24	$246.22	$6,968.94	28.3
Site 3	$15.48	$172.91	$188.38	$4,209.00	22.3
Site 4	$2.19	$41.59	$43.78	$4,933.00	112.7
Site 5	$0.00	$0.00	$0.00	$4,457.33	N/A
Site 6	$29.46	$1.05	$30.50	$1,207.33	39.6
Site 7	$67.42	$0.82	$68.25	$1,207.33	17.7
Site 8	$64.33	$0.96	$65.29	$1,166.67	17.9
Site 9	$30.45	$0.86	$31.31	$1,166.67	37.3
Site 10	$1.42	$2.02	$3.45	$4,416.67	1281.5

On average, AeroBarrier and Aeroseal (when applicable) offered $121 a year in gas and electric energy savings leading to an average payback period of 25.5 years for the eight test sites with meaningful energy savings. Sites 5 and 10 were excluded from this average due to seeing negligible savings. The savings for Sites 5 and 10 were also calculated in the hypothetical scenario where these units were located on the third floor of the building. From this exercise, Site 5 saw a total savings of $58.85/year and Site 10 saw a total savings of $69.29/year providing much more reasonable savings.

In addition to Sites 5 and 10, Site 4 also saw slight savings that led to an unacceptable payback period of 112.7 years. The site did see savings as large as $43.78 per year, however, these savings are nowhere near the rate to pay off the cost to install AeroBarrier within 30 years. This poor payback is due to only tightening the home 20% in combination with the higher cost to install AeroBarrier at this two-story site, which required more prep-work, a longer sealing and clean-up time, and more materials. Thus, for the seven best sites, the savings from AeroBarrier and Aeroseal (when applicable) are projected to be $132 a year leading to a payback period of 21.4 years.

In addition to the total cost-effectiveness of the technologies, the utility rates using the improvements from AeroBarrier and Aeroseal were analyzed separately to determine the cost-effectiveness of each technology for Site 2. This comparison is presented in Table 27.

Table 27. AeroBarrier and Aeroseal Cost-Effectiveness for Site 2

	Electric Savings per Year	Gas Savings per Year	Total Retrofit Cost	Total Savings per Year	Payback Period (Years)
AeroBarrier	$14.44	$176.71	$3,766.00	$191.15	19.7
Aeroseal	$4.27	$45.84	$3,202.94	$50.10	63.9

Site 2 saw the largest savings in heating and minimal savings for cooling. This is rather reasonable for the Sonoma climate due to how temperate the summers are. When separating out both technologies, AeroBarrier saved an additional $141.05 compared to Aeroseal. This leads to an acceptable payback period of 19.7 years for AeroBarrier and a longer payback period of 63.9 years for Aeroseal. However, the ducts that were sealed using Aeroseal were relatively tight. If Aeroseal was used on leakier duct systems than those tested, it is likely that the Aeroseal measure would see greater savings leading to a more acceptable payback period.

Conclusions

AeroBarrier was installed in ten sites and Aeroseal was installed in three of the ten. The AeroBarrier sealant was highly effective in reducing infiltration, on average sealing the envelope by 83.3% and reducing the whole home infiltration by 57%. All sites saw envelope infiltration improvements between 60.7% - 96.5%. However, this vast improvement from the AeroBarrier did not translate to reduced whole building leakage that would provide ample energy savings for every site to be cost-effective. The factors seen that could cause a site to not to be cost-effective could depend on the magnitude of leaks in parts of the home that aren't addressed by AeroBarrier, such as leaky window frames, leaky floors, or a leaky duct system. For these cases, it would be recommended to perform additional sealing around the site that AeroBarrier can't seal or to use Aeroseal and/or replace leaky ducts. In another example, it appeared the middle floor apartment units saw hardly any savings from the aerosol sealing in the Sonoma County climate. The modeling for these sites implied that the infiltration provided free cooling for the apartments, which caused the energy use to increase or remain constant as the unit was tightened. For these scenarios, opening windows or balanced mechanical ventilation would be recommended to bring in fresh air to allow internal loads to escape that were previously exfiltrating through leaks prior to any sealing. This added ventilation can potentially mitigate the increase in energy use seen from the models to maintain indoor temperature setpoint from these trapped internal loads. In addition to AeroBarrier, Aeroseal also proved to be very effective when sealing duct systems. Improvements in duct leakage ranging from 20% for the site that received manual duct repair prior to the Aeroseal, and 76% - 93% were seen among the two apartment units, leading to an average improvement of 70%.

Cost-Effectiveness

The average cost to install AeroBarrier for the ten sites was $2,392.20 and the average cost of Aeroseal for the three applicable sites was $3,234.31, which came out slightly above the cost of AeroBarrier. For 8 of the 10 sites, the technologies showed to offer a payback of 25.5 years, which is considered cost-effective relative to the 30-year criterion. When comparing Aeroseal to AeroBarrier for one of the single-family homes, AeroBarrier offered 76.9% of the total energy savings, leading to a payback period of 19.7 years for AeroBarrier and 63.9 years for Aeroseal.

Lessons Learned

AeroBarrier has a high potential to be very beneficial to homeowners, however, the technology showed some undesirable results. Many of the sites responded that they found aerosol particles around their home, such as in their door jambs, on door latches, around electrical outlets, and on their flooring. One of the occupants reported they found particles to clean after 4-months. It is recommended that contractors spend more time cleaning the site prior to leaving so the brunt of the cleaning does not fall upon the homeowner or tenant. In addition, since this technology is newer to the retrofit market, contractors should be trained on any piece of equipment that can be damaged from the sealant and instructed how to protect it, such as a combustion water heater or carpet. It is also important for contractors to be well-versed in combustion air ventilation and perform combustion appliance zone (CAZ) tests such as those defined by the Building America Solutions Center (https://basc.pnnl.gov/resource-guides/combustion-appliance-zone-caz-testing) to ensure sealing does not create any combustion safety hazards. It is also important to follow ASHRAE 62.2 minimum fresh air requirements by installing mechanical ventilation if the home is sealed below the minimum guideline.

Future Research

From the three points of reference consisting of the initial leakage, initial post-retrofit leakage, and the leakage taken 11–19 months after the AeroBarrier installation, it was found the effectiveness of air sealing degraded 27% on average. This 27% still leaves the sites relatively tight, however it is unknown if the sealant will continue to degrade over time, or if this average is skewed by new leaks not caused by AeroBarrier degradation. Further research is recommended to take multiple blower door measurements from one month to 3 years after the retrofit to determine to what extent and how rapidly the sealant degrades.

3.6: PCM in Commercial Applications

Lead Locally evaluated PCMs in two principal applications, one in residential attics and one in commercial attics and/or drop ceilings. The residential application of PCMs included a significant number of performance and cost uncertainties and was considered an applied research technology. The results of the residential PCM evaluation were addressed in the *Phase Change Materials in Residential Applications Final Report* (Hendron & Chally, 2022).

This section addresses the application of PCMs as a retrofit for commercial buildings, which was a more proven application involving less risk to building owners because many more commercial PCM installations exist, Cost remains a significant market barrier and ideal target building sectors are not well defined. As a result, more buildings were tested, with less comprehensive instrumentation. For tech demos, our primary objective was to evaluate overall energy savings, cost-effectiveness, and occupant satisfaction in a variety of situations to identify unexpected systems interactions or other issues that could affect the range of building sectors or ceiling types for which the technology would be recommended or incentivized.

Introduction

PCMs are materials that absorb heat as they melt and release heat as they freeze. There are several types of PCMs with different strengths and weaknesses, including paraffins, hydrated salts, and organic materials. PCM melting points can be tuned to match the needs of the application, making PCMs an appealing technology for use in buildings. PCMs do not contribute to the R-value of the building envelope, but when installed adjacent to the insulation, PCMs can reduce or delay large temperature differences across the insulation, thereby reducing heat transfer into or out of the conditioned space. When installed in drop ceilings, they add thermal storage capability that improve comfort and delay peak cooling demands to times when electricity is less expensive and less of a strain on the grid.

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.

The macro-encapsulated inorganic PCM products Templok and Infinite R, sold by Insolcorp through Lead Locally partner Winwerks, were the technologies evaluated for this demonstration project. Since the time of this project, Infinite R has been discontinued as a product line for Insolcorp.

Templok is a rigid product with PCM stored in 9”x9” cells contained within a hard plastic 2’x2’ package that can be easily placed above ceiling tiles, as shown in Figure 10. The product is generally used to provide thermal storage within ceiling plenums but can also be used in wall or attic applications. Insolcorp predicts 20%-30% savings in heating and cooling load for Templok installed in ceiling applications. A summary of product specifications published by Insolcorp is provided in Table 28.

Figure 10: Templok PCM Tiles in Drop Ceiling

Image credit: Insolcorp, LLC

Table 28: Templok Physical Properties

Physical Properties	Values
Melting Point	65 - 80°F
Latent Heat	86 BTU/lb
Thermal Conductivity	0.15 W/ft/K Liquid
	0.38 W/ft/K Solid
Dimensions	23.75” X 23.75”
	16” X 23.75”
Thickness	0.25”
Weight	1.3 lb/ft^2

For Infinite R, the compound is stored in a white poly film pocket and sealed in a multilayer white poly film, as shown in Figure 11. The PCM comes in a variety of melting points ranging from 66-84°F. This product was generally recommended for attic installation, either above or below the insulation, and between ceiling joists. Infinite R PCM mats have the published characteristics and performance values shown in Table 29.

Figure 11: Infinite R PCM mat

Table 29: Infinite R Physical Properties

Physical Properties	Values
Melting Point	66 - 84°F
Latent Heat	86 BTU/lb·°F
Thermal Conductivity	0.16 W/ft/K Liquid
	0.33 W/ft/K Solid
Dimensions	24.5” X 48”
	16.5” X 48”
Thickness	0.25”
Weight	0.75 lb/ft^2

The two PCM products have comparable specifications. The key differences are that Templok is in a rigid package and has more PCM per unit area while maintaining the same thickness. The additional PCM storage capacity comes with additional weight, but Insolcorp has performed structural analysis confirming that a well-maintained suspended ceiling system and standard ceiling tiles can support the weight of Templok panels.

To charge and discharge heat from the PCM during the summer in commercial building applications, it is helpful to have significantly lower temperature settings at night versus during the day, either through nighttime ventilation cooling or pre-cooling using the HVAC system. During peak demand hours, the cooling system can be turned off or operated with a higher set point with minimal expected loss in comfort. Even with no change in set point, the PCM will likely reduce peak electricity use for cooling even if it hasn't fully frozen. During the winter, PCM works most effectively in applications where there are large internal heat gains during the day, and where the thermostat is set back at night. This reduces warm-up time in the morning while minimizing overheating during the day. PCM also be applied as one component of a wind-vented roof system if a roof replacement is planned for a commercial building and can be installed in exterior or interior walls. These applications are outside the scope of this technology demonstration project.

The performance of PCMs in commercial buildings can be enhanced when combined with a building automation system that controls set points in a manner that maximizes energy storage and minimizes electricity use during the peak demand period. Improvements to the efficiency of the HVAC system will reduce the energy savings potential of PCMs. Similarly, smaller thermal gains from improved lighting and equipment efficiency may negatively impact energy savings for PCMs, especially in the summer. If ducts are located in the dropped ceiling, the PCM may be exposed to larger temperature excursions during hot or cold weather, which could enhance overall effectiveness.

Based on information currently available, it is expected that commercial buildings with the following characteristics would save the most energy:

1. Large outdoor diurnal temperature swings during all seasons
2. Wintertime thermostat setback and summertime set up at night, or willingness to include HVAC scheduling following the retrofit
3. Year-round building occupancy
4. Significant day and evening occupancy at least five days per week, with minimal operation at night
5. Large internal heat gains
6. Dropped tile ceilings

Commercial sectors such as retail, restaurants, office, and manufacturing appear to be the most promising applications. Schools and medical facilities may not be ideal locations. Mixed climate zones such as Sacramento and Fresno are likely to achieve greater energy savings than milder climates like Sonoma County or the Bay Area, although there is the potential to eliminate the need for cooling altogether in mild climates.

Technology Benefits

- Up to 10-30% heating and cooling energy savings
- Peak demand reduction
- More stable interior temperatures
- Material is thin and lightweight
- Easy to install in many applications, including dropped tile ceilings
- Less prone to water damage than insulation

Technology Uncertainties

- Savings may be less than expected due to mild Sonoma County climate
- Variations in operating profiles and internal gains may affect energy savings for different commercial building sectors
- Cost-effectiveness within a 5-10 year timeframe may be difficult to achieve
- Contractors and trades have minimal experience with PCMs in commercial applications.

Research Questions

The Team attempted to answer the following research questions through the demonstration of PCMs installed in or above commercial ceilings:

- What is the preferred melting point for the PCM in typical commercial applications?
- Is there sufficient heat transfer rate to fully charge and discharge the PCM under a range of operating conditions representative of commercial buildings?
- What is the heating/cooling load reduction and peak demand reduction that results from the addition of PCM?
- What is the cost-effectiveness of adding PCMs to commercial roofs/ceilings in Sonoma and Mendocino Counties?
- Does the PCM demonstrate durability and effectiveness after being installed in commercial ceilings for an extended period?
- What commercial building characteristics lead to cost effective installations of PCMs?
- How can building owners determine that their space is a good candidate for the technology?

Methodology

For the technology demonstration phase, the retrofits consisted of 1000-2000 ft^2 of either Templok or Infinite R macro-encapsulated PCM installed in an existing dropped ceiling or above the ceiling under unconditioned attic or buffer spaces. The area limit was based on rebate budget limitations for the demonstration project; there were no physical restrictions on ceiling area that may include PCMs. For all buildings, only a subset of the ceiling area was retrofitted unless the building owner was willing to fund the cost of the PCM mats for the remaining area.

Ten field test sites were targeted within Sonoma and Mendocino Counties using the SCP web site and e-mail communications for recruitment. The criteria for these sites are outlined in Table 30. Some criteria were essential for consideration of a test site, others received points ranging from 1-10 based on the importance of meeting the criteria. Owners of the sites with the highest scores were offered a PCM retrofit using SCP match funding to subsidize the cost up to 100%, in exchange for installing the PCM, supporting energy and comfort monitoring activities, and participating in a questionnaire about comfort impacts. If an owner declined, the site with the next highest score was contacted.

Table 30: Technology Demonstration Site Selection Criteria for PCMs in Commercial Buildings

Category	Criterion	Criterion Value	Criterion Weight (1-10)
Occupants/Owner	Occupied?	Yes	8
	Owned by current occupants?	Yes	8
	Operational year long?	Yes	Essential
	Hours of operation	Daytime and evening	9
	Days of operation	5/week or more	7
	TOU rate schedule?	Yes	5
	Employees of energy industry?	No	2
	Realistic owner expectations?	Yes	Essential
	Financial support for retrofit by owner	Yes	10
	Owner enthusiastic?	Yes	8
Site	Number of floors	1	2
	Building type	Retail, restaurant, manufacturing	5
	Ceiling area	<2,000	5
	CA Climate Zone	2	10
	Safe work environment?	Yes	Essential
	Practical installation barriers?	No	Essential
	Practical installation challenges?	No	10
	Located near other sites?	Yes	3
	Features similar to other sites?	Yes	1
	Roof type	Flat	8

Building Envelope	Attic insulation R-value	>30	5
	Ceiling type	Dropped	10
Mechanical	HVAC system functional?	Yes	Essential
	Central Cooling?	Yes	10
	Propane heating?	No	10
	Electric heating?	Yes	10
	Summer pre-cooling?	Yes	10
	Asbestos present?	No	Essential
	Ecobee thermostat?	Yes	4
	Building automation system?	Yes	10

The baselines for the field testing were the test sites prior to retrofit. At least six months of monitored data were collected following site selection, including partial or full winter and summer seasons.

Key data points during the pre-retrofit period included the following:

- Temperatures of the conditioned space
- Outside temperature
- Heat flux through the ceiling (at one site)
- Air temperature inside the drop ceiling (depending on application)
- Attic temperature (depending on application)

The frequency and extent to which the PCM froze and melted each day was monitored for 6-9 months following the retrofit by including the following additional post-retrofit data points:

- Heat flux above and below the PCM (at one site)
- Surface temperature above and below the PCM (at one site)

To estimate energy savings, utility bills were analyzed to quantify the change in heating and cooling energy following the retrofit. Because a large number of variables can impact space conditioning loads, utility bills cannot always accurately capture the energy savings associated with the PCM if the impact is small and the variability in operating conditions is large. Building owners agreed not to perform additional energy efficiency retrofits during the test period, to minimize the need to separate PCM savings from other sources of energy savings. Weather normalization was performed to eliminate possible weather effects. In cases where building operations changed significantly, the use of pre- and post-retrofit surveys helped identify those differences, although they could not be adjusted for without more detailed monitoring and energy modeling that was outside the scope of this technology demonstration project. However, measured temperature data could at least confirm whether the PCM was exposed to temperatures on both sides of its melting point, providing an opportunity for the PCM to store energy as designed and achieve the savings expected based on previous studies by the manufacturer.

PCMs for commercial roofs/ceilings would advance to the deployment phase and be included in the Advanced Energy Center if the following success criteria were met:

- Heating and cooling electricity savings and peak demand reduction in excess of 10% for spaces retrofit with PCMs
- More stable interior temperatures during work hours
- No issues with durability when the PCMs are exposed to realistic operating conditions during the 6-9 month test period
- Potential for cost-effectiveness in several building types
- No significant occupant complaints related to the PCMs

Results and Analysis

Ten test sites were targeted for this study, although several site recruiting challenges made it difficult to identify suitable sites. Despite the relative simplicity of the technology and its installation, very few businesses volunteered for PCM installation. Many of the initial volunteers rented their spaces and were unable to secure landlord support for the project. Several cited weight concerns, although Insolcorp had performed structural analysis to verify that standard drop ceilings could readily withstand the weight of PCM as long as there was no underlying structural damage. To compound the difficulties, the onset of the COVID-19 pandemic caused several interested businesses to withdraw from the project or become unresponsive. Each site was assigned a score based on the sum of the Criteria Weights (see Table 30) for each criterion that was met. Ultimately six sites that achieved adequate scores were secured, and the project team decided that this was an adequate sample size to evaluate the performance of the technology in diverse applications, and to identify any major barriers to large scale deployment. A summary of the six test sites is provided in Table 31.

Table 31: PCM Technology Demonstration Sites

Site #	Building/Space Function	Score	Product	Installed Location	PCM Area	PCM Melting Point
11	Lecture hall	84	Templok	Drop ceiling	1,000 ft^2	75°F
57	Restaurant (Thai)	110	Templok	Drop ceiling	2,000 ft^2	72°F
58	Restaurant/wine tasting	92	Infinite R	Attic, above insulation	1,600 ft^2	77°F above kitchen, 73°F elsewhere
59	Restaurant (Pizza)	108	Templok	Drop ceiling	1,000 ft^2	75°F
60	Restaurant (Deli)	89	Templok	Drop ceiling, mechanical	1,300 ft^2	75°F for drop ceiling,

				room above dining area		77°F for dining area
61	Classroom/office	106	Templok	Drop ceiling	1,600 ft^2	77°F

Four of the selected sites were restaurants with both cooking and dining areas. These sites were a good fit for PCM because the large internal gains and variable temperatures would help drive the melting and freezing processes. The other two sites were educational areas, which weren't viewed as ideal candidates because space temperatures are generally more constant. However, Site 61 did not have space cooling, and the classrooms tended to overheat during the summer. This test provided an opportunity to see if comfort could be significantly improved during the summer months by storing energy in the PCM as it melted during warm afternoons, then releasing energy as the PCM freezes during the cooler summer nights. All building occupants with drop ceiling PCM applications and central cooling were encouraged to use a 10°F overnight thermostat set-back for pre-cooling during the summer, to help freeze the PCM when electricity was less expensive and minimize air conditioner use during peak hours in the late afternoon and evening as the PCM melted.

All of the sites included drop ceiling areas for PCM installation and used the Templok material, except Site 58, which had a residential-style ceiling and used Infinite R. Just prior to installation at Site 58, leaks had appeared with Infinite R mats in the attics of two of the residential PCM test sites that were being tested as part of a separate Lead Locally research project, but the Project Team had not yet identified the cause. The building owner was made aware of the leakage concerns. The owner was told that if he decided to proceed with installation, he should place the material above the insulation to minimize the chance of damage to the ceilings. Since there was no evidence of PCM leaks after nearly a year in storage, the building owner decided to install the PCM and keep a close eye on the material and packaging for potential signs of degradation.

For many of the sites, the temperature in the drop ceiling or attic was monitored prior to purchase of the PCM, which allowed the Project Team to select melting points that best fit the application. For a couple of the restaurants, there was significant overheating in the kitchen and dining areas. A higher melting point (77°F) material was selected for those areas. Site 61 was a school with no air conditioning, making it another good candidate for high melting point PCM. The other sites generally had more well controlled summer temperatures, and a lower PCM melting point of 72°F or 75°F was selected.

All of the sites were self-installations, except Site 61 for which an insulation contractor was hired. After inspecting Site 57, Frontier staff assisted with supplemental PCM installation beyond what the business owner and her family were able to perform on their own. Most of the sites only used about 50-75% of the material provided, because of weight concerns, installation challenges, or overly optimistic estimates of available ceiling area.

The instrumentation packages installed at the six demonstration sites are summarized in Table 32. Three sites were monitored using dataloggers that communicated results to Frontier engineers in real time (Sites 58, 60, and 61), while the others used lower cost battery powered sensor modules with local memory storage that required on-site downloading at the end of the project.

Table 32: Instrumentation Used at PCM Demonstration Sites

Site #	Building/Space Function	Measured Data	Locations	Sensor Type
11	Lecture hall	Temperature	Interior space; ceiling plenum	HOBO temperature and relative humidity (T/RH) sensor
57	Restaurant (Thai)	Temperature	Dining area; ceiling plenum	HOBO T/RH sensor
58	Restaurant/wine tasting	Temperature	Kitchen and lobby; attic above kitchen and lobby	HOBO thermocouples, T/RH sensor, and gateway
59	Restaurant (Pizza)	Temperature	Dining area; ceiling plenum between dining area and kitchen	HOBO T/RH sensor
60	Restaurant (Deli)	Temperature	Dining area; office hallway	HOBO thermocouples, T/RH sensor, and gateway
61	Classroom/office	Heat Flux/ Temperature	Classroom and office, plenum above classroom and office	Hukseflux FHF02 foil sensors; wired thermocouples

Important dates throughout the field test period are summarized in Table 33. Three of the six sites included a pre-retrofit monitoring period ranging from 8 to 16 months. The other three sites had recruitment delays that required immediate installation of PCM to keep the projects on schedule. However, pre-retrofit utility bills were available for all sites. Site 11 was a special case, because the addition of PCM was part of a larger building repurposing and renovation project. As a result, no pre-retrofit base case was available for comparison without performing whole-building energy modeling, which was beyond the scope of this technology demonstration project.

Table 33: Key Dates for PCM Demonstration Sites

Site #	Pre-Retrofit Monitoring Period	Installation Date	Post-Retrofit Monitoring Period	Decom-missioning Date	Monitoring Issues

11	N/A	6/4/21	6/4/21-3/20/22	3/21/22	
57	N/A	3/30/21	3/31/21-3/2/22	3/3/22	
58	8/13/20-12/14/21	12/15/21	12/16/21-4/18/22	Ongoing	No hot weather data post-retrofit
59	N/A	3/25/21	3/31/21-3/2/22	3/3/22	
60	7/15/20-3/26/21	3/27/21	3/28/21-3/2/22	3/3/22	Sensors above drop ceiling in hallway moved during installation, not sure exactly when
61	7/18/20-3/9/21	3/10/21	3/11/21-1/30/22	1/31/22	Heat flux sensor above the office was cut by the PCM installation crew

The following sections present the results for the seven test sites in the form of case studies. Because each site offered its own unique challenges, the energy savings and cost-effectiveness analyses must be put into context to fully understand whether the technology was successful in each application.

Site 11 Results

The installation at Site 11 consisted of about 1,000 ft^2 of 75°F melting point Templok placed above the ceiling tiles in a lecture room. A melting point slightly higher than the typical classroom temperature was selected because the ceiling was elevated (~15 ft) and significant temperature stratification was expected. The business owner performed the installation after viewing the training video developed by the vendor, and it reportedly took about 2 hours. No significant installation challenges were encountered, although the high ceiling required a tall ladder for access, presenting minor additional safety concerns. Temperature sensors were installed near the thermostat and in the drop ceiling plenum to verify that the PCM was exposed to diurnal temperature swings conducive to melting and freezing.

Representative summer temperature profiles and the PCM melting point are shown in Figure 12, and winter profiles are shown in Figure 13. During the summer, it is evident that the PCM was exposed to temperatures above and below the melting point, and we expect that the PCM should have been performing as designed. No pre-cooling was performed by the occupants. During the winter season, the thermostat setting was significantly lower, and the PCM did not reach the melting point. As a result, it is unlikely that there was any heating energy savings for this application, but it should be remembered that the main objective of this project was to reduce or shift cooling energy. There were no signs of PCM leaks or other panel degradation at the conclusion of the test period.

Figure 12: Summer Temperature Profiles – Site 11

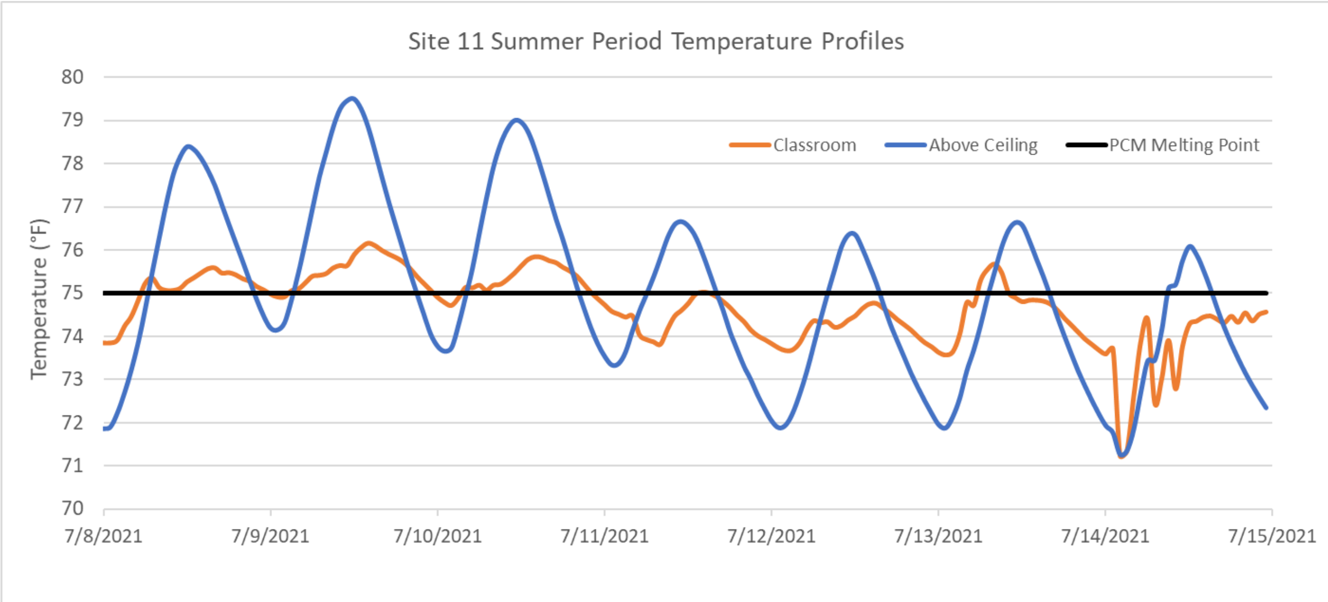
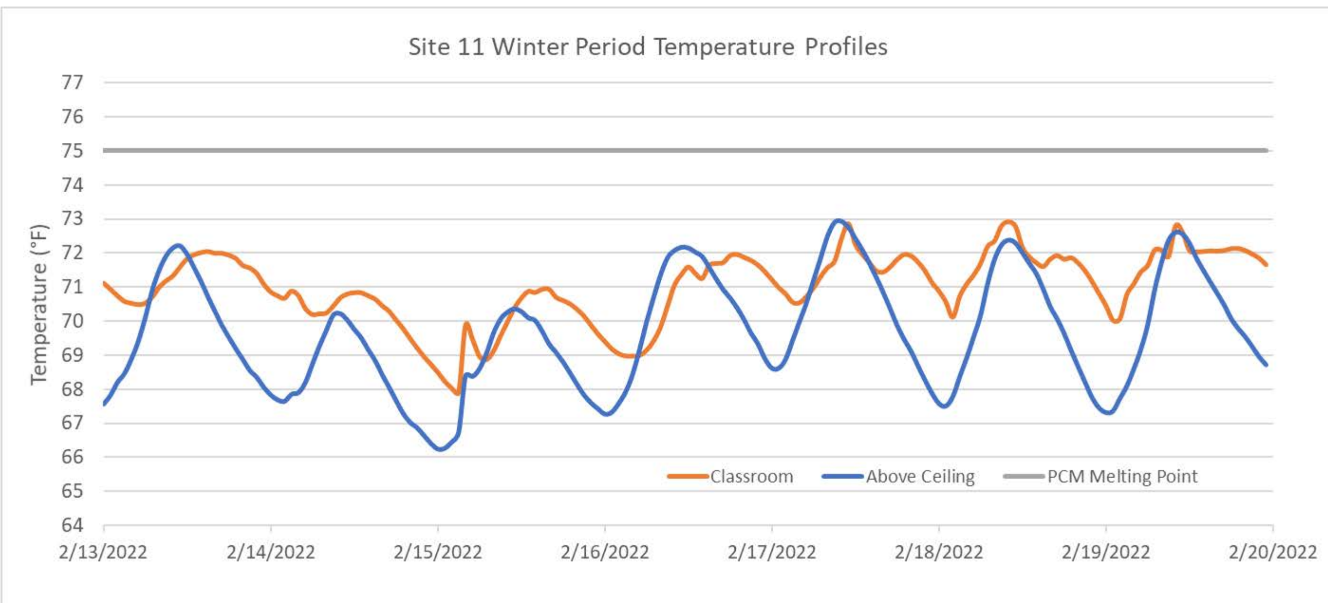


Figure 13: Winter Temperature Profiles – Site 11



Without a relevant pre-retrofit case for comparison, there were very few conclusions that could be drawn about energy and cost savings from the test data. No utility bill analysis was performed for Site 11, and consequently there was no cost-effectiveness analysis. However, we do know the approximate cost of installation, which was $3,598 for materials and about $600 for labor assuming two people participated in the 2-hour installation process, for a total installed cost of $4,198.

Site 57 Results

The PCM installed at the Thai restaurant was placed above the drop ceiling in the dining area. The PCM had a melting point of 72°F. No installation challenges were identified. Temperature sensors were installed near the thermostat and above the drop ceiling to verify that the PCM was exposed to diurnal temperature swings conducive to melting and freezing.

Representative post-retrofit summer temperature profiles and the PCM melting point are shown in Figure 14, and winter profiles are shown in Figure 15. There is no indication that the restaurant was pre-cooled during the summer. The dining area temperatures were kept higher than expected in summer, and cooler than expected in winter. As a result, there was limited exposure of the PCM to its 72°F melting point during hot and cold weather. However, during swing seasons, the ceiling temperature was more consistently above and below the melting point (see Figure 16), suggesting that comfort may have been more readily sustained without HVAC usage during milder weather conditions. There were no signs of PCM leaks or packaging degradation at the conclusion of the test period.

Surveys provided by the business owner indicate that prior to retrofit, there were comfort issues related to non-uniform temperatures throughout the restaurant. The surveys also indicated that windows were used frequently for cooling and fresh air, and fans were used to enhance comfort. Post-retrofit survey results indicated that the restaurant was always comfortable throughout the building and fans were no longer used, but windows were still used occasionally for free cooling and ventilation. In the months leading up to the PCM retrofit, the restaurant was heavily impacted by issues related COVID-19, including temporary closures and reduced capacity for social distancing. By the time of the retrofit, restaurant operations were seemingly back to normal.

Figure 14: Summer Temperature Profiles – Site 57

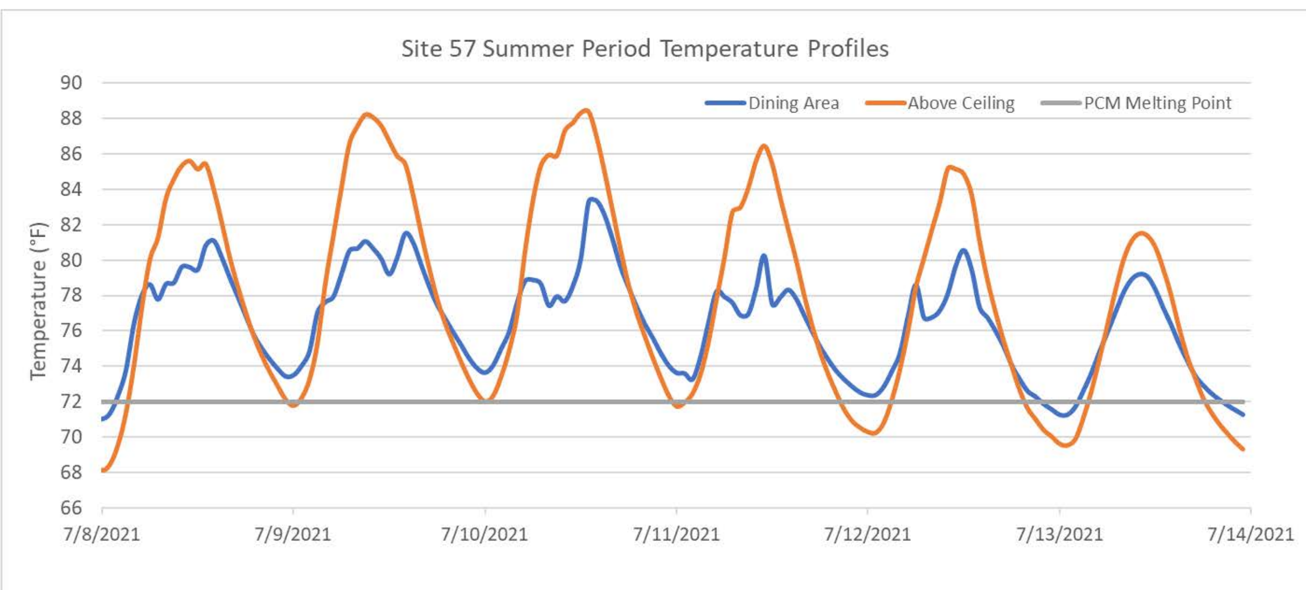


Figure 15: Winter Temperature Profiles – Site 57

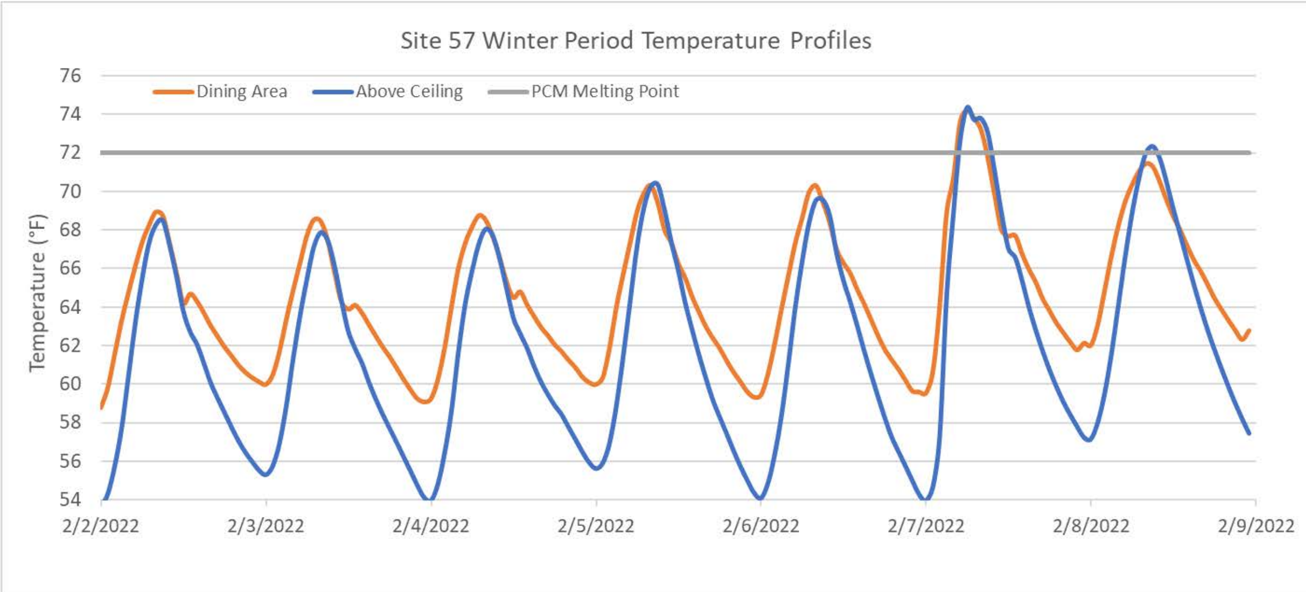
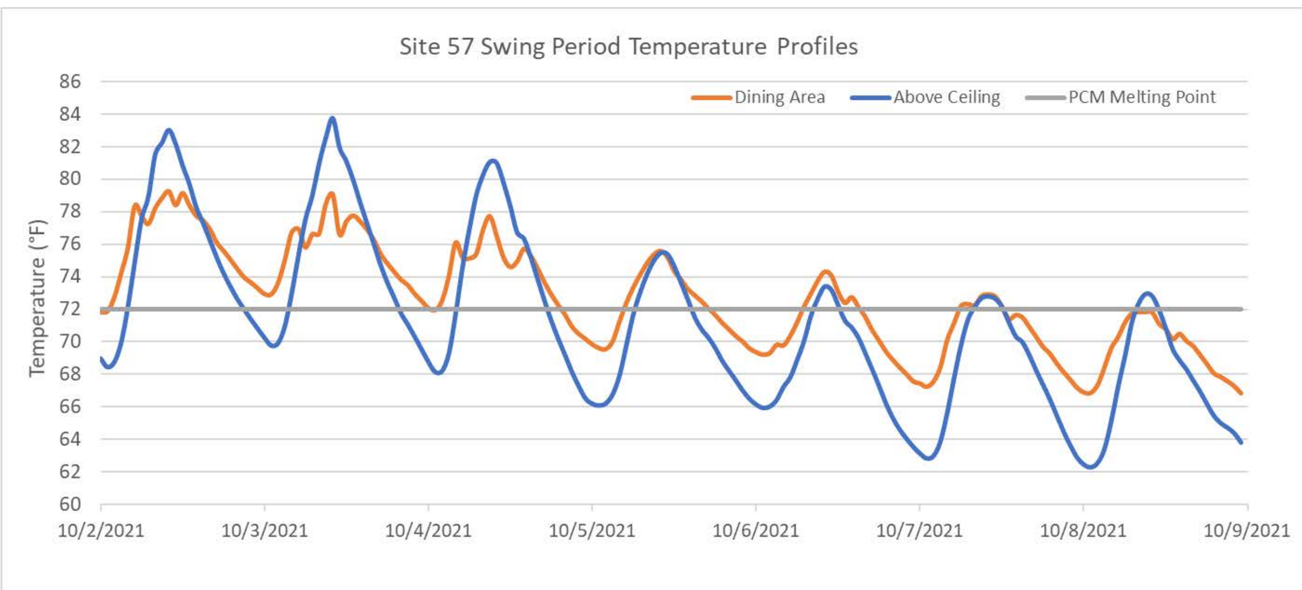


Figure 16: Swing Season Temperature Profiles – Site 57



Energy savings for Site 57 was based on weather normalized utility bills before and after the retrofit, using the procedure described in Section 2.4 with an assumed balance point of 65°F. The Coefficient of Variation of the Root Mean Squared Error (CVRMSE) for this method was 7.0% for electricity and 10.3% for gas during the pre-retrofit period, which is better than the ASHRAE Standard 14 criteria of <20% for adequate predictive capability when less than 12 months of data is available. Slightly better values of CVRMSE could be achieved by using balance point temperatures other than 65°F, but the optimal balance points were often unrealistic (in the 30-40°F range for Site 57) and were therefore rejected. Because the year just prior to the retrofit coincided with the outbreak of the COVID-19 pandemic, we examined savings relative to both the year before the retrofit and the year before that. This introduced some additional uncertainty in the analysis, because operational changes may have been made to the business over time, but this uncertainty was likely much smaller than the effect of COVID-19. The results are summarized in Table 34, and indicate that both gas and electricity use were lower following the PCM retrofit. There are no other known changes to the building between the pre-COVID case and the post-retrofit case, though it is possible something changed that was not captured in the participant survey.

Table 34: Utility Bill Analysis of Site 57

	Annual Electricity (kWh)	Annual Natural Gas (kBtu)	Total Annual Site Energy (MMBtu)
Pre-Retrofit, Pre-COVID	28,469	275,800	372.9
Pre-Retrofit, During COVID	28,107	256,300	352.2
Post-Retrofit	27,658	244,300	338.6
Savings versus Pre-COVID	**811**	**31,500**	**34.3**
% Savings versus Pre-COVID	**2.8%**	**11.4%**	**9.2%**

The cost-effectiveness analysis for Site 57 is provided in Table 35. Material costs were tracked by Frontier, and the self-installation cost was based two hours of work (as reported by the business owner) by the business owner and two hours of work by a Frontier field engineer at an average rate of $150/hour. The estimated simple payback was 7.9 years, which would be acceptable to many business owners, especially given expected comfort benefits.

Table 35: Cost-Effectiveness Analysis for Site 57

	Site 57
Annual Electricity Savings (kWh)	811
Average TOU Electricity Price ($/kWh)	$0.319
Annual Natural Gas Savings (kBtu)	31,500
Average Natural Gas Price ($/kBtu)	$0.0154
Total Annual Cost Savings ($/year)	$744
Material Cost ($)	$5,263
Installation Cost ($)	$600
Total Measure Cost ($)	$5,863
Simple Payback (years)	7.9

Site 58 Results

Site 58 is a restaurant/tasting room at a local winery. The owner had concerns about overheating in the kitchen area during busy periods, but the tasting area and the rest of the building had fairly stable temperature conditions. There was no drop ceiling at this site, so Infinite R was installed above the attic insulation, similar to residential applications. A higher melting point (77°F) was used above the kitchen to address the overheating concerns in that area, and a melting point closer to the thermostat setting (74°F) was used elsewhere. Temperature sensors were installed in the attic above the kitchen and wine tasting areas, and in the kitchen itself. This site had a change of ownership that delayed installation until December 2021, and recommissioning of the sensors occurred in January 2022. Consequently, there is limited post-retrofit data available for analysis, especially during hot weather. The PCM installation was performed by the business owner's preferred contractor, but specific cost details are unavailable.

The summer temperature profiles for the pre-retrofit period are shown in Figure 17. During this period, the COVID-19 pandemic was still affecting business significantly, and it's unclear if the kitchen was used as extensively as it normally would. But large kitchen temperature excursions around noon are evident in the data. The attic was warmer than expected above the tasting area, but there were periods when the PCM above both the kitchen and tasting area should have been freezing and melting. Representative pre-retrofit winter temperature profiles from January 2021 are shown in Figure 18. It appears from the data that the restaurant and tasting area were not operational during most of the winter, which is likely when the winery was sold, and transitional activities were happening. It's interesting that the attic areas above the wine tasting room were much more stable than above the kitchen, possibly due to poor insulation in that area resulting in larger heat gains from below, which was evident during Frontier's site visit. Regardless, the lack of operation and very low thermostat settings make it impossible to determine if the PCM would melt very often during the winter.

Figure 17: Pre-Retrofit Summer Temperature Profiles – Site 58

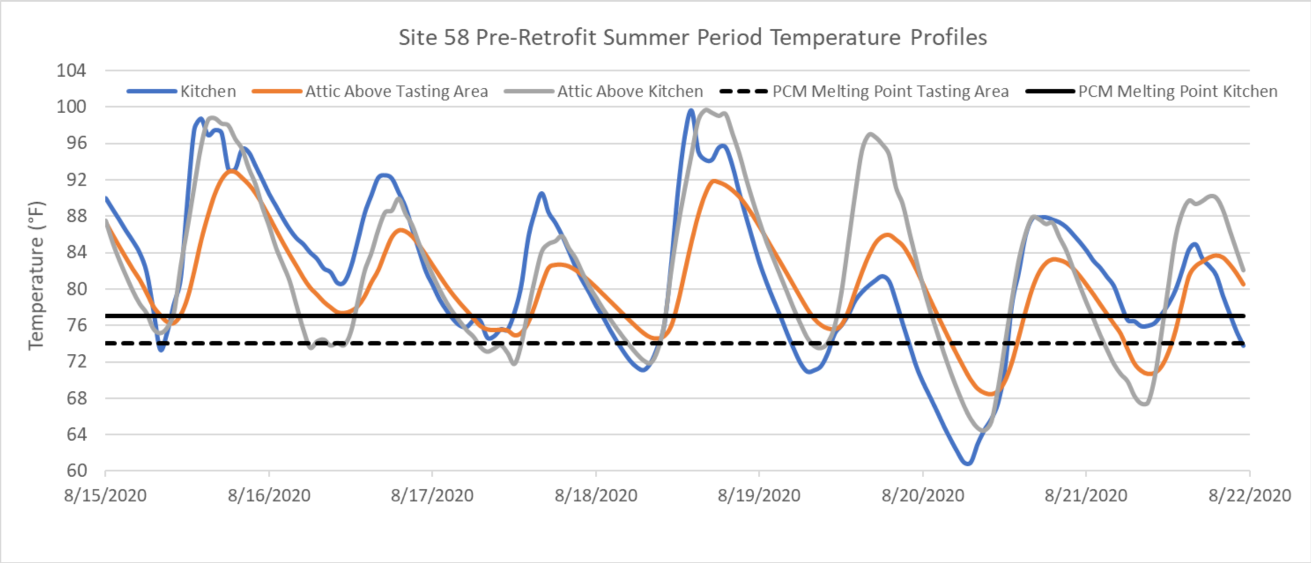
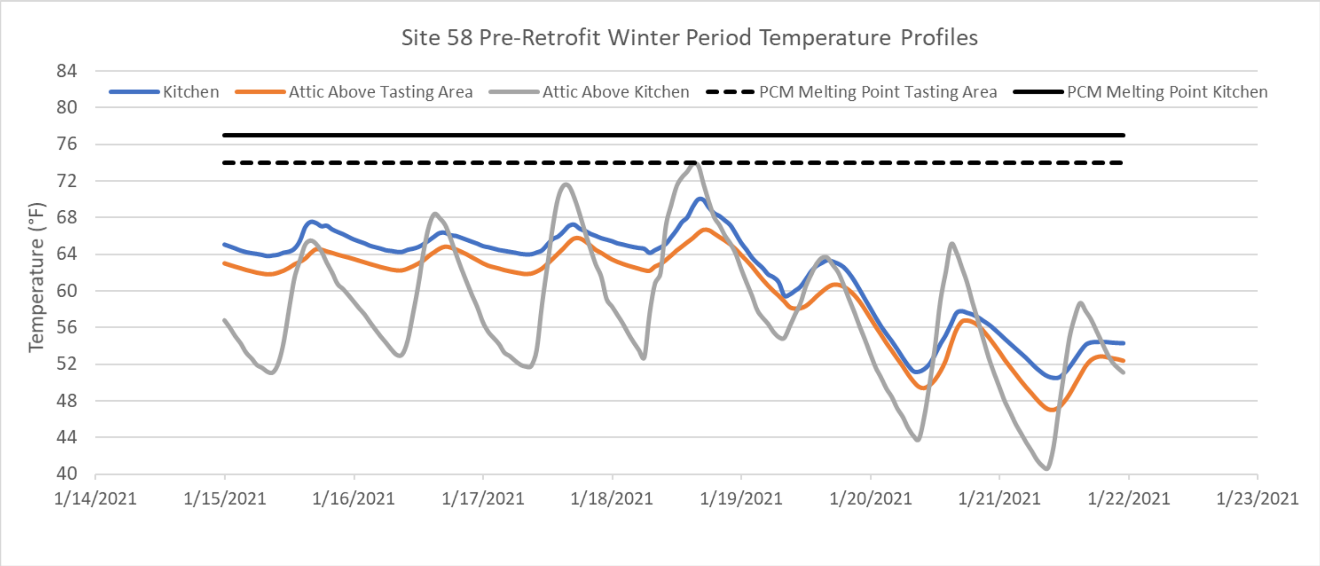
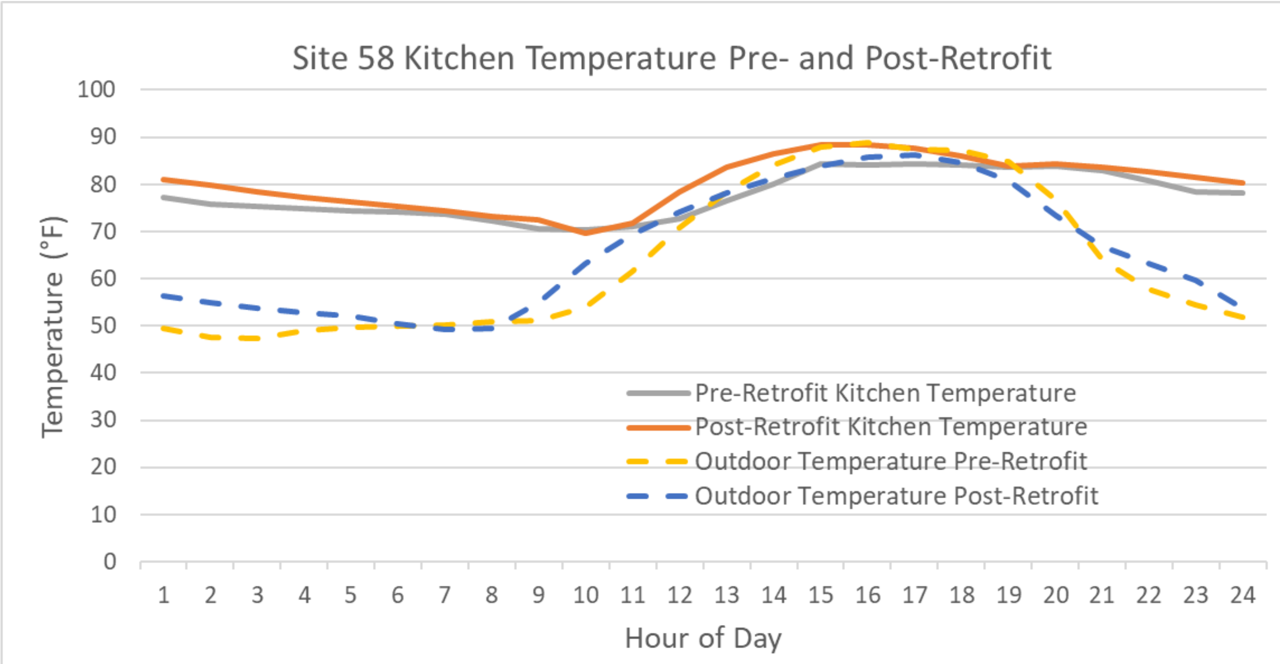


Figure 18: Pre-Retrofit Winter Temperature Profiles – Site 58



Following the PCM installation, kitchen temperatures were examined to determine if peak temperatures were reduced. Kitchen and outdoor temperatures for days with comparable weather conditions are shown in Figure 19. Even though the outdoor temperature was slightly warmer for the pre-retrofit case, the temperature in the kitchen was warmer after the retrofit. Several other days were compared, and the results were similar. It is certainly possible that reduced cooking activity during the pre-retrofit period played a role in this result, but unfortunately the data does not support improved comfort levels in the kitchen due to the installation of PCM.

Figure 19: Kitchen Temperature Profiles – Site 58



Survey responses from the building owner were not provided for the winery. No leaks or other signs of PCM degradation have been identified at this site.

Weather-normalized utility bill analysis assuming a balance point of 65°F was performed using the procedure described in Section 2.4. The results are summarized in Table 36. The CVRMSE for this method was 24% for electricity during the pre-retrofit period, which is beyond the ASHRAE Standard 14 criteria of <20% for adequate predictive capability when less than 12 months of data is available, indicating that the curve fit is unreliable. The building was heated with propane, but the timing of propane use is difficult to quantify because it is purchased in bulk, and we were unable to track propane use for this project. Due to the lack of warm weather post-retrofit data, the regression analysis results for the cooling season are highly uncertain. In addition, the data suggests there was a major change in building operations in late 2019 that doubled electricity use, making the pre-COVID energy use unreliable as a basis for comparison. Unfortunately, this means that both heating and cooling energy are unreliable for this project, as well as the base load pre-COVID, but the results are presented for completeness.

Table 36: Utility Bill Analysis of Site 58

	Annual Electricity (kWh)	Annual Natural Gas (kBtu)	Total Annual Site Energy (MMBtu)
Pre-Retrofit, Pre-COVID	43,353	0	147.9
Pre-Retrofit, During COVID	72,687	0	248.0
Post-Retrofit	81,976	0	279.7

Savings versus Pre-COVID	**-38,623**	**0**	**-131.8**
% Savings versus Pre-COVID	**-89.1%**	**0.0%**	**-89.1%**

The cost-effectiveness of the PCM installed at Site 58 could not be determined with sufficient accuracy, but the information that is reliable is presented in Table 37. Material costs were tracked by Frontier, and installation costs were estimated based on a contractor working 4 hours at an average rate of $150/hour.

Table 37: Cost-Effectiveness Analysis for Site 58

	Site 58
Annual Electricity Savings (kWh)	Unknown
Average TOU Electricity Price ($/kWh)	$0.319
Annual Propane Savings (gal)	Unknown
Average Propane Price ($/gal)	Unknown
Total Annual Cost Savings ($/year)	Unknown
Material Cost ($)	$4,737
Installation Cost ($)	$600
Total Measure Cost ($)	$5,337
Simple Payback (years)	Unknown

Site 59 Results

The PCM installed at the pizza restaurant was placed above the drop ceiling in the dining area. The PCM had a melting point of 75°F. No installation challenges were identified, although during instrumentation it was evident that much less PCM was installed by the business owner than expected, perhaps less than 50%. The installation process reportedly took about two hours. Temperature sensors were installed near the thermostat in the dining area and above the drop ceiling between the kitchen and dining area to verify that the PCM was exposed to diurnal temperature swings conducive to melting and freezing.

Representative post-retrofit summer temperature profiles and the PCM melting point are shown in Figure 20, and winter profiles are shown in Figure 21. Unfortunately, it appears that the drop ceiling space was significantly warmer than expected, even during the winter, and the PCM probably did not freeze very often, if at all. There is no indication that the restaurant was pre-cooled during the summer, which may have helped to freeze the PCM at night. There were no signs of PCM leaks or packaging degradation at the conclusion of the test period.

Surveys provided by the business owner indicate that prior to retrofit, indoor dining was no longer provided to customers due to COVID-19 issues. As a result, the cooling set point was higher than it was previously. The surveys also indicated that windows were used frequently for fresh air, and ceiling fans were used to enhance comfort. Indoor temperatures were generally uniform throughout the building. Post-retrofit survey results indicated that the number of workers and customers generally increased from about 6-7 to about 30, because indoor dining was again available. The restaurant continued to be comfortable throughout the building and ceiling fans were used, but windows were no longer used for ventilation.

No leaks or other signs of PCM degradation have been identified at this site.

Figure 20: Summer Temperature Profiles – Site 59

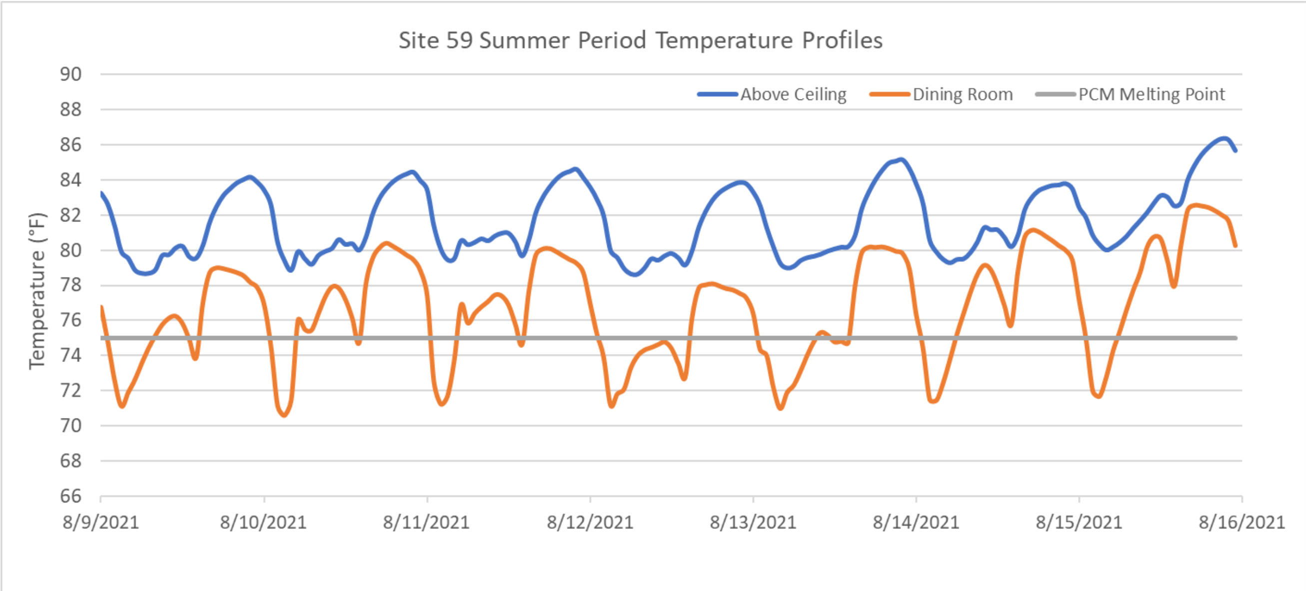
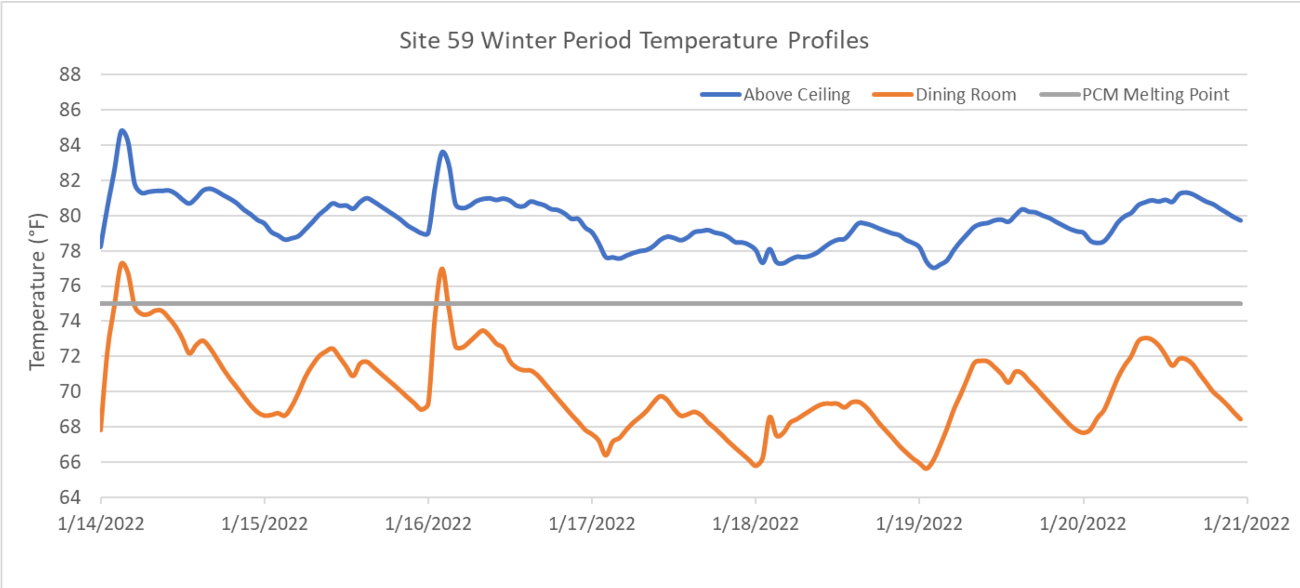


Figure 21: Winter Temperature Profiles – Site 59



Energy savings for Site 59 were based on weather-normalized utility bills before and after the retrofit, using the procedure described in Section 2.4 with an assumed balance point of 65°F. Because the year just prior to the retrofit coincided with the outbreak of the COVID-19 pandemic, we examined savings relative to both the year before the retrofit and the year before that. This introduced some additional uncertainty in the analysis, because operational changes may have been made to the business over time, but this uncertainty was likely much smaller than the effect of COVID-19. The CVRMSE for this method was 7.6% for electricity and 10.1% for gas during the pre-retrofit period, which is better than the ASHRAE Standard 14 criteria of <20% for adequate predictive capability when less than 12 months of data is available. The results are summarized in Table 38.

Table 38: Utility Bill Analysis for Site 59

	Annual Electricity (kWh)	Annual Natural Gas (kBtu)	Total Annual Site Energy (MMBtu)
Pre-Retrofit, Pre-COVID	89,451	546,400	851.6
Pre-Retrofit, During COVID	85,296	455,100	746.1
Post-Retrofit	94,840	515,500	839.1
Savings versus Pre-COVID	**-5,389**	**31,000**	**12.6**
% Savings versus Pre-COVID	**-6.0%**	**5.7%**	**1.5%**

The cost-effectiveness analysis for Site 59 is provided in Table 39. Material costs were tracked by Frontier, and the self-installation cost was based two hours of work (as reported by the business owner) for two people at an average rate of $150/hour. The increase in electricity use after the retrofit resulted in negative total savings based utility bill analysis. However, the impacts of COVID likely played a large role, along with other potential changes in building operation.

Table 39: Cost-Effectiveness Analysis for Site 59

	Site 59
Annual Electricity Savings (kWh)	-5,389
Average TOU Electricity Price ($/kWh)	$0.319
Annual Natural Gas Savings (kBtu)	31000
Average Natural Gas Price ($/kBtu)	$0.0154
Total Annual Cost Savings ($/year)	-$1,242
Material Cost ($)	$3,698
Installation Cost ($)	$600
Total Measure Cost ($)	$4,298
Simple Payback (years)	No payback

Site 60 Results

This site was a deli where PCM was installed in both a drop ceiling in the back hallway and on the floor of an unconditioned mechanical room above the dining area. Higher temperature PCM (77°F) was installed above the dining room because the business owner indicated that the cooling system had trouble maintaining the set point when the room was occupied or when the weather was particularly warm. A melting point of 75°F was used in the drop ceiling. The business owner's family installed the PCM, and minimal difficulty was reported except that some areas of the mechanical room were difficult to access. As a result, less PCM than expected was installed, perhaps about 75%. Total installation time for two people was about 7 hours.

The pre-retrofit temperature profiles for the dining area during a typical summer week are shown in Figure 22. Post-retrofit summer temperature profiles are shown in Figure 23. The daily temperatures above the ceiling crossed the PCM melting point every day during hot weather, indicating that significant melting and freezing cycles occurred. The data demonstrates the uncomfortably warm temperatures of the dining room both before and after the PCM retrofit. There is no indication that comfort was improved due to the PCM, although the dining room experienced more frequent temperature fluctuations for unknown reasons, possibly continued degradation of the cooling system that has experienced ongoing performance issues according to the business owner.

Figure 22: Pre-Retrofit Summer Temperature Profiles – Site 60 Dining Room

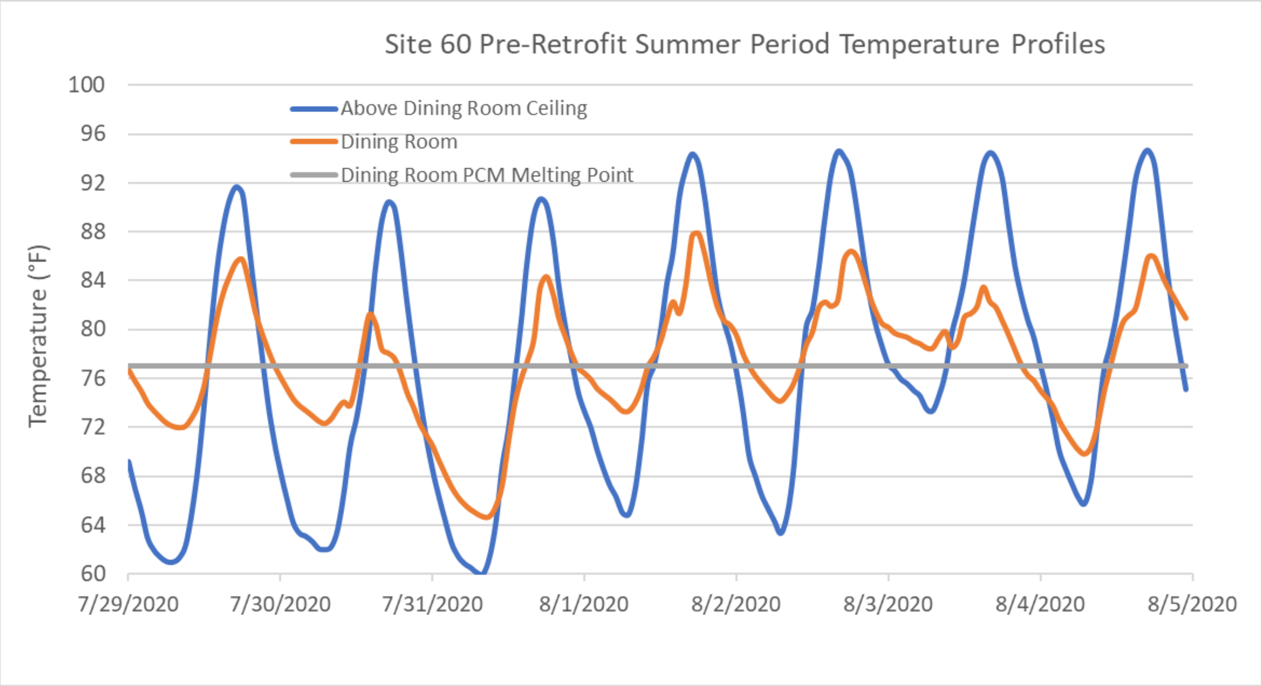
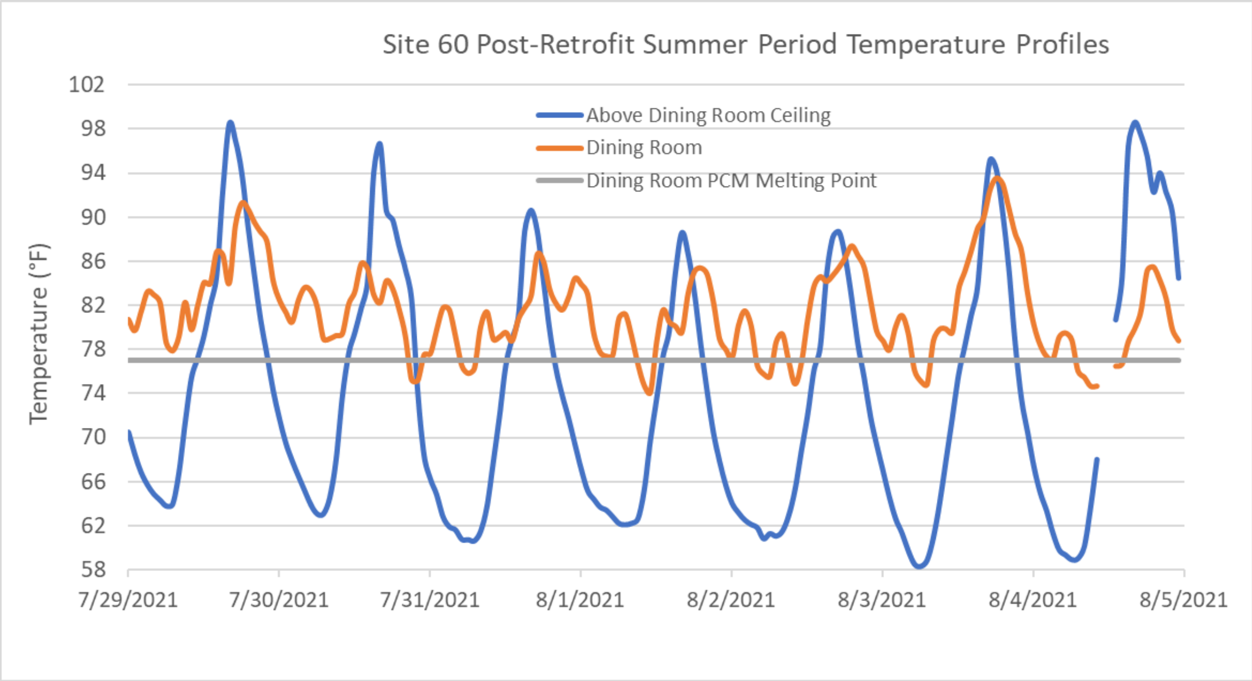


Figure 23: Post-Retrofit Summer Temperature Profiles – Site 60 Dining Room



Typical winter temperature profiles for the dining room and the space above are shown in Figure 24 and Figure 25. The temperature above the dining room ceiling generally did not reach the melting point of the PCM, so no energy savings is expected during the winter months. There is again evidence of temperature instability throughout the day, but it is almost certainly unrelated to the PCM, which would have remained frozen during both time periods.

Figure 24: Pre-Retrofit Winter Temperature Profiles – Site 60 Dining Room

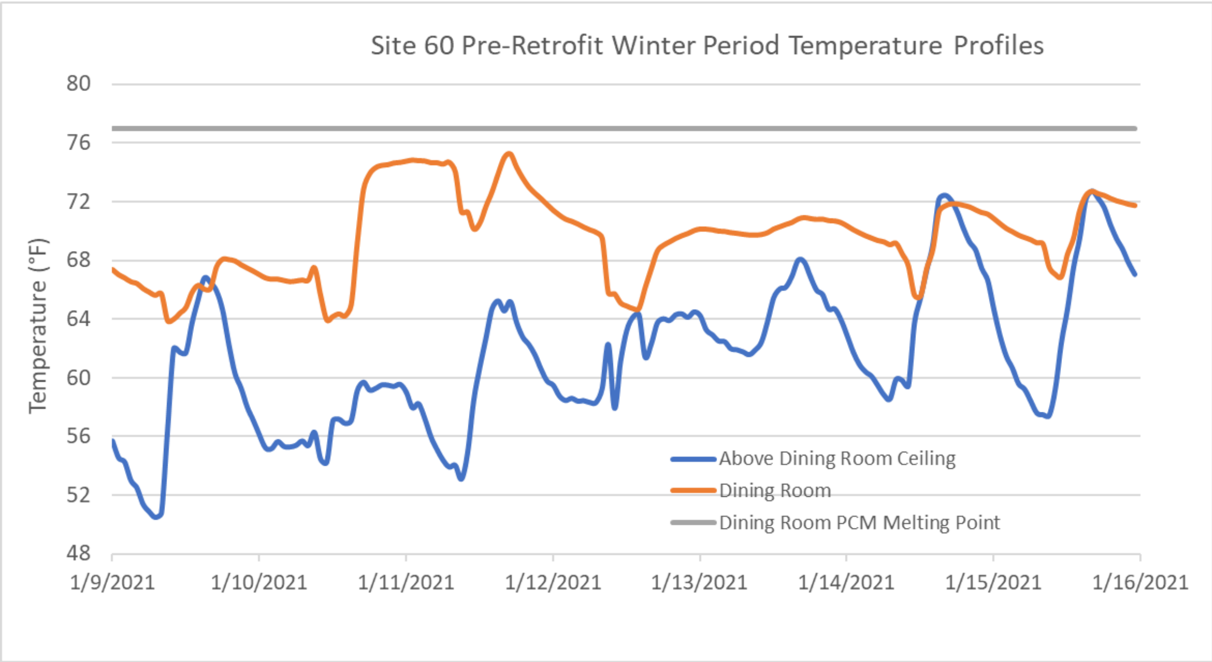
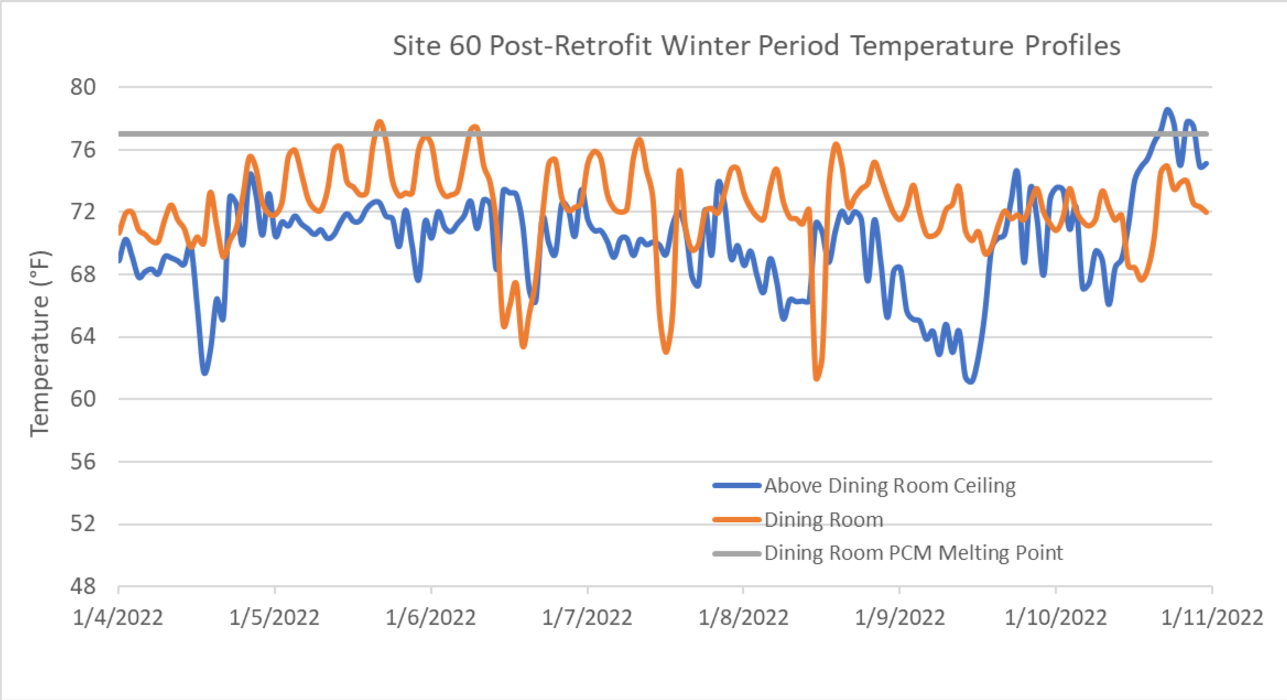


Figure 25: Post-Retrofit Winter Temperature Profiles – Site 60 Dining Room



The pre-retrofit temperatures of the office area where PCM was installed in the drop ceiling are shown in Figure 26. The temperature sensor in the drop ceiling was moved sometime during the post-retrofit period, and the readings for that period are therefore unreliable. However, it is evident that during the summer, the temperature in the drop ceiling is generally higher than the melting point of the PCM. The pre-retrofit winter temperatures in the office area are shown in Figure 27. Except for one day where the building was kept unusually warm, the drop ceiling remained below the melting point of the PCM. During swing seasons, the PCM was exposed to freezing and melting temperatures more often, but the HVAC benefits would have been lower during these periods. This illustrates the challenge of selecting melting points that are beneficial during all seasons in a drop ceiling application.

Figure 26: Pre-Retrofit Summer Temperature Profiles – Site 60 Office Area

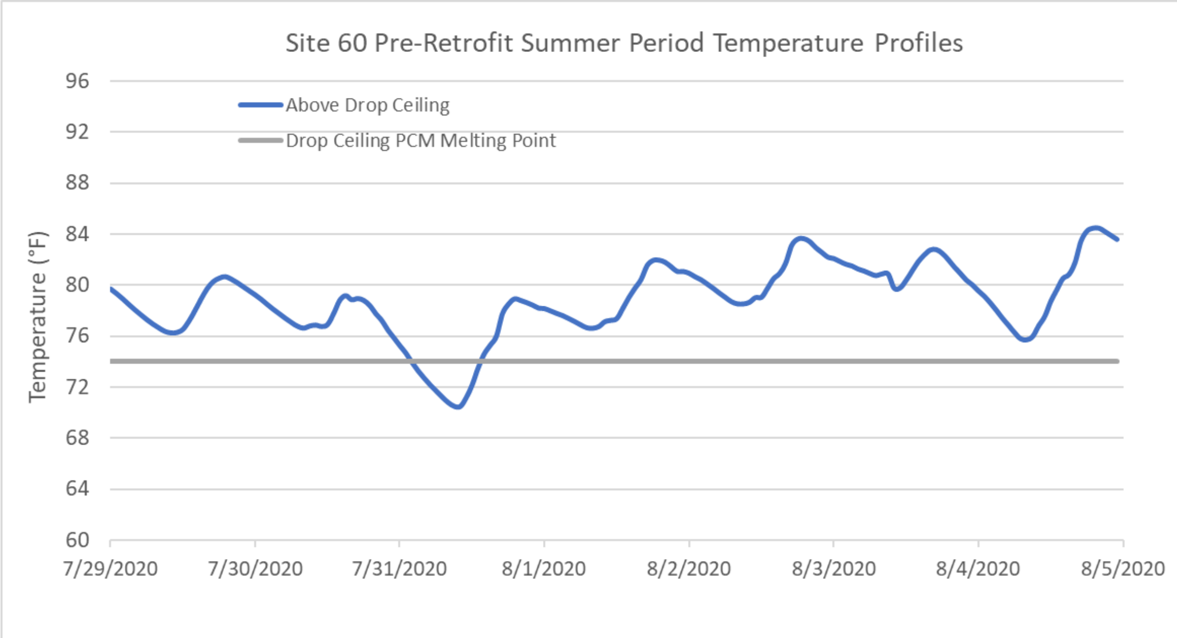
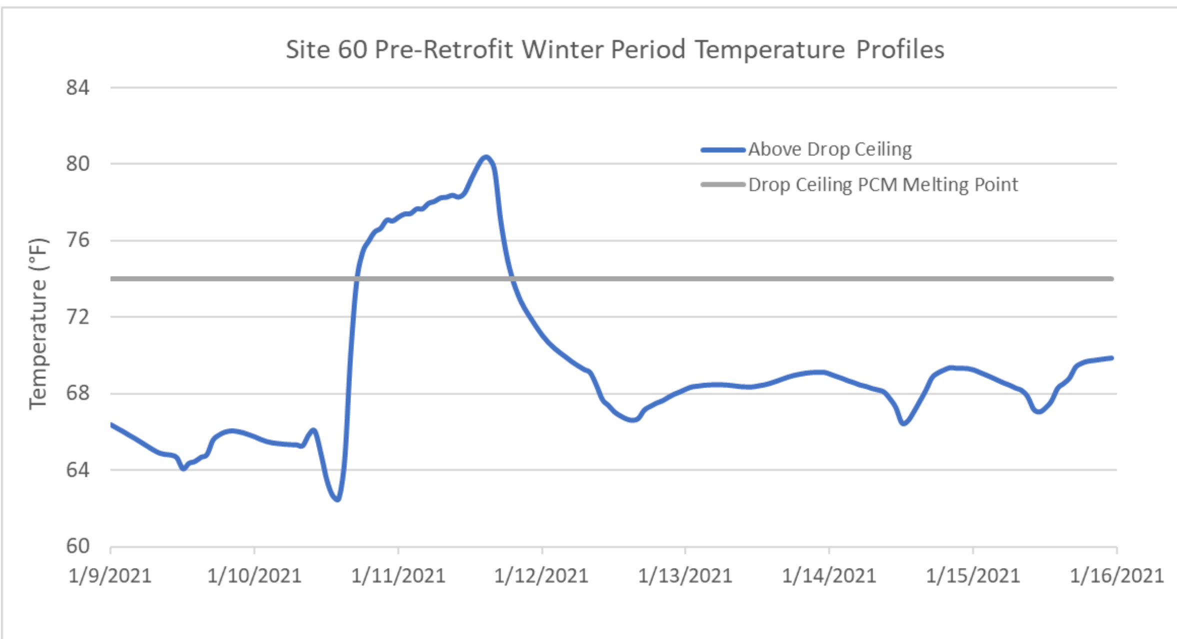


Figure 27: Pre-Retrofit Winter Temperature Profiles – Site 60 Office Area



The surveys provided by the business owner prior to the retrofit indicated that COVID-19 had a very large effect on business in 2020, and during this time period there were temporary closures, reduced hours, and relaxed heating and cooling set points. Business operations were back to normal by the time of the retrofit, except for a public safety power shutdown by PG&E in the summer of 2021. The business also shut down its walk-in refrigeration system, which could have affected electricity use post-retrofit. The surveys also indicated that the building had thermal comfort issues prior to the retrofit, and windows and ceiling fans were sometimes used for ventilation and air distribution. Following the retrofit, the summertime comfort issues remained, ceiling fan use continued, and windows were no longer used for fresh air. But the owner indicated that warm air seemed to remain longer in winter. No issues with PCM leaks or other durability issues were identified.

Energy savings for Site 60 were calculated based on weather normalized utility bills before and after the retrofit, using the procedure described in Section 2.4 with an assumed balance point of 65°F. Because the year just prior to the retrofit coincided with the outbreak of the COVID-19 pandemic, we examined savings relative to both the year before the retrofit and the year before that. This introduced some additional uncertainty in the analysis, because operational changes may have been made to the business over time, but this uncertainty was likely much smaller than the effect of COVID-19. The CVRMSE for this method was 10.3% for electricity and 14.5% for gas during the pre-retrofit period, which is better than the ASHRAE Standard 14 criteria of <20% for adequate predictive capability when less than 12 months of data is available. The results are summarized in Table 40, and indicate 2.8% savings for electricity, 28.5% savings for natural gas, and 15.9% total savings in site energy. The installation of PCM and shut down of the walk-in freezer were the only known changes to the building between the pre-COVID and post-retrofit years, but it is unlikely that the freezer had a significant impact on natural gas usage. There is always uncertainty when using utility bills to estimate energy savings because there are numerous drivers of energy use, and it is impossible to exclude other possible contributors.

Table 40: Utility Bill Analysis for Site 60

	Annual Electricity (kWh)	Annual Natural Gas (kBtu)	Total Annual Site Energy (MMBtu)
Pre-Retrofit, Pre-COVID	45,464	160,600	315.8
Pre-Retrofit, During COVID	40,663	123,500	262.2
Post-Retrofit	44,203	114,800	265.6
Savings versus Pre-COVID	**1,261**	**45,800**	**50.1**
% Savings versus Pre-COVID	**2.8%**	**28.5%**	**15.9%**

The cost-effectiveness analysis for the installation of PCM at Site 60 is shown in Table 41. Material costs were documented by Frontier. Installation costs are based on 7 hours for two people with a total rate of $200/hour. Simple payback was calculated to be 5.5 years, which was a very favorable result at this site.

Table 41: Cost-Effectiveness Analysis for Site 60

	Site 60

Annual Electricity Savings (kWh)	1,261
Average TOU Electricity Price ($/kWh)	$0.319
Annual Natural Gas Savings (kBtu)	45800
Average Natural Gas Price ($/kBtu)	$0.0154
Total Annual Cost Savings ($/year)	$1,108
Material Cost ($)	$4,680
Installation Cost ($)	$1,400
Total Measure Cost ($)	$6,080
Simple Payback (years)	5.5

Site 61 Results

Site 61 was a preschool facility with no air conditioning. The PCM was installed above drop ceilings in several areas, including classrooms, offices, and a kitchenette. A relatively high melting point (77°F) Templok product was selected in order to help manage overheating during the summer months. The installation was performed by a trained contractor hired by SCP, because the business owner was facing financial challenges due to the impacts of the COVID-19 pandemic. Temperatures and heat flux through the ceiling were monitored in the classroom and one of the offices.

The pre-retrofit summer temperature profiles in the classroom are shown in Figure 28. The drop ceiling area consistently reached temperatures above and below the melting point, and the PCM was expected to freeze and melt consistently during the summer. The lack of air conditioning resulted in large daily temperature swings. Pre-retrofit summer temperatures for the office are shown in Figure 29, and the results are very similar. Pre-retrofit winter temperatures for the classroom and office are shown in Figure 30 and Figure 31, respectively. The preschool was not yet open at this time, and the temperatures were kept between about 55°F and 65°F all day, well below the melting point of the PCM. Even with a higher thermostat setting, it was not expected that the PCM would contribute much savings during the coldest months.

Figure 28: Pre-Retrofit Summer Temperature Profiles – Site 61 Classroom

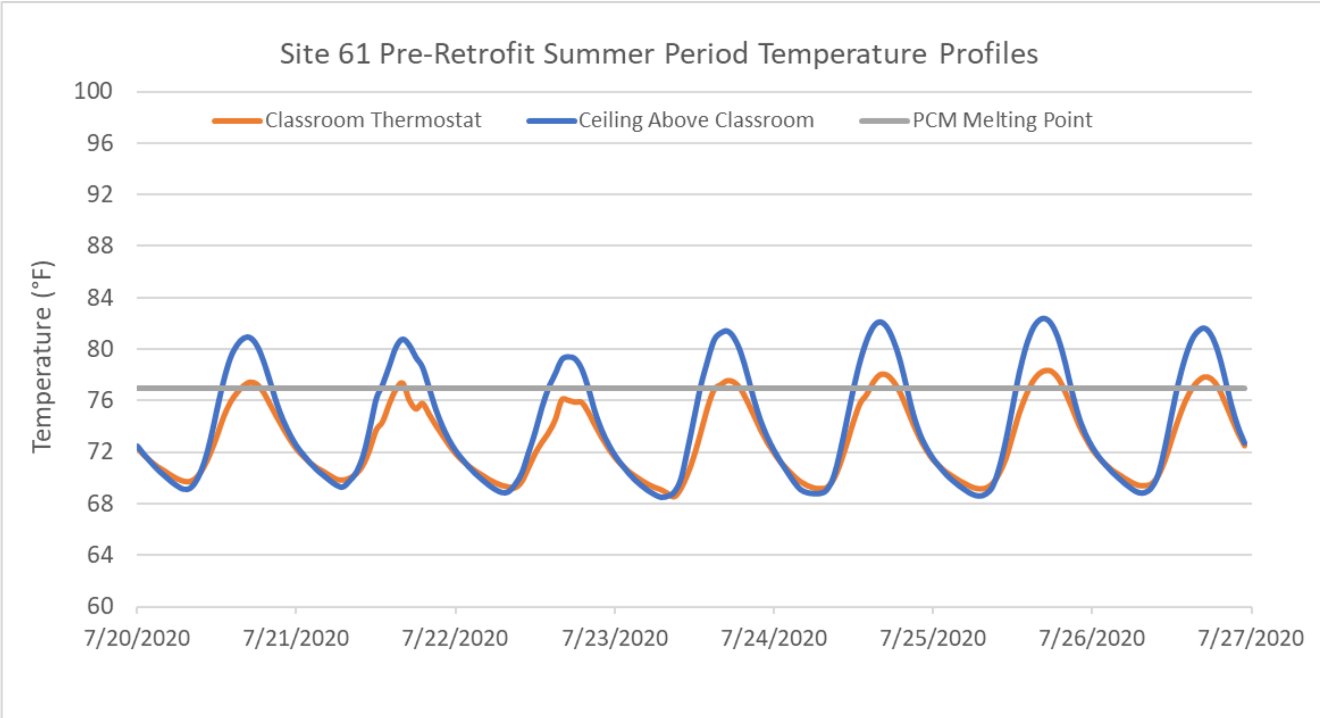


Figure 29: Pre-Retrofit Summer Temperature Profiles – Site 61 Office

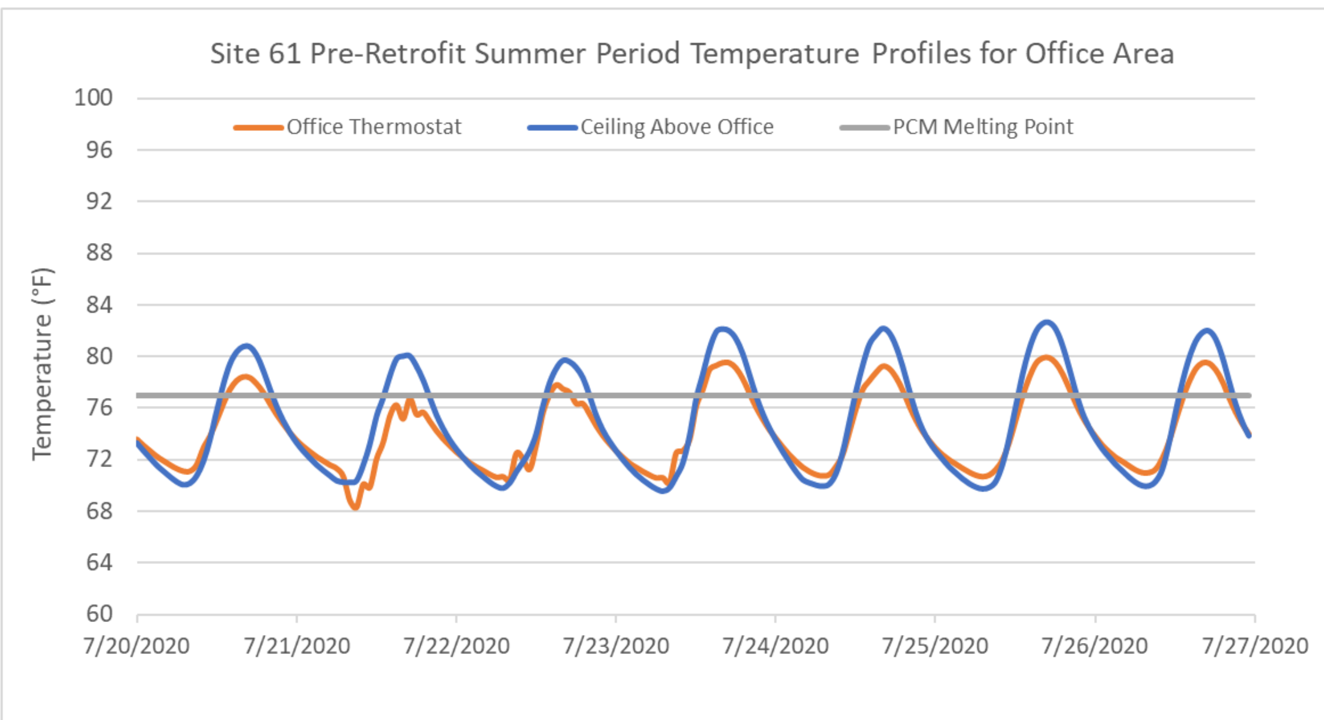


Figure 30: Pre-Retrofit Winter Temperature Profiles – Site 61 Classroom

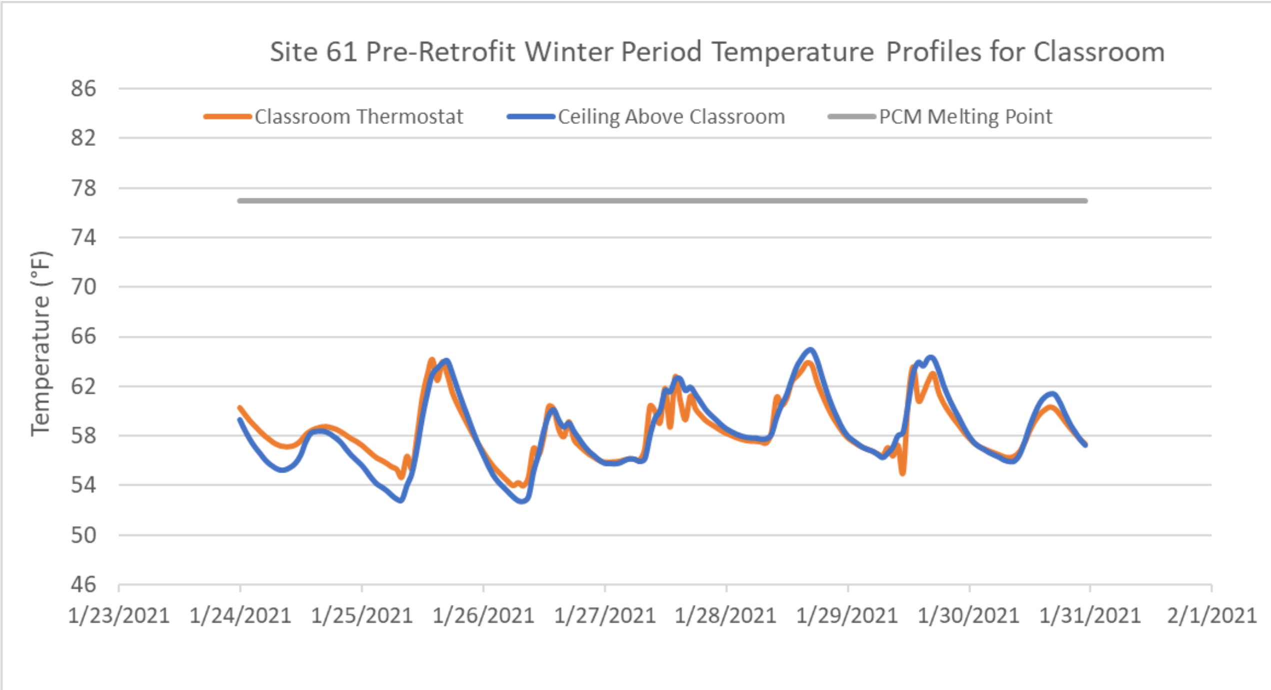
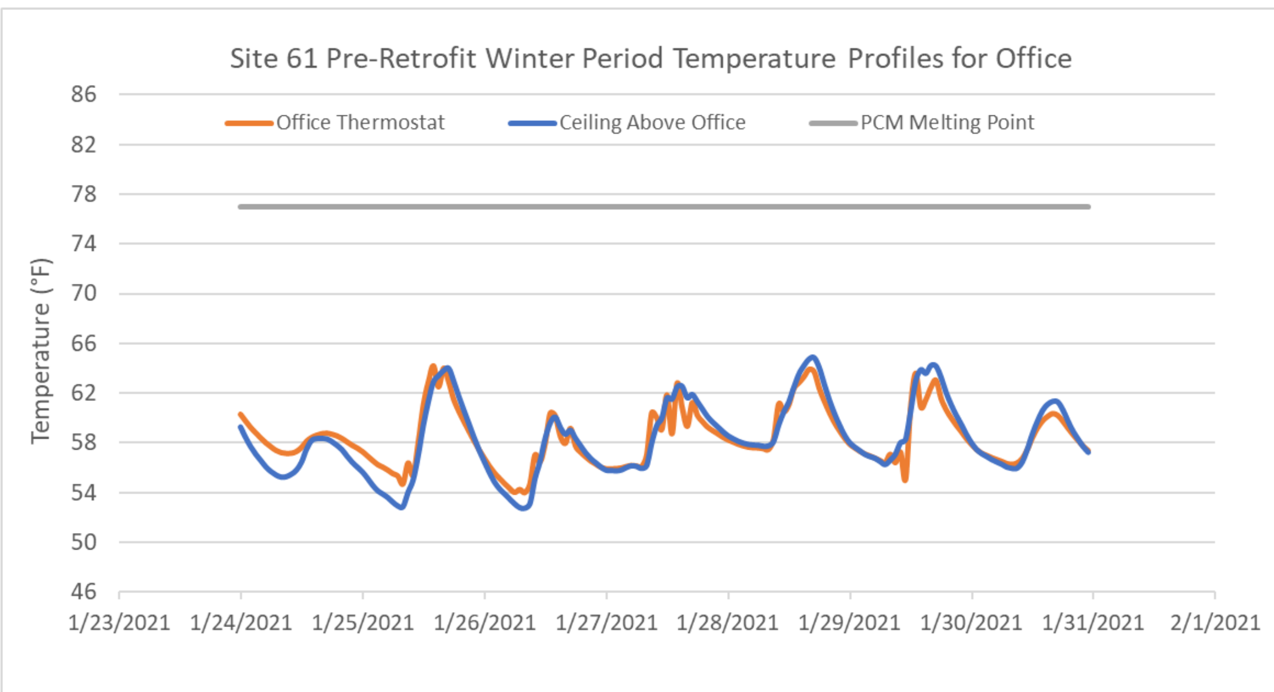


Figure 31: Pre-Retrofit Winter Temperature Profiles – Site 61 Office



A comparison of pre- and post-retrofit temperatures in the classroom during the week of July 20th are shown in Figure 32. The comparison is difficult because the weather conditions were different in 2020 versus 2021, but for days with similar temperatures it appears that the classroom remained a bit cooler, perhaps by 1-2°F. It is likely this is attributable to the PCM, but there could have been differences in internal gains as well. There is also some evidence of delayed temperature response or flattening of the curve at the warmer temperatures in the post-retrofit case, which may be caused by the PCM freezing and melting. Similar results are evident in the office, as shown in Figure 33. Winter profiles are not presented here because the changes in operation and thermostat settings would make the comparison meaningless. However, the data confirms that the preschool was operational by December 2021.

Figure 32: Summer Temperature Profiles Before and After Retrofit – Site 61 Classroom

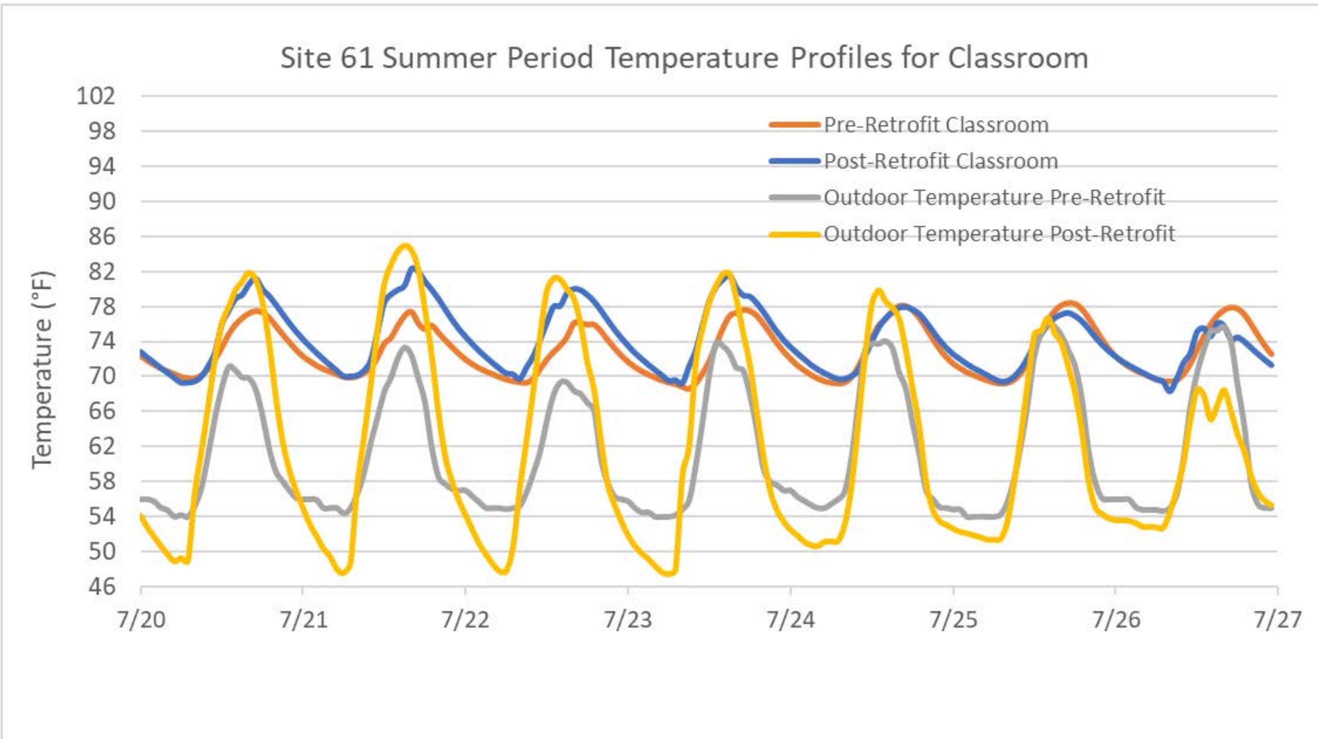
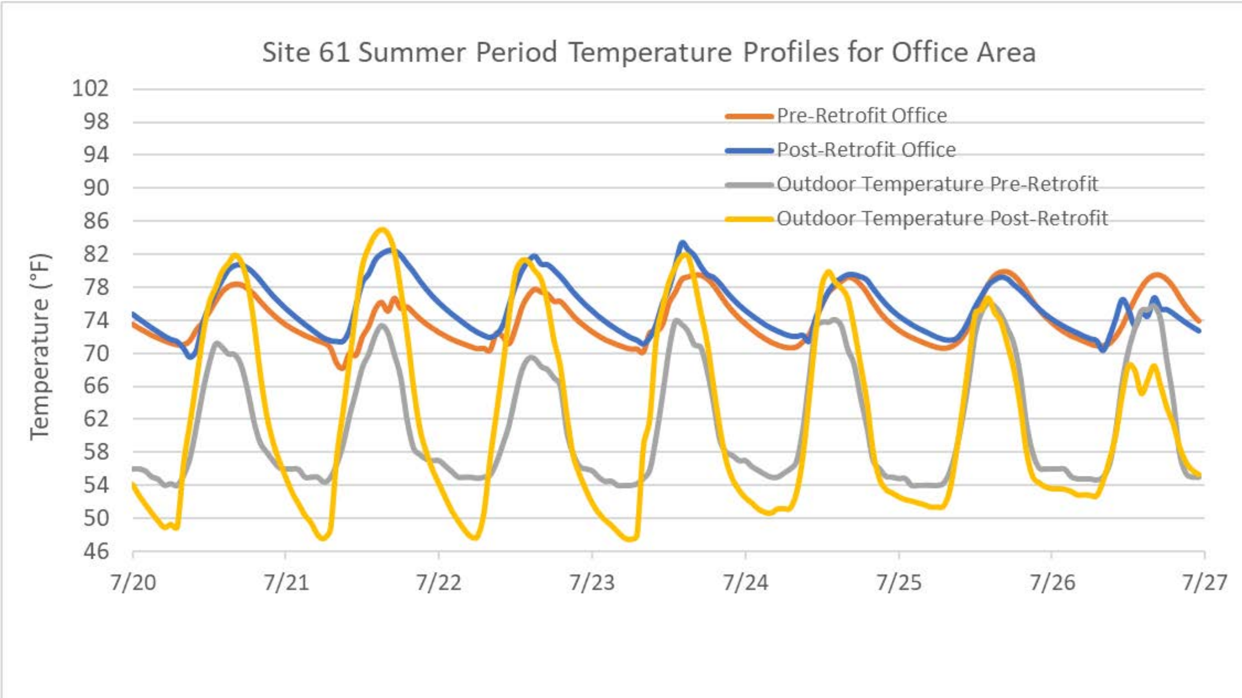


Figure 33: Summer Temperature Profiles Before and After Retrofit – Site 61 Office



Heat flux from the classroom into the drop ceiling was monitored before and after the retrofit. The results for the week of July 20 are shown in Figure 34. As expected, the heat transfer reversed direction following the PCM installation, and the melting of the PCM served to cool the classroom as it warmed up during the day. The stored energy was released back into the classroom at night when there was no need for cooling. No energy savings would be expected because there was no air conditioning, but the heat flux data provided an explanation for the lower peak temperatures in the classroom during hot summer days. There was an additional heat flux sensor installed above the ceiling in the office, but it was broken sometime during the installation and did not provide meaningful results.

Heat flux results for the classroom during the week of January 18 before and after the retrofit are shown in Figure 35. There was minimal freezing and melting of the PCM during this period, and for most of the time the heat flux is about the same before and after the retrofit considering the difference in weather conditions. However, it is evident from the temperature data that significant night-time setback of the thermostat occurred after the retrofit, resulting in large spikes in heat flux as the space warmed up or cooled down in response. There is no reason to believe that the PCM played a role in these spikes.

Figure 34: Summer Heat Flux Before and After Retrofit – Site 61 Classroom

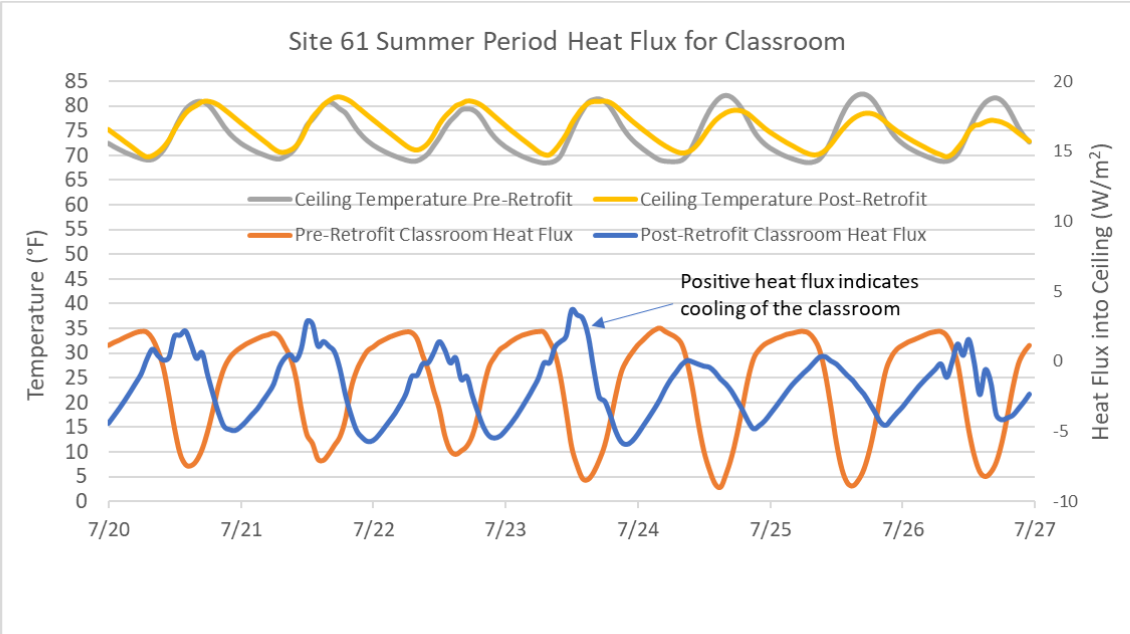
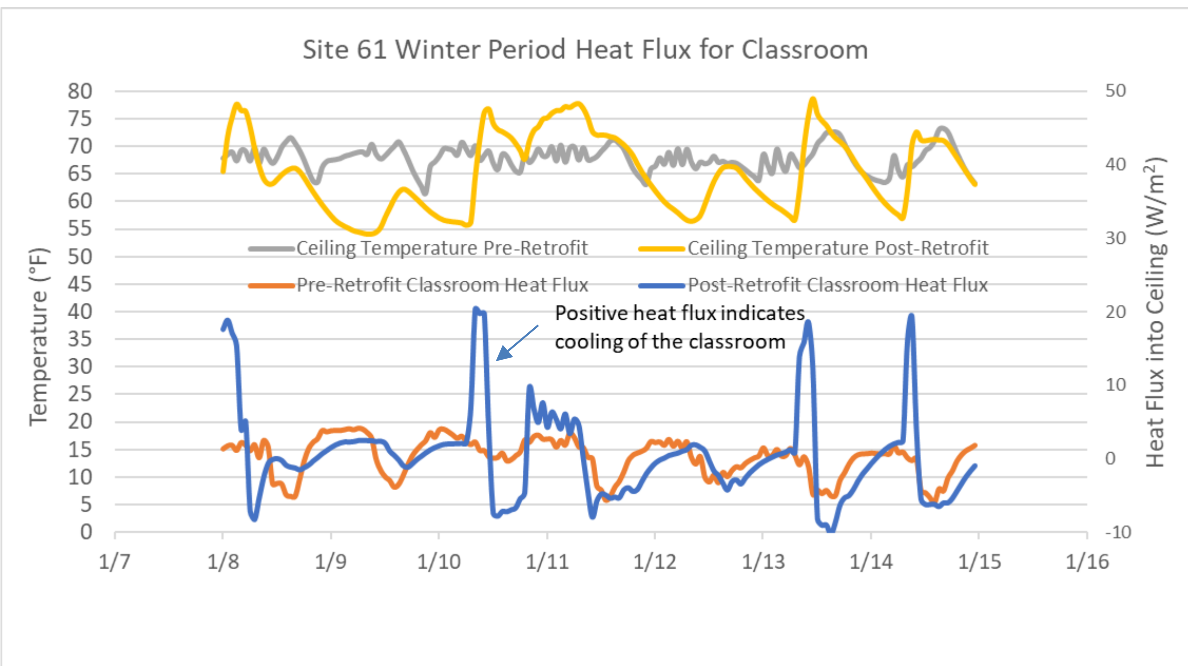


Figure 35: Winter Heat Flux Before and After Retrofit – Site 61 Classroom



Surveys provided by the business owner stated that the HVAC system was malfunctioning, and the preschool was either closed or operating at 40% capacity for much of the pre-retrofit period. There were also significant comfort issues, especially during the summer. Windows, fans, and space heaters were all used at times. The post-retrofit survey indicated that the comfort issues remained, a portable air conditioner was added, and the PCM has caused some deformation or cracking of the ceiling tiles.

Energy savings for Site 61 were calculated based on weather normalized utility bills before and after the retrofit, using the procedure described in Section 2.4 with an assumed balance point of 65°F. For this site, the year just prior to the retrofit coincided with the outbreak of the COVID-19 pandemic, and the business wasn't operational for the prior year. Neither base case provides a fair comparison, but the year immediately prior to the retrofit is probably slightly better. The results are summarized in Table 42, and indicate an increase of 17.7% for electricity, 34.4% savings for natural gas, and 0.7% total increase in site energy use. The CVRMSE for this method was 27.5% for electricity and 118.7% for gas during the pre-retrofit period, which does not meet the ASHRAE Standard 14 criteria of <20% for adequate predictive capability when less than 12 months of data is available. There is very large uncertainty in these results, and it is not recommended that these numbers be cited or used in an overall assessment of PCM in commercial buildings.

Table 42: Utility Bill Analysis for Site 61

	Annual Electricity (kWh)	Annual Natural Gas (kBtu)	Total Annual Site Energy (MMBtu)
Pre-Retrofit, Pre-COVID	7,538	13,200	38.9
Pre-Retrofit, During COVID	26,875	44,400	136.1
Post-Retrofit	31,635	29,100	137.1
Savings versus During COVID	**-4,760**	**15,300**	**-1.0**
% Savings versus During COVID	**-17.7%**	**34.4%**	**-0.7%**

The cost-effectiveness analysis for the installation of PCM at Site 61 is shown in Table 43. Material costs were documented by Frontier. Installation costs were provided by the contractor. However, due to the lack of an appropriate reference case for this site, the cost-effectiveness calculation is not reliable.

Table 43: Cost-Effectiveness Analysis for Site 61

	Site 61
Annual Electricity Savings (kWh)	-4,760
Average TOU Electricity Price ($/kWh)	$0.319
Annual Natural Gas Savings (kBtu)	15,300
Average Natural Gas Price ($/kBtu)	$0.0154
Total Annual Cost Savings ($/year)	Not reliable

Material Cost ($)	$5,463
Installation Cost ($)	$1,100
Total Measure Cost ($)	$6,563
Simple Payback (years)	Not reliable

Conclusions

A summary of the energy savings and cost-effectiveness analysis for the three test sites with reliable results is provided in Table 44. The long-term material cost for Site 57 was assumed to be about 60% of the actual cost, and Site 59 was assumed to be 70% of the actual cost, based on the amount of PCM that was left over after installation. The actual material costs for Site 60 seemed realistic, but the installation time was cut in half to better align with other sites and to reflect the unique installation challenges at that site. The results indicate that for sites similar to those selected for this demonstration project, the technology leads to an average of 8.9% whole-building energy savings and a simple payback period of 20 years assuming a mature market.

Table 44: Energy and Cost Savings Summary for PCM in Commercial Buildings

	Site 57	Site 59	Site 60	**Average**
Actual cost of measure (equipment + installation)	$5,863	$4,298	$6,080	**$5,414**
Projected long-term cost of measure (equipment + installation)	$3,758	$3,189	$5,380	**$4,109**
Annual electricity savings (Site kWh)	811	-5,389	1,261	**-1,106**
Annual gas savings (Site kBtu)	31,500	31,000	45,800	**36,100**
Annual Energy savings (Site MMBtu)	34.3	12.6	50.1	**32.3**
% energy savings (whole building)	9.2%	1.5%	15.9%	**8.9%**
Annual TOU utility bill savings ($)	$744	-$1,242	$1,108	**$203**
Simple payback (years) (actual)	7.9	No Payback	5.5	**26.6**
Simple payback (years) (projected long-term)	N/A	N/A	N/A	**20.2**

There are several important conclusions and lessons learned from this project that could be valuable for utility programs, researchers, PCM manufacturers, building owners, and other stakeholders:

- There appears to be significant energy savings for PCM installed in drop ceilings, especially if the melting point is properly aligned with the temperature of the ceiling during the cooling months.
- Comfort improved in certain cases according to the business owners, but it was only quantifiable when there was no air conditioning.
- The Templok product appears to be durable based on observations over a year after the retrofit.
- The weight of the product caused a number of concerns with business owners prior to installation, and in one case it appears that some of the ceiling tiles have cracked or deformed due to the weight. Further documentation of the structural analysis performed by the vendor would be helpful, along with additional guidance on installation best practices.
- COVID-19 created several challenges for the project, affecting site recruitment and reliable calculation of pre-retrofit energy usage.
- The installation process seemed to be quick and efficient for most business owners and contractors.
- There was a large amount of leftover material at nearly every site, mainly because some of the areas targeted for PCM were not as safely accessible as they seemed to be during the site visit.
- Lab testing of the technology would be helpful for determining optimal temperatures and actual energy savings under controlled conditions. This project and most of the published information is based on case studies that may or may not be representative of all applications and climate zones.

Based on the results of this study, the Templok technology seems very promising for further deployment in the right applications. Incentives may be necessary to ensure cost-effectiveness for business owners.

3.7: Nighttime Ventilation

Introduction

High-Level Description of Technology and its Applications

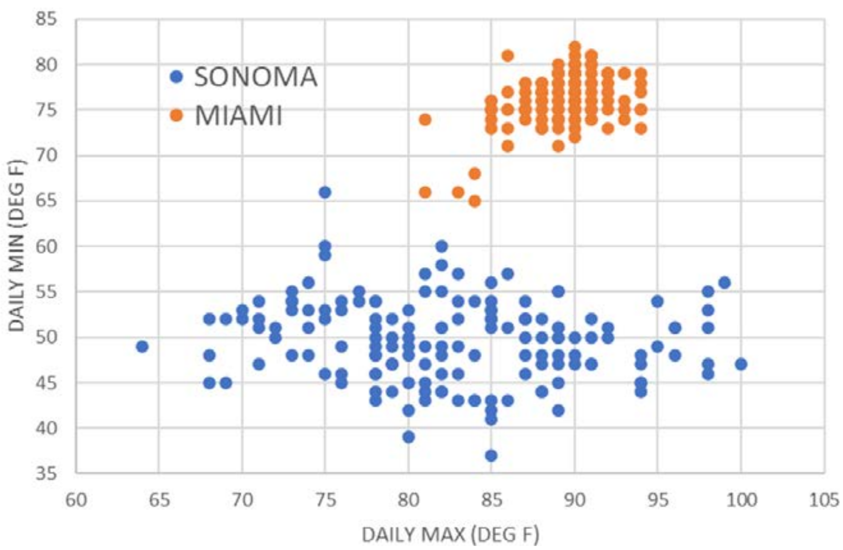
Residential Nighttime Ventilation (NTV) cooling has demonstrated benefits for reducing energy used in residential cooling, achieved by flushing the home with cool outdoor air at night, to reduce indoor air temperatures throughout the day, and delay the time the air conditioner (AC) has to start working, or even eliminate the need for compressor-based cooling altogether on suitable days.

The benefit is realized even for homes that do not have central AC. In these homes, adding NTV will actually increase energy use (by running central fans to provide ventilation). However, it will provide significant benefits by providing improved thermal comfort—eliminating or reducing the number of days when the indoor temperatures become uncomfortably hot. And despite this increase in energy consumption, it is considered an energy conservation measure, because many homeowners without AC contemplate adding it, so improving thermal comfort in these homes may prevent the installation of new central AC systems, which would come at a very steep energy cost.

This project adapts NTV technology to provide improved thermal comfort in homes without central AC. It adds an outdoor air duct and damper to existing ductwork and fans present in a central heating system. Allowing occupants to stay cool without AC using controls that automatically turn on the existing furnace fan to bring in cool nighttime air during the summer to precool the home. Anytime it's hot inside but cooler outside (typically at night or in the morning), the fan will run. If it becomes uncomfortably cool inside the NTV system turns the fan off. Once it becomes hotter outside than in, the system cannot provide any additional benefit and the fan turns off. Depending on the weather conditions and the quality of the air sealing and insulation of the building envelope, the overnight cooling may last throughout the day and keep the occupants reasonably comfortable.

NTV cooling is well suited to the climate in the Sonoma region. Figure 36 illustrates the summer temperatures in the region: some high daytime maximum temperatures, but consistently low nighttime temperatures. This is contrasted with a region such as Miami, which has less extreme high dry-bulb temperatures, but does not have the necessary nighttime low temperatures (it also has excessively humid air at night, with high wet-bulb temperatures).

Figure 36: Summer Daytime High Dry-Bulb Temperatures Versus Nighttime Low Temperatures in Two Climate Zones.



Technology benefits include:

- Provides some amount of cooling and improved thermal comfort for homes that do not have AC. Allows homes to add amenity while avoiding the threat of increasing utility loads caused by adding AC.
- Provides an alternative to whole house fans. Allows air filtration—important in areas such as Sonoma County, with frequent wildfire smoke problems.
- Provides an alternative to window air-conditioning units. More efficient, provides ventilation air and flushing of indoor contaminants, provides comfort throughout the home and not in just one room.

Problem Statement

The research questions addressed were:

- Can NTV reduce the rate of installation of AC in Sonoma County climates?
- How acceptable is it as a replacement for AC?
- What is the energy penalty and life-cycle cost compared with baseline and with hypothetical scenario with AC installed?
- What are the training requirements and what installation problems should be anticipated?

Technology uncertainties at the beginning of the study included:

- Finding homes that could be at risk of adding air conditioning without some improvement in thermal comfort.
- How often comfort can be ensured the next day.
- Typical existing fan/duct sizes compared with required air exchange overnight.
- Not known if home can get by using lower heating air-flow rates.
- Use of existing forced air unit (FAU) blower fan and motor: These are not optimized for efficiency, and their energy use in this application has not been well studied.
- Unknown whether "off the shelf" components will be appropriate or if there is additional configuration that is needed to test the technology.

Methodology

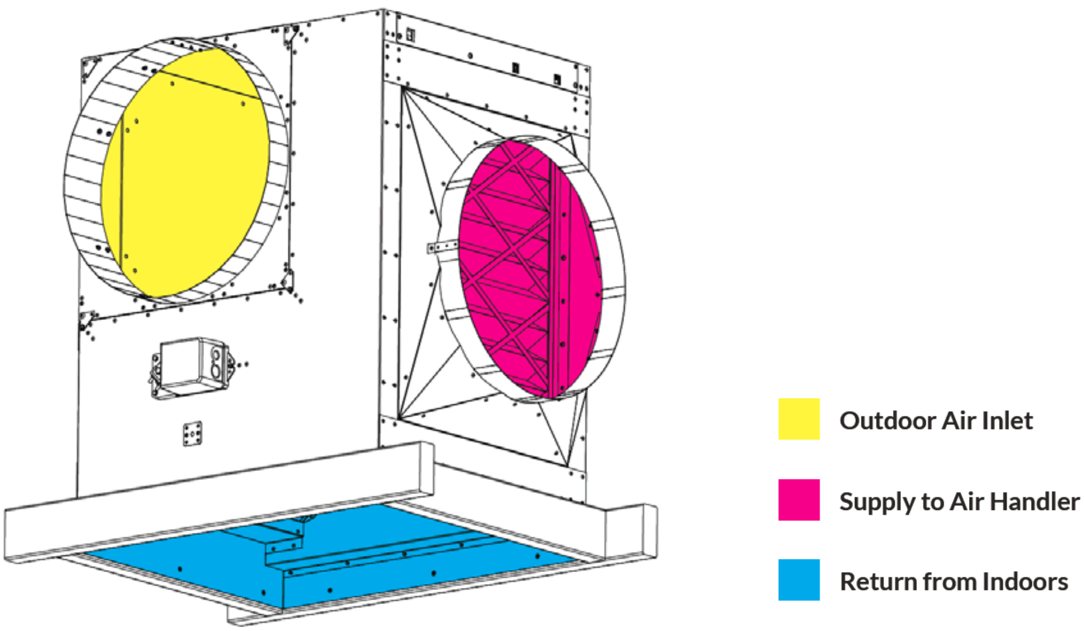
Detailed Description of Measure

The NTV technology investigated in this study consists of a damper assembly and control system retrofitted to bring outside air into the return plenum of a pre-existing ducted central heating system located in an attic. Specifically, each NTV system includes:

- Economizer box, provided by AirScape (https://airscapefans.com/products/residential-economizer). Figure 37 shows the configuration of the box. It includes a damper, actuator, and a control board that controls the operation of the damper and overrides the thermostat's operation of the fan when appropriate.
- Outdoor air temperature sensor, provided with the economizer box, to help determine when it is cool enough outside to bring in outside air.

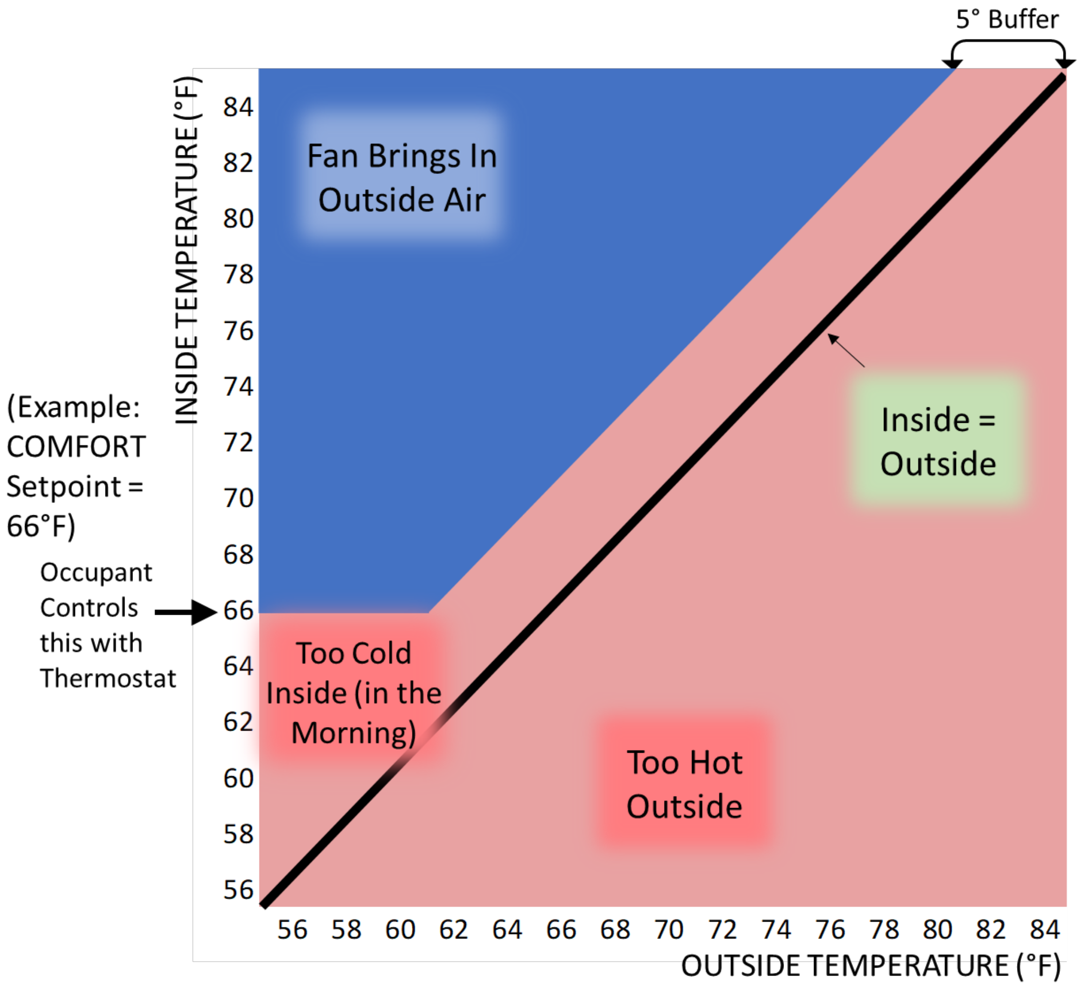
- Outdoor air duct, provided by contractor.
- Outdoor air vent, located either in the roof or gable wall, added by contractor.
- Installation of the box between the existing return grille and FAU return plenum.
- Connection to existing thermostat, to control the operation of the fan.
- Additional wiring to adapt the economizer box for operation in a home without AC, rather than a home with AC—which is the standard application of the box.

Figure 37: Configuration of AirScape Economizer Box. This box includes a damper (not shown), which determines whether the fan will supply outside air or return air.



During winter, the outside air damper is always closed, and the thermostat controls the forced-air unit as usual, turning on the fan whenever there is a call for heating. Figure 38 illustrates how the NTV system is controlled during the summer. The fan will be turned on and the damper opened so long as it is too hot inside (the indoor air temperature is greater than the thermostat's cooling setpoint) and it is not too hot outside (the outdoor air temperature is at least five degrees below the indoor air temperature). The five-degree buffer is selectable using a dip-switch on the economizer box controller, and is used to ensure that the system does not cycle open and closed too frequently. If there is no call for cooling or the outdoor temperature is higher than the indoor temperature, the fan is turned off and the outdoor air damper is closed. The thermostat is put in COOL mode, with the fan mode set on AUTO, and it is typically programmed with a "Pre-Cooling" setpoint of about 65-70°F from bedtime until noon, and a "Comfort" setpoint of about 75-80°F from noon until bedtime.

Figure 38: Illustration of Control of NTV System.



During cooling season, whenever indoor and outdoor air conditions are in the “pink” zone, the fan is off, and the outside air damper is closed. Whenever they are in the “blue” zone, the damper opens, and the fan turns on.

Figure 39 shows that as designed by the manufacturer, the economizer controller rather than the thermostat is expected to control the compressor. The thermostat tells the economizer that there is a call for cooling, and the economizer uses the outdoor air sensor to determine whether to pass this call on to the compressor or just open the outdoor air damper and allow the blower to be activated. If this wiring were used in a home without AC, however, it would cause the fan to operate anytime there was a call for cooling, although when it is too hot outside to bring in outside air, the fan should turn off. To get around this problem, the research team devised a workaround that included installation of two relays to control the fan appropriately. Figure 40 shows the wiring diagram required for this adaptation of the economizer installation.

Figure 39: Wiring Diagram Provided with AirScape Economizer Box, for Use with an Air Conditioner

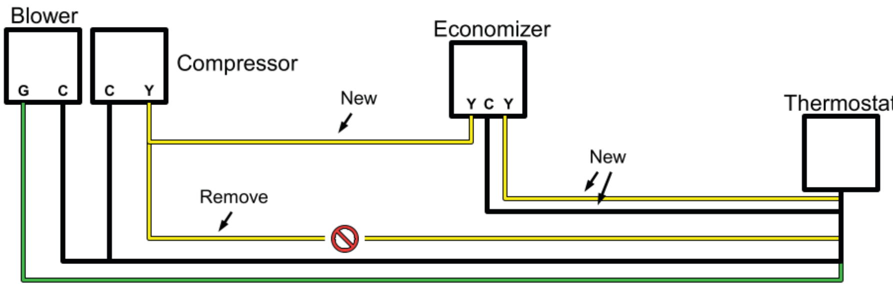
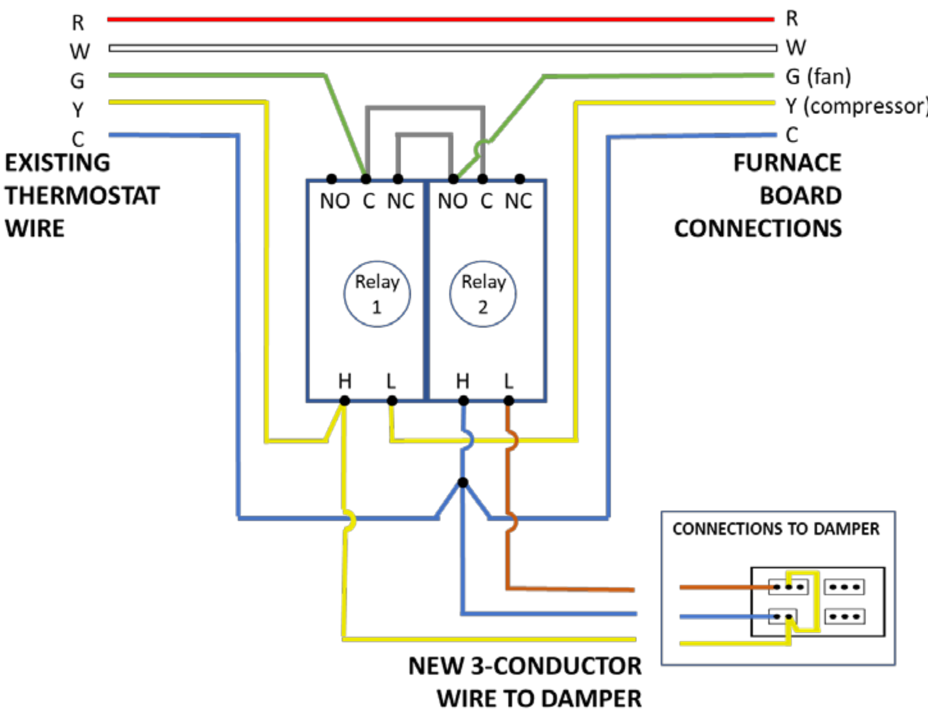


Figure 40: Wiring Diagram Used for NTV, for Use in Homes Without AC



One of the economizer boxes was installed in the laboratory and connected to a fan, in order to ensure that the system behaved as expected during all operating modes. It worked as expected with a range of filtration ratings, total external static pressures, and airflow rates.

Field Testing

To confirm the operation of the NTV system, assess its energy impacts, and gauge the response of occupants to the system, NTV systems were installed in ten homes within the SCP service territory. They were installed by a local HVAC contractor, working closely with program technicians to obtain training on system installation. The program technician also installed instrumentation and monitoring systems to measure the energy used by the forced-air unit's fan, which is the only energy consumed by the NTV system (aside from the damper motor and actuator). To complete the analysis, small temperature sensor/dataloggers (HOBOs) were used to assess interior temperatures before and after the retrofit, and surveys were conducted with the occupants before and after the retrofit.

Site Selection

Recruitment for this demonstration was integrated with recruitment for a number of technology demonstrations, described elsewhere in this report. The field test was targeted to recruit approximately ten sites. The initial criteria for inclusion in the field study included:

- Volunteer:
  - Volunteer for Heating & Cooling
  - Volunteer for Insulation & Air Sealing
- Occupancy:
  - Single Family
  - Occupied
  - Owned by current residents
  - Occupants will remain for 2 years
  - Full time residence
  - Owner enthusiastic about study
- HVAC:
  - No Central Cooling
  - No plan to install Central Cooling
  - Working Central Heating
- Field Study Considerations:
  - Realistic Owner Expectations
  - No Practical Installation Barriers
  - Safe Work Environment
  - No Asbestos
  - No HVAC Asbestos Ducts
  - No Renovation Plans in the next 2 years
  - Less than 2000 sqft of conditioned space

54 of the 210 sites included in the program recruitment met these criteria. Other considerations included:

- Duct sizing
- Maximum airflow through FAU
- Location of system in attic
- Layout of system (including location of return) and space available for added components
- Overall condition of system (e.g., duct leakage, blower fan capacity)
- Envelope airtightness (can it be brought to adequate levels of leakage to maintain comfort during the warmest periods following pre-cooling?)

Site visits were conducted to assess the applicability of the installation. The sites visited were assessed for the ability to install a roof or gable vent, the presence of only a single return duct, the availability of power in the attic, the lack of expected need to do drywall alterations, and the absence of any other complications. Ten sites were selected by using a weighted assessment of these criteria, and homeowners were invited to participate and asked to sign participation agreements.

Methods of Calculating Energy Savings

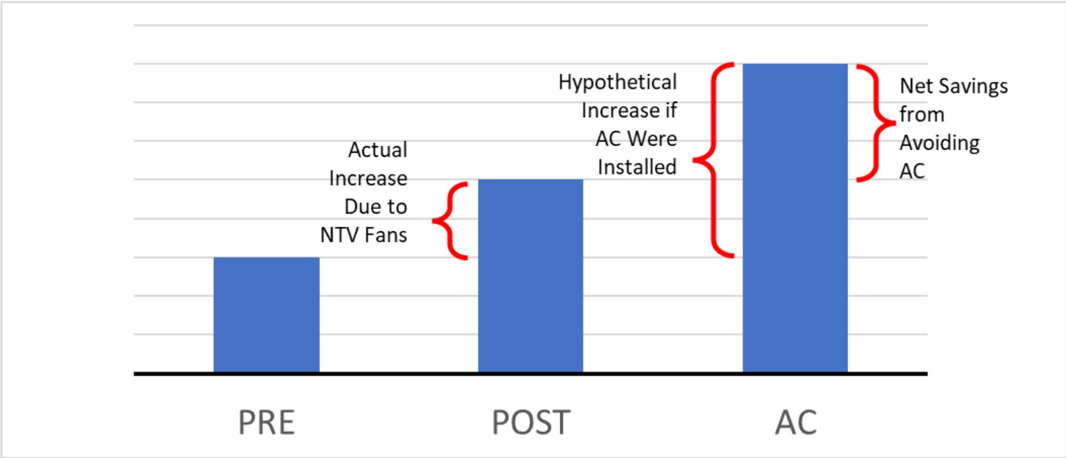
Overall Savings Analysis Approach

The overall approach to savings analysis is summarized in Table 45 and Figure 41. Since the desired outcome of the retrofit was to avoid a hypothetical installation of an AC, the baseline to which the post-retrofit performance should be compared is conceptually complex. In this report, we estimate the difference between the PRE and POST conditions, to determine the actual increase in energy use due to retrofit, in summer and potentially in winter. The most important comparison, however, is between the hypothetical consumption with an added central AC and the post-retrofit condition—AC and POST. This is referred to as the net savings.

Table 45: Scenarios Used in Savings Analysis

Scenario	Cooling Solution	Winter Whole Home	Summer Cooling
PRE (Baseline #1)	Actual pre-retrofit condition: neither AC nor NTV	Utility gas bills before retrofit, normalized to post-retrofit weather.	Assumed cooling energy use = 0.
POST	Actual post-retrofit condition: NTV	Utility gas bills after retrofit.	Regression of measured fan energy against actual temperature, applied to typical year weather.
AC (Baseline #2)	Hypothetical: Central AC Added	*Not evaluated.*	Modeled AC energy use for a typical home / typical year weather.
Net Savings		Difference between PRE and POST indicates any winter penalty for NTV.	Difference between AC and POST.

Figure 41: Illustration of Net Impacts of Actually Adding NTV and Hypothetically Adding AC



Utility Bills

Analysis of utility bills was done to detect any increases in winter consumption due to the presence of the NTV system (for example, due to possible admission of too much outside air caused by leaks in the damper assembly or outside air ducts), and the expected increase in energy use due to the addition of fan operation during the summer. (Since the AC scenario was hypothetical, there were no corresponding utility bills to analyze). Since the PRE condition had no energy use for HVAC, it was not necessary to weather normalize the summer electrical use. Gas use (proxy for heating impacts) however was normalized by determining the heating degree difference each hour during the PRE and POST periods and summing them over the year. This was done using a base-temperature selected for each home (the base-temperature that resulted in intercept = 0 when pre-retrofit hourly energy was regressed against the hourly difference between the actual temperature and the candidate base-temperature—if greater than 0). Utility bills and weather data were available from May 2018 through April 2022.

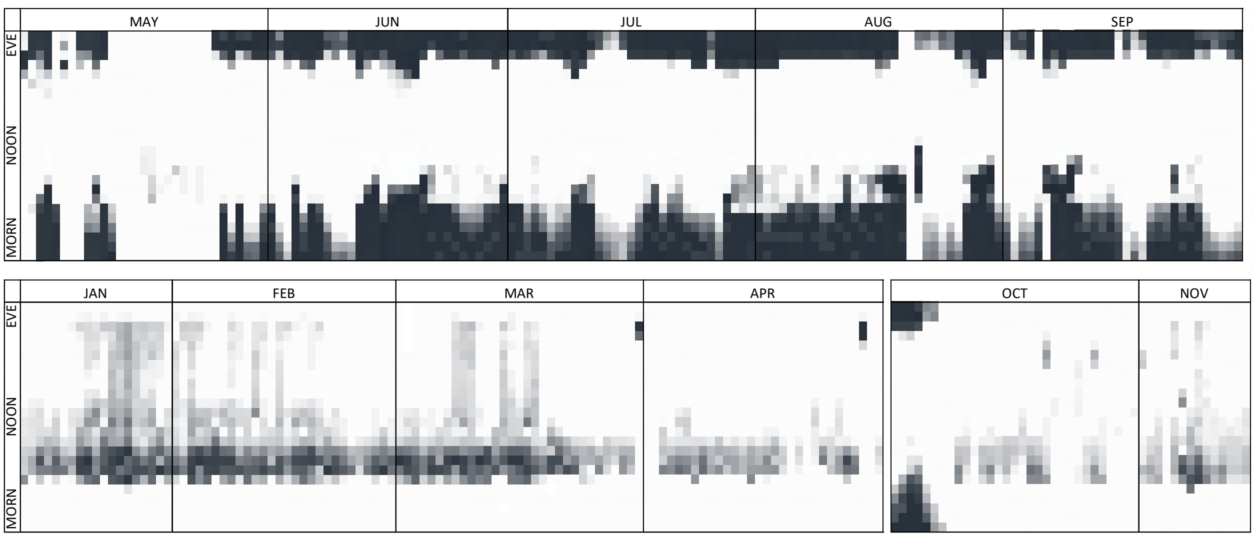
Measured NTV Fan Energy Use

The primary data used for analysis was site-monitored furnace air-handler unit (FAU) fan energy use. The monitoring consisted of installation of current transformers to monitor the power of the FAU fan and voltage measurement. These were connected to a Wattnode watt-hour transducer mounted inside an instrument enclosure mounted near the FAU in the attic. Also in this enclosure was a Raspberry Pi based datalogger that collected data from the Wattnode using Modbus. The data logger system pushed data it collected through an internet connection directly to the Frontier Energy secure FTP server every hour, via a cellular modem. Once collected, the 5-second interval data were cleaned, archived, and reviewed periodically.

These energy data were merged with outdoor air temperature data obtained from a weather service (gladstonefamily.net). Five-minute data were logged from a weather station selected for each site, with a secondary weather station used to fill any gaps in data from the primary station. The data from these two sources were merged and aggregated to provide hourly data for analysis.

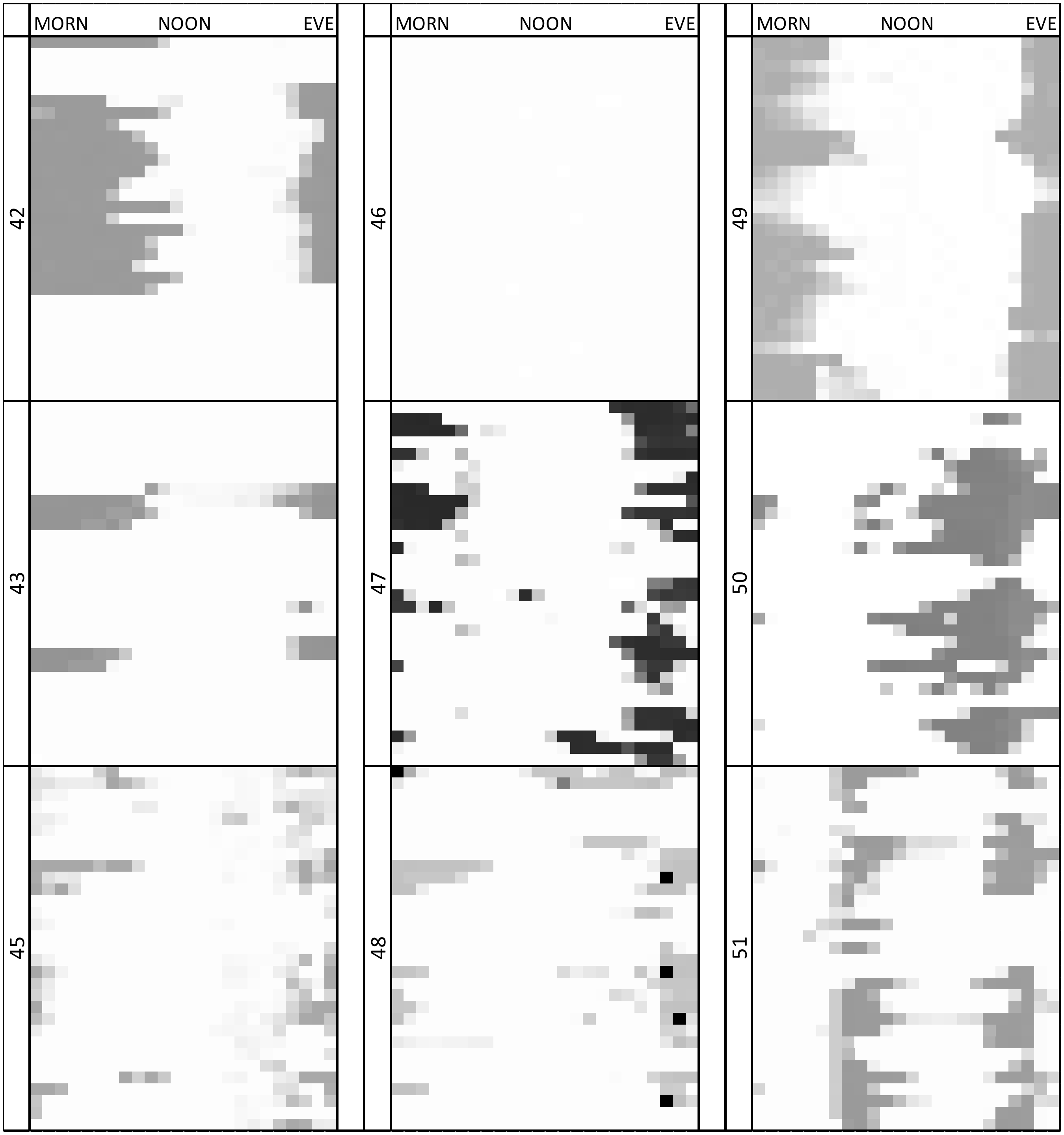
Analysis of post-retrofit measured fan energy use from 2021 revealed that it was difficult to differentiate between fan operation for heating and NTV. But the daily variations, illustrated in Figure 42, had quite a different pattern during the summer compared to the winter seasons. This Figure illustrates this pattern at one test site, showing each hour's fan energy (white = 0, black = maximum kWh for year, gray = something in between) as a small square. Every day of the year is shown horizontally, and every hour of the day is shown vertically. During the summer, NTV fan use occurred at night and into the next morning, while heating use typically occurred mostly in the late morning and early evening hours. By visually differentiating the energy use patterns over the year, it was possible to identify that cooling appeared to be occurring generally from May through September, but generally not from January through April or October through November. This was consistent across all sites. All the fan energy in May-September was assumed to be for NTV, and all fan energy for October – April was assumed to be for heating, and therefore neglected. For all of the analysis that follows, it is assumed that the cooling season was May through September.

Figure 42: Patterns of Fan Energy Use in Summer and Winter (Site 49)



This same graphical analysis was useful to detect the specific patterns of NTV use at different sites. Figure 43 illustrates the patterns at all sites for which data were available, for one specific post-retrofit month: July 2021 (the chart format is similar to Figure 42, but rotated). Some sites (e.g., 42 and 49) show that the fan was used from late in the evening thru mid-morning of the next day. Other sites (e.g., 50 and 51) show that the fan use was concentrated in the evening and morning but did not run all night. The fan did not run at all at site 46.

Figure 43: Fan Energy Use Patterns at Different Sites (July 2021)



Because of the dynamic nature of this measure (high hourly outdoor temperatures in the afternoon do not correspond to times of high fan energy use), it didn't make sense to create an hourly regression. The energy consumption of the home in the evening and following morning reflect the temperature earlier in the day. Therefore, a daily correlation was used. Some of the factors considered were:

- The daily energy use is expected to correlate more closely with the maximum temperature of the day than the average temperature.
- The energy use is expected to correlate more closely with the previous day's temperature than the current day's temperature.
- The energy use in the evening and next morning are expected to correlate more closely with the first day's peak temperature than a midnight-to-midnight day.

Daily temperature correlations were applied to Typical Meteorological Year (TMY3) weather data, to estimate the following day's fan energy use for NTV from May 1 – September 30 (at all other times, daily energy use was assumed to be zero).

In order to estimate cost savings with time-varying rates, the daily energy use resulting from this model had to be distributed over the hours of the day. The first step in doing this was to calculate the number of hours per day that a fan of a given wattage (estimated from measurements) would have to run to account for the daily energy use. The most common pattern (see Figure 42) was for the fan to start in the evening and then continue until sometime in the morning. The average number of operating hours was calculated for each site for each day: counting it as "operating" if the hourly energy use was above 8 Wh. The number of morning hours (before 4 pm) and evening hours were also calculated. From this, it was determined that on average 57% of operating hours were in the morning (midnight to 4pm), and 43% in the evening (4pm to midnight).

An hourly schedule could be manufactured from these statistics. The number of daily operating hours to use in our manufactured schedule was determined from the daily kWh (calculated from applying the correlation coefficients to the TMY outdoor air temperature), assuming that on average the fan used about 300 Wh/hour. The number of operating hours from midnight until 4 pm was 57% of this value, and the number of operating hours from 4 pm to midnight was 43% of this value.

Energy use during each operating hour was the total daily energy use divided by the number of assumed operating hours (to address any rounding errors). An 8760-hour profile of NTV hourly fan energy was manufactured from this analysis. This was added to the hourly baseload energy resulting from a whole building simulation to come up with a whole-home energy use hourly profile for the NTV scenario.

Building Simulation

To estimate the energy saved by using NTV instead of central AC, a typical small home was modeled in EnergyPlus. This prototype was a 1960's vintage home, with an unfinished attic, uninsulated walls and uninsulated slab on grade construction, R13 insulation in the vented attic, 2 bedrooms, 20% duct leakage, and envelope leakage of 15 ACH50. It had a central heating system with gas furnace and the AC was a SEER 13 unit. The heating setpoint was 65˚F and the cooling setpoint varied by hour (taken from Title 24 modeling software: varying from 78°F to 83°F). The house was simulated using TMY3 weather data from Santa Rosa. The output of this simulation resulted in an hourly estimation of baseload (non-HVAC) energy use for the home, and total heating electricity and cooling electricity (for the model with AC). Note that the simulation was only used to model the cooling load, and the simulated heating and baseload were not used. The POST scenario used the same hourly estimation of baseload energy use, along with the NTV fan energy use derived from the daily temperature correlation described above.

Cost and Cost Effectiveness

Technology Costs

The costs for this technology were estimated to average approximately $1,400 (ranging from $1000 to $1800) for installation, and $750 for materials. Actual costs will be discussed later in the Results and Analysis section.

Modeled Energy Bill Impacts

A rates calculator was used to estimate bill impacts for the different scenarios, under flat and TOU rates. The flat rate used was SCP's E1 rate, and the TOU rate was SCP's E-TOU-C rate. These were applied to the simulated whole building energy use for the PRE, AC, and POST scenarios. The net savings between the AC scenario and the POST (NTV) scenario were calculated and reported. The simple payback time was calculated using that estimate of cost savings.

Homeowner Satisfaction

Homeowner satisfaction was gauged in two ways: through measuring of indoor air temperatures before and after the retrofit, and through surveys before and after the retrofit and an online satisfaction log throughout the monitoring period.

Measured Indoor Air Temperatures

Indoor air temperatures were measured by sending HOBO temperature/RH loggers to each home as soon as the homes were selected. The loggers were programmed to collect only dry-bulb temperature data at five-minute intervals. Two loggers were mailed to each site, along with instructions to place one in a main living area, and another in another frequently occupied location, such as a bedroom. The loggers had a finite amount of memory—insufficient to collect data throughout the entire study. Therefore, in the middle of the study, occupants were asked by email to harvest the data and send it to the researchers. Detailed instructions were provided for downloading and sending the data using the HOBO smartphone app. This proved to be quite reliable and convenient. When the retrofit and monitoring equipment were installed, the researcher replaced the batteries on the HOBOs, downloaded data, and relaunched the loggers. At the end of the study, when the researchers decommissioned each site, the loggers were retrieved, and the data were again downloaded.

Likelihood of Avoiding Installation of Air Conditioning

The premise of installing NTV as an energy efficiency measure relies on the assumption that there are a significant number of homes that currently do not have air conditioning but would be likely install air conditioning if they do not have access to NTV, in order to make their homes more comfortable.

This was gauged in the pilot demonstration by surveying the occupants of the demonstration homes before installation of NTV and again after it was used for at least one summer. The hypothesis was that the fraction of households that report that they are likely to install AC at some point will decline after they are exposed to NTV.

An online survey was distributed to all participants in November 2019, and a similar survey was administered after the demonstration in April 2022. The questions included the following:

- Why do you currently NOT have air conditioning?
- How likely do you think it is that you will install Central AC in your home in the next five years?
- Consider the following hypothetical scenarios. In each of these scenarios, how likely do you think it would be that you would decide to install Central AC in the next 5 years?
  - Financial Issues:
    - You suddenly acquired just enough money to purchase Central AC
    - You suddenly acquired a significant amount of money – enough to meet your higher priority expenses, and have enough left over to install Central AC
    - You found out about a great sale on Central AC
    - The cost of electricity went down dramatically
  - Comfort Issues:
    - You found that installation of a Nighttime Ventilation system did not significantly improve your comfort in your home
    - You added a new member to your household who was more sensitive to high temperatures
    - You found yourself entertaining more often
    - A temporary heat wave occurred resulting in uncomfortable temperatures for 3-4 days in a row
    - The climate were to change such that there were more very hot days every summer in your region
  - Other Issues:
    - Something about your home changed so that you were now technically able to install Central AC
    - Carbon emissions fell to a point that it was no longer necessary to reduce energy use
    - Some friends or neighbors added Central AC in their homes and told you about it
    - Your spouse or other family member were to “give in” and allow you to install Central AC

The results of the pre-retrofit survey are summarized below in Figure 44 and Table 46. Half of the participants reported they were not likely to install AC in the next 5 years, and two were neutral. Only two participants felt it was likely that they would install AC in the next 5 years. One participant did not respond to the survey. None of the types of issues presented were very likely to convince any of the homeowners to change that intention, although comfort was the issue that came the closest to making it likely that they would change their minds.

Figure 44: Pre-Retrofit Survey Assessment of Likelihood of Installing Air Conditioning

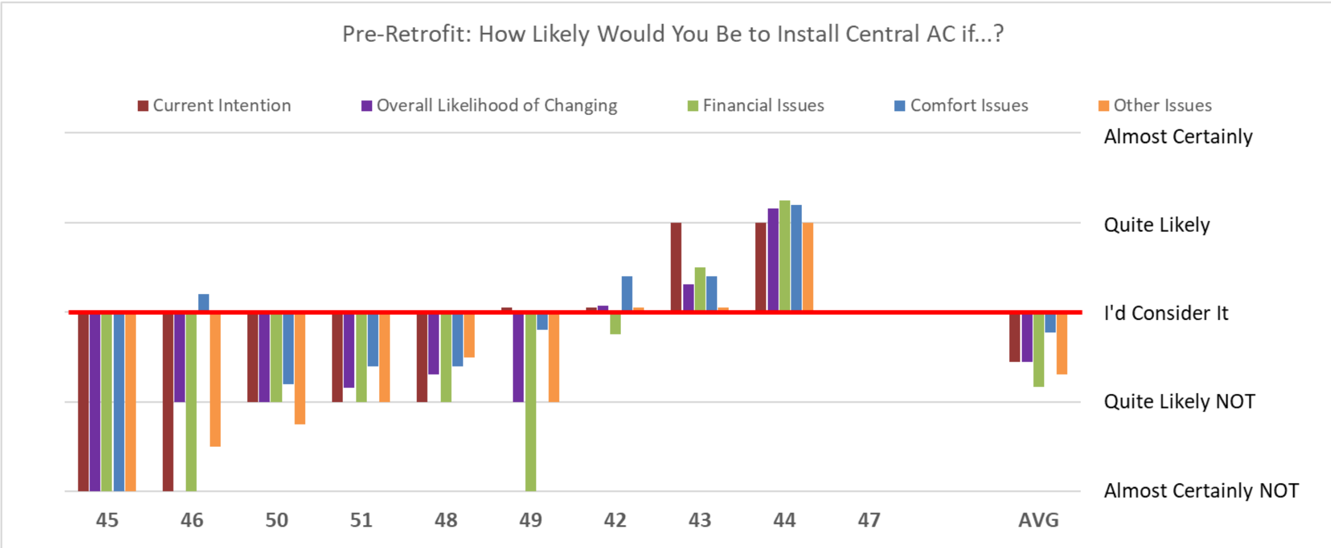


Table 46: Intention to Install AC in the Next Five Years, and Factors that Could Change that Intention

Site	Current Intention	Overall Likelihood of Changing	What if...		
			Financial Issues	Comfort Issues	Other Issues
42	I'm Considering It	I'm Considering It	I'm Considering It	I'm Considering It	I'm Considering It
43	Quite Likely	I'm Considering It	I'm Considering It	I'm Considering It	I'm Considering It
44	Quite Likely	Quite Likely	Quite Likely	Quite Likely	Quite Likely
45	Almost Certainly NOT	Almost Certainly NOT	Almost Certainly NOT	Almost Certainly NOT	Almost Certainly NOT
46	Almost Certainly NOT	Quite Likely NOT	Almost Certainly NOT	I'm Considering It	Quite Likely NOT
47					
48	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	I'm Considering It
49	I'm Considering It	Quite Likely NOT	Almost Certainly NOT	I'm Considering It	Quite Likely NOT
50	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT
51	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT
AVG	Quite Likely NOT	Quite Likely NOT	Quite Likely NOT	I'm Considering It	Quite Likely NOT

Satisfaction Log

Throughout the monitoring period, occupants were encouraged to record their impressions of the NTV system, through an online survey. The instructions that were provided included a QR code for the survey, and they were periodically encouraged by email to go back to the survey and record their comments. This survey asked about how they were operating the system (set points and schedules), as well as how often they overrode the thermostat. They were asked how comfortable their family had been, and how well the system was working for their family.

Results and Analysis

Installations

NTV was installed at 10 sites in the SCP service territory, between July 2020 and April 2021. Table 47 summarizes the homes that were included in the demonstration. Most of the sites were small to medium, although one larger home was included. Most of the homes were older: the vintage of the homes was equally split between pre-sixties, sixties, and nineties. All of the homes were in Santa Rosa except for two in Petaluma and one in Guerneville.

Table 47: Summary of NTV Installations and Sites

Site	Location	Sqft	Size Range*	Built	Vintage	Installation Date
42	Santa Rosa	1,782	Medium	1964	Sixties	7/23/20
43	Santa Rosa	1,337	Small	1942	Pre-Sixties	12/7/20
44	Santa Rosa	1,681	Medium	1967	Sixties	4/9/21
45	Santa Rosa	873	Tiny	1930	Pre-Sixties	11/30/20
46	Petaluma	1,868	Medium	1968	Sixties	3/11/21
47	Petaluma	2,121	Large	1999	Nineties	3/2/21
48	Santa Rosa	1,467	Small	1958	Pre-Sixties	8/11/20
49	Santa Rosa	1,495	Small	1991	Nineties	12/16/20
50	Guerneville	1,160	Small	Unknown	Unknown	1/22/21
51	Santa Rosa	1,298	Small	1998	Nineties	9/25/20

Technology Issues

A single HVAC (C20) contractor was hired to install all the NTV systems. Instructions were provided on how to do the installation, and the research team technician worked with the installer on the first few sites to help in the training and address any confusion or concerns. At most sites, the installation was completed in about one day, while at some sites it required more than a day.

The contractor was uncomfortable with the custom-wiring required to add the relays to adapt the economizer controller for homes without AC, so the research team technician carried out this part of the installation for all sites as they visited each site to install the fan power monitoring instruments and communications equipment. Even if the system were provided with pre-adapted wiring, it would still require wiring into the existing thermostat and furnace controller, which the contractor was uneasy about.

At most sites, installation went smoothly. Some specific findings were:

1. At one site (Site 51), the framing of the attic did not allow for installation of the full economizer box. The contractor spent some time trying to resolve the issue, but it could not be made to fit. The research team technician eventually developed a jury-rigged solution with a set of interlocked duct dampers installed in the outdoor air and return ducts.
2. At another site (Site 49), the Building Inspector judged that the alterations triggered Title 24 Energy Code requirements (duct modification over 40'), and required a duct test, additional alterations such as installing a 24" wide elevated attic catwalk, installing a 30" x 30" service platform for the FAU to provide future access to the unit, and to splice into an existing electrical line and install a junction box, new light switch, and light, and verify carbon monoxide detector in common area. This necessitated a $440 change order.
3. It was complex to integrate the systems with smart thermostats. The system had to "trick" the thermostat into controlling a fan and not a compressor, but smart thermostats were able to detect that the AC did not turn on. This caused error messages that could confuse occupants.

Instructions to Homeowners

When the system was installed at each site, an instruction sheet was provided, including the following instructions:

COOLING SEASON:	
Thermostat Schedule	Play around with a schedule that makes you comfortable and minimizes energy use
"Pre-Cooling" Setpoint	• From **bedtime till noon**: About **65-70°F**
	• The lower this is, the more pre-cooling you will get, but the more energy you will use.
	• Increase this if you are too cool in the morning or if you think the fan is running more than it needs to at night.
"Comfort" Setpoint	• From about **noon till bedtime**: About **75-80°F**
	• The higher this is, the less fan energy you may use under some circumstances, but the warmer you may feel.
	• Decrease this if you are too warm in the afternoon or early evening on mild days.
Thermostat Settings	Thermostat Mode: **COOL** Fan mode: **AUTO**
Thermostat Temporary Override	Temporarily increase or decrease the temperature setting as needed for comfort. Make sure it is a **TEMPORARY OVERRIDE** and not a PERMANENT HOLD.
Windows	Opening windows at night will make the system even more effective. **Just make sure it is cooler outside than inside when you open them, and make sure you close them in the morning.**

HEATING SEASON:			
Thermostat Mode:	HEAT	Fan mode: AUTO	Program thermostat as usual

SPRING, FALL, OR VACATION:		
Thermostat Mode:	OFF when not needed	Fan mode: AUTO

Energy Savings

Utility Bills

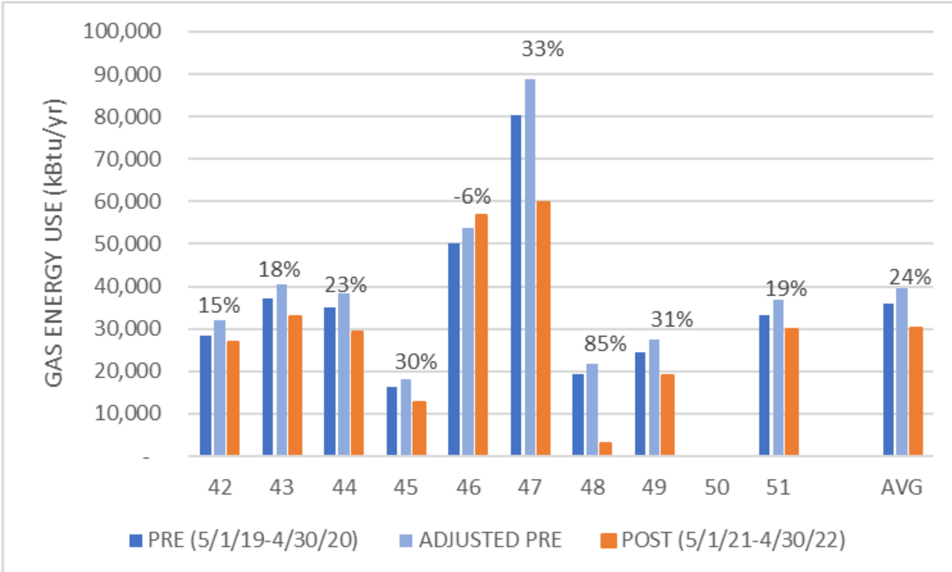
Utility bills and weather data were available from May 2018 through April 2022. Since the retrofits were conducted between Summer 2020 and Spring 2021, a pre-retrofit period of May 1, 2019 thru April 30, 2020 was used, and a post-retrofit period of May 1, 2021 through April 30, 2022 was used. Table 48, Table 49, Figure 45, and Figure 46 summarize the energy use from the utility data. Pre-retrofit and post-retrofit data are shown, as well as the adjusted pre-retrofit data for gas consumption (weather correlations developed pre-retrofit, applied to weather statistics from the post-retrofit period). Note that the HDD base temperature for two sites seem physically counterintuitive, although they numerically do represent the data collected. Also shown are the HDD base temperatures determined from analysis of the daily weather data and energy use for gas consumption, and the absolute and percent savings (savings divided by adjusted pre-retrofit use).

Analysis of utility bills confirmed that natural gas use did not increase between pre- and post-retrofit, suggesting that there was no heating penalty due to the presence of the economizer box and outdoor air duct. In fact, weather normalized energy actually went down on average by 9,600 kBtu per year, or 24%. Of course, there could be many other changes that happened between the PRE and POST periods—most notably the emergence of the COVID pandemic. However, it is reassuring that no increase was identified. Note also that Site 48 installed a heat pump, which understandably reduced natural gas consumption considerably. Without this home, natural gas savings were closer to 8,500 kBtu per year or 20%. Note that natural gas data were missing for home 50, as propane was used to heat that home.

Table 48: Utility Whole Home Gas Use

	WHOLE-HOME NATURAL GAS (kBtu)										
SITE	*42*	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*	*AVG*
PRE-RETROFIT (5/1/19-4/30/20)	28,400	37,200	35,000	16,400	50,000	80,400	19,200	24,400		33,300	36,000
ADJUSTED PRE-RETROFIT	31,900	40,400	38,400	18,000	53,800	88,700	21,800	27,600		37,000	39,700
HDD BASE (°F)	62.7	72.6	68.1	67.2	80.1	66.6	60.9	61.1		65.1	67.1
POST-RETROFIT (5/1/21-4/30/22)	27,000	33,100	29,300	12,600	56,800	59,800	3,200	19,200		29,800	30,100
SAVINGS	4,900	7,300	9,000	5,500	-3,000	28,900	18,600	8,400		7,100	9,600
SAVINGS PERCENT	15%	18%	23%	30%	-6%	33%	85%	31%		19%	24%

Figure 45: Utility Whole Home Gas Use

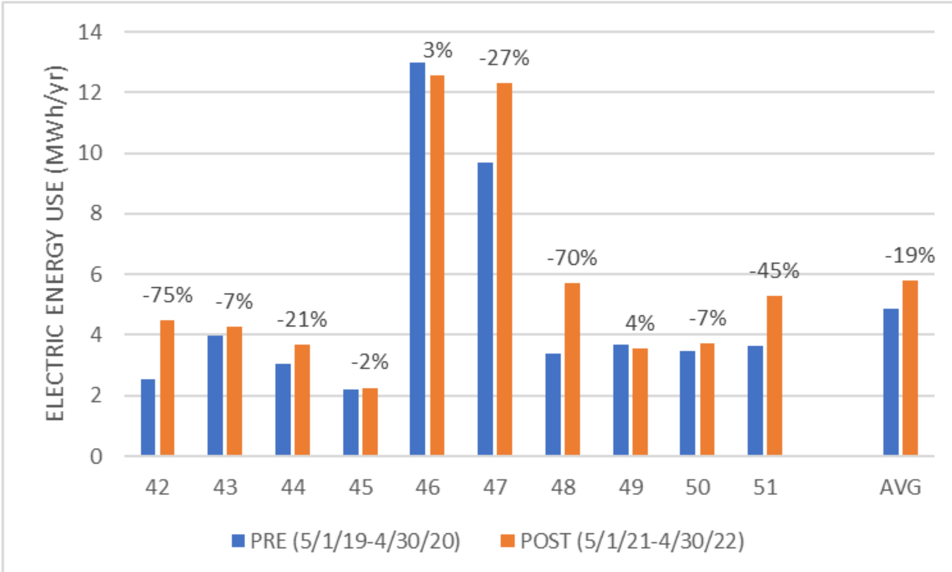


As shown in Table 49 and Figure 46, electric bills did increase, as expected. On average, annual whole-home electric energy use went up by about 915 kWh, or 19%. This is likely due to a combination of the extra energy used for the NTV fan and other factors such as COVID. This is also driven by the two homes (42 and 48) which did install air conditioning. Without the consumption of these two homes, the average electric bill increase was only 610 kWh or 11%.

Table 49: Utility Whole Home Electricity Use

	WHOLE-HOME ELECTRIC (MWh)										
SITE	*42*	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*	*51*	*AVG*
PRE-RETROFIT (5/1/19-4/30/20)	2.6	4.0	3.0	2.2	13.0	9.7	3.4	3.7	3.5	3.6	4.9
POST-RETROFIT (5/1/21-4/30/22)	4.5	4.3	3.7	2.3	12.6	12.3	5.7	3.5	3.7	5.3	5.8
SAVINGS	-1.9	-0.3	-0.6	-0.1	0.4	-2.6	-2.3	0.1	-0.2	-1.6	-0.9
SAVINGS PERCENT	-75%	-7%	-21%	-2%	3%	-27%	-70%	4%	-7%	-45%	-19%

Figure 46: Utility Whole Home Electricity Use



Measured NTV Fan Energy Use

The fan energy use measured during the post-retrofit analysis period (May 1 thru September 30 of 2021) is shown in Table 50, Table 51, and Figure 47. Table 50 shows the maximum hourly Wh/hour (roughly equivalent to watts) for each site. Sites 44, 46, and 48 do not look reasonable, and they are not included in the average. Site 47 is the only site that had a floor area over 2,000 ft^2, so its fan was likely larger than in other sites. An average of about 400 watts seems reasonable for a small home residential forced air unit.

Table 50: Maximum Hourly Fan Energy Use

	42	43	44	45	46	47	48	49	50	51	AVG*
Max Wh/hr	404	426	Missing	356	6	826	1,619	334	506	404	465

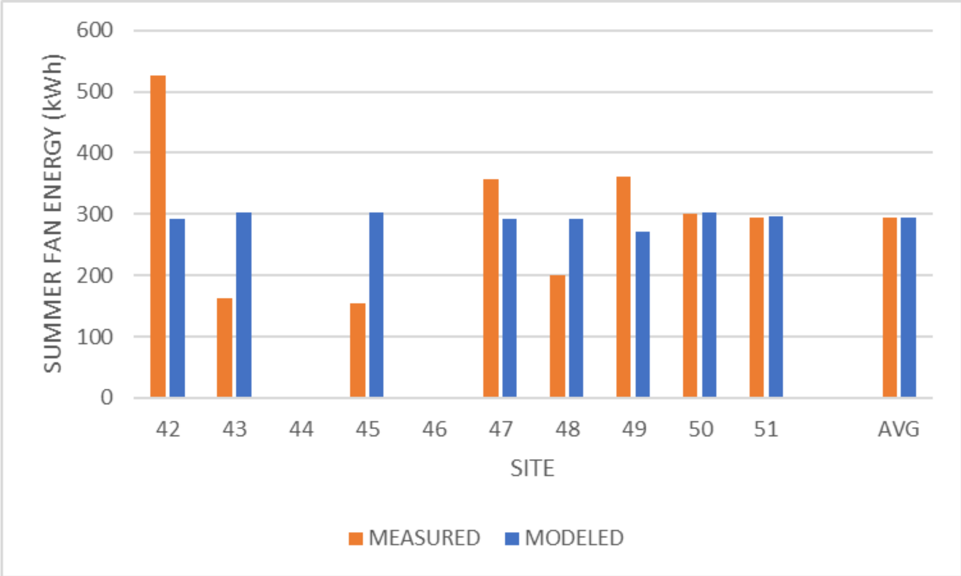
Table 51 and Figure 47 show the total fan energy use for a cooling season. The average was about 295 kWh over the cooling season.

Table 51: Measured and Modeled Summer Fan Energy

Summer 2021 kWh	42	43	44	45	46	47	48	49	50	51	AVG
MEASURED	525.9	163.4		153.3		357.0	201.3	361.8	300.0	294.6	294.6
MODELED	292.4	302.1		302.1		292.8	292.4	271.0	302.1	296.5	293.9

Modeled is using regression

Figure 47: Measured and Modeled Summer Fan Energy



Modeled is based on regression analysis

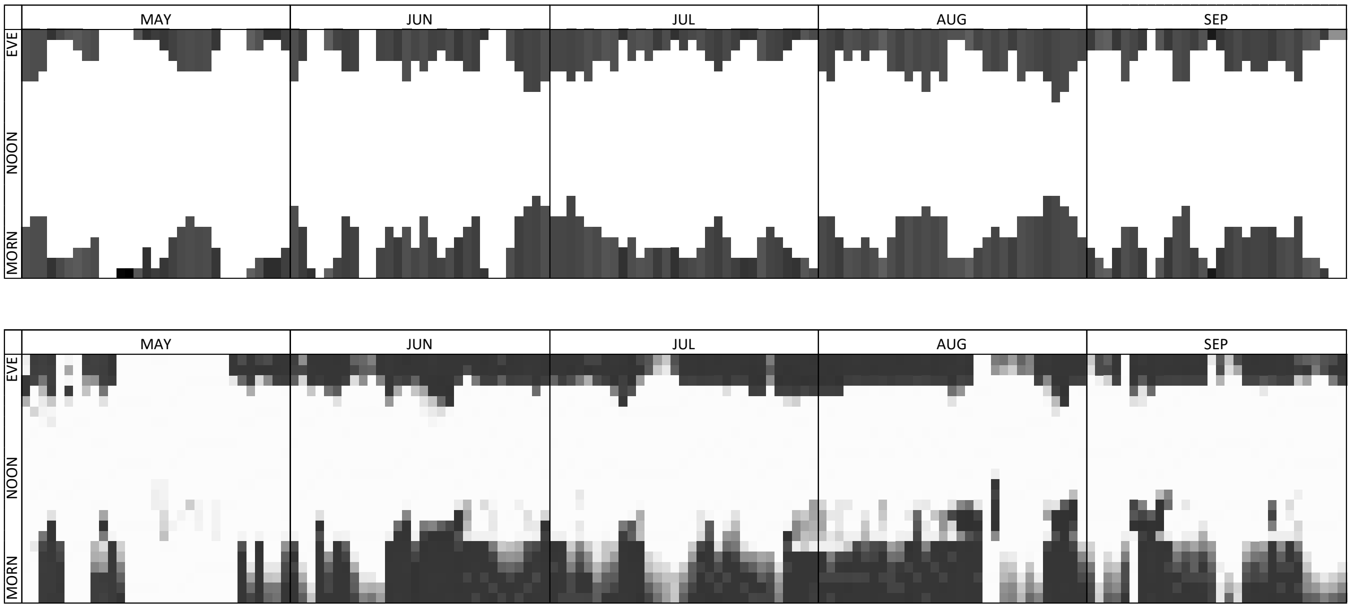
When regressing actual daily temperature with measured fan energy use, the coefficient of determination (R^2) was analyzed using different assumptions. It was determined that correlating the maximum daily outdoor air temperature with the energy use that evening plus the next morning (evening defined as after 4 pm, and morning defined as before 4pm) fit the data the best. From this analysis, the average correlation coefficients were calculated, to best fit all the data across all sites:

- Slope: 0.11822
- Intercept: (7.6203)

The "MODELED" row in Table 51 and bars in Figure 47 correspond to the resulting energy use when the overall correlation coefficients were applied to each site's weather data. These show that on average, the summer energy use across sites is generally consistent between the measured and modeled values.

The regression coefficients were applied to the TMY3 dataset used for the simulation, so that the energy use for the POST scenario would be comparable to the simulated energy use for the AC scenario. The daily fan energy use obtained from this regression analysis was spread out across evening and morning hours. Figure 48 shows this manufactured fan energy use profile, in comparison with the actual measurements from one of the sites, to illustrate how representative this schedule is.

Figure 48: Manufactured Fan Energy Use Profile [Based on Typical Weather (top) Compared with Actual Measured Profile for Site 49 with Actual Weather (bottom)]



Building Simulation

Table 52 shows the predicted energy savings—comparing modeled POST energy use (using the correlation with TMY3 weather data) with simulated AC and baseload energy use. NTV was analyzed only May – September, but the simulation did predict AC use before May and after September. It is possible that an air-conditioned home would begin cooling earlier in the season than a home with NTV, but to be conservative, we assumed May – September cooling season for both the AC and POST scenarios, and zero cooling energy at other times.

Overall net savings from avoiding installation of AC were 46% of cooling energy use and 4% of whole home energy use. In the AC scenario, 66% of cooling energy use was on-peak, while after the retrofit (with NTV), only 8% of cooling energy use was on-peak. Therefore, on-peak cooling energy use was reduced by 93%, while off-peak cooling energy use was increased by 44%. For the whole home, in the AC scenario 34% of energy use was on-peak, while after the retrofit (with NTV), only 30% of cooling energy use was on-peak. Therefore, on-peak whole home energy use was reduced by 15%, while off-peak home energy use was increased by 1%.

Table 52: Simulated Cooling and Whole Home Energy Use

	COOLING ENERGY (kWh)					WHOLE HOME ENERGY (kWh)				
MONTH	PRE	AC	POST	SAV	SAV%	PRE	AC	POST	SAV	SAV%
1	-	-	-	-	0%	576	576	576	-	0%
2	-	-	-	-	0%	520	520	520	-	0%
3	-	-	-	-	0%	546	546	546	-	0%
4	-	-	-	-	0%	507	508	507	-	0%
5	-	41	41	1	2%	510	551	551	1	0%

6	-	130	58	72	55%	457	587	515	72	12%
7	-	122	57	65	53%	468	590	525	65	11%
8	-	167	76	91	54%	474	641	551	91	14%
9	-	68	52	16	23%	474	542	526	16	3%
10	-	-	-	-	0%	514	557	514	-	0%
11	-	-	-	-	0%	513	513	513	-	0%
12	-	-	-	-	0%	574	574	574	-	0%
TOTAL	-	528	284	244	46%	6,134	6,706	6,418	244	4%
On Peak	-	347	23	324	93%	1,924	2,298	1,947	350	15%
% On Peak	0%	66%	8%	0%		31%	34%	30%		
Off Peak	-	181	261	(80)	-44%	2,298	4,408	4,471	(63)	-1%

Cost and Cost Effectiveness

Technology Costs

Table 53 summarizes the actual costs of installation of NTV. Note that at Site 51, the air handling unit was not amenable to installing the economizer box, and a jury-rigged damper system was assembled. The cost of this installation was not comparable to the other sites, so its costs were not included in the reported average cost. The average system cost over $3,500 to install, which was significantly higher than the originally expected average of about $1,400, due to COVID and general labor cost increases in the region during the time of the installation. The cost of the economizer box was slightly higher than expected: $980 (including tax and shipping) vs. $750. It is expected that both labor and material costs could be reduced by about 10% in a mature market, as contractors become more familiar with the technology and the economizer box is mass produced. Contractors will have the added task of wiring the unit to the existing thermostat, which was provided by the research team in this demonstration, however if wiring modifications are incorporated into the design of the economizer controller, this will not be a significant increase.

For a fair comparison, energy savings between the AC and POST scenarios would be compared to the *incremental* cost of the NTV equipment, not the full cost. A quick internet search found that the installed cost of a new central AC system is equal to about $600 per ton, plus $2,000. Assuming 1 ton of cooling for every 400 square feet, estimated costs for the AC scenario are shown in Table 53 as well.

Table 53: Installation Costs of NTV and AC

Site	Labor	Materials	Total Cost	Mature Market Cost	AC Total Cost
42	$ 3,557	$ 980	$ 4,536	$ 4,082	$ 5,208
43	$ 3,194	$ 980	$ 4,174	$ 3,757	$ 4,407
44	$ 3,242	$ 980	$ 4,222	$ 3,800	$ 5,026
45	$ 3,371	$ 980	$ 4,351	$ 3,916	$ 3,571
46	$ 3,780	$ 980	$ 4,760	$ 4,284	$ 5,362
47	$ 3,825	$ 980	$ 4,805	$ 4,325	$ 5,818

48	$ 3,243	$ 980	$ 4,223	$ 3,801	$ 4,641
49	$ 3,818	$ 980	$ 4,797	$ 4,317	$ 4,691
50	$ 3,592	$ 980	$ 4,572	$ 4,115	$ 4,088
51*	$ 590	$ 980	$ 1,570	$ 1,413	$ 4,336
AVG*	**$ 3,514**	**$ 980**	**$ 4,493**	**$ 4,044**	**$ 4,757**

**Site 51 was a custom application and was installed in-house. Site 51 not included in average*

Modeled Energy Bill Impacts

Energy bills were estimated using a rates calculator that used standard flat and TOU rates from SCP, which take into account time varying rates (for TOU) as well as tiered rates for both. The annual costs are summarized in Table 54, along with the savings (or penalty) associated with differences in costs between scenarios. As expected, there is a cost penalty for installing NTV, but a larger penalty for installing AC. The net savings from avoiding installing an air conditioner are positive. Savings are higher using TOU rates, as expected, although it is surprising that there is not more of a difference between the flat rate and the TOU rate.

Table 54: Annual Whole-Home Electricity Costs for Alternative Rate Scenarios

RATE	ANNUAL COSTS			SAVINGS		
	PRE	POST	AC	Increase for NTV (PRE-POST)	Increase for AC (PRE-AC)	Net Savings (AC-POST)
Flat (E1)	$ 1,747	$ 1,839	$ 1,934	$ (93)	$ (187)	$ 94
Time of Use (E-TOU-C)	$ 1,767	$ 1,869	$ 1,998	$ (102)	$ (231)	$ 129

Table 55 combines the results from Table 53 and Table 54 and analyzes the financial impacts of installing NTV. For most sites, the incremental cost of installing NTV instead of AC is negative (NTV is less expensive than AC), although the incremental energy savings is positive. When calculating a simple payback time (SPT), it is usually expected that the incremental cost is positive and is paid back in annual energy savings. If incremental equipment costs are negative, however, the result is a negative SPT, which is nonsensical. These negative SPTs and a negative average SPT are reported in Table 55 for completeness, although in summary, the overall SPT is reported as zero at those sites, meaning that the measure is economical on day one and requires no time to pay back.

Table 55: Financial Analysis of PRE, POST, and AC Scenarios

SITE	PRE		POST		AC		NET SAVINGS (AC vs POST)		
	Equip Cost	Annual Energy Cost	Equip Cost	Annual Energy Cost	Equip Cost	Annual Energy Cost	Increased Equip Cost	Reduced Energy Cost	SPT
42	$ -	$ 1,767	$ 4,536	$ 1,869	$ 5,208	$ 1,998	$ (672)	$ 129	(5.21)
43	$ -	$ 1,767	$ 4,174	$ 1,869	$ 4,407	$ 1,998	$ (233)	$ 129	(1.80)
44	$ -	$ 1,767	$ 4,222	$ 1,869	$ 5,026	$ 1,998	$ (804)	$ 129	(6.23)
45	$ -	$ 1,767	$ 4,351	$ 1,869	$ 3,571	$ 1,998	$ 780	$ 129	6.04

46	$ -	$ 1,767	$ 4,760	$ 1,869	$ 5,362	$ 1,998	$ (602)	$ 129	(4.67)
47	$ -	$ 1,767	$ 4,805	$ 1,869	$ 5,818	$ 1,998	$ (1,013)	$ 129	(7.85)
48	$ -	$ 1,767	$ 4,223	$ 1,869	$ 4,641	$ 1,998	$ (418)	$ 129	(3.24)
49	$ -	$ 1,767	$ 4,797	$ 1,869	$ 4,691	$ 1,998	$ 106	$ 129	0.82
50	$ -	$ 1,767	$ 4,572	$ 1,869	$ 4,088	$ 1,998	$ 484	$ 129	3.75
51*	$ -	$ 1,767	$ 1,570	$ 1,869	$ 4,336	$ 1,998	$ (2,766)	$ 129	(21.44)
AVG*	**$ -**	**$ 1,767**	**$ 4,493**	**$ 1,869**	**$ 4,757**	**$ 1,998**	**$ (263)**	**$ 129**	**(2.04)**

**Site 51 was a custom application and was installed in-house. Site 51 not included in average*

Homeowner Satisfaction

Measured Indoor Air Temperatures

Indoor air temperatures, monitored and logged using Hobo dataloggers, were downloaded at various points throughout the study, and analyzed to determine whether the homes were more comfortable after the retrofit than before. Because of issues with battery life and memory filling up, there is not a full dataset for all sites.

For each site, the temperatures were compared for each logger over the pre and post summer seasons, and tabulated. Table 56 provides a summary for those sites that have measured temperatures for corresponding time periods before and after the retrofit. The metrics reported are the:

- Maximum air temperature: the highest indoor air temperature measured throughout the pre and post datasets.
- Average max air temperature: the average over the pre and post datasets of the maximum daily indoor temperature.
- Number of days with max indoor air temp > 80°F: the total number of days in the pre and post datasets that had a peak indoor temperature over 80°F.

These statistics were calculated for the two temperature sensors added at the site (one in the living area and one in a secondary location such as a bedroom). The table also presents a summary of the *outdoor* air temperature for the same periods, and a summary of the number of days in the analysis period for each site.

The results indicate that in almost all cases, temperatures were lower in the post-retrofit dataset, indicating that NTV had a positive comfort impact, although the OAT was also lower during that period. In the one case where the POST period was hotter, the OAT was also hotter.

Table 56: Summary of Measured Summer Indoor Air Temperatures Before and After NTV Retrofit

METRIC	SITE	LIVING ROOM		BEDROOM		OAT	
		PRE	POST	PRE	POST	PRE	POST
Maximum Air Temperature	45	82.4	78.8	100.0	100.0	96.5	91.8
	48			83.2	87.9	106.0	116.0

	49			87.2	79.9	116.0	102.0
	50	87.6	84.5	85.0	80.9	106.0	102.0
Average Max Air Temperature	45	72.2	71.7	73.8	73.4	78.7	78.9
	48			74.7	75.2	83.4	83.5
	49			76.5	73.2	84.0	81.0
	50	79.1	77.4	75.9	74.9	87.5	82.4
Number of Days with Max Indoor Air Temp > 80°F or Max Outdoor Air Temp >90°F	45	2	0	2	1	5	2
	48			5	4	36	35
	49			22	0	35	20
	50	16	10	5	3	15	10
Number of Days Included	45	27	27	27	27	27	27
	48			58	58	58	58
	49			136	136	136	136
	50	42	42	42	42	42	42

Likelihood of Avoiding Installation of Air Conditioning

Figure 49, Figure 50 and Table 57 show the results of the occupant survey after completion of the study. Two occupants remained firmly in the position that they were not likely to install AC, and most hypothetical changes would not sway them. One home reported that they were less likely to install AC than before the study and one reported that they were more likely than before to install AC. Two sites actually did install AC over the course of the study. Figure 50 summarizes these changes graphically.

It is notable that two households had babies over the course of the study. One chose to add AC because of that, and the other reported that they are now somewhat likely to install AC after reporting previously that they were somewhat unlikely. It is also notable that the other home that installed AC did it because their heating system failed, and they wanted to replace it with a heat pump (although they reported that they don’t plan to use the AC much). Another home reported that when it is time to replace their heating system, they will replace it with a heat pump, and are therefore somewhat likely to install AC.

Other changes that led to an increased reported likelihood of installing AC included increases in outdoor temperatures due to climate changes and increased incidence of smokey air. The homes that signed up for the demonstration were presumably more interested than average in pursuing improved comfort, and it is possible that other homes that were not initially interested would remain uninterested in installing AC. The results of this analysis are not conclusive, and so no probability analysis was attempted to adjust expected energy savings.

Figure 49: Post-Retrofit Survey Assessment of Likelihood of Installing Air Conditioning

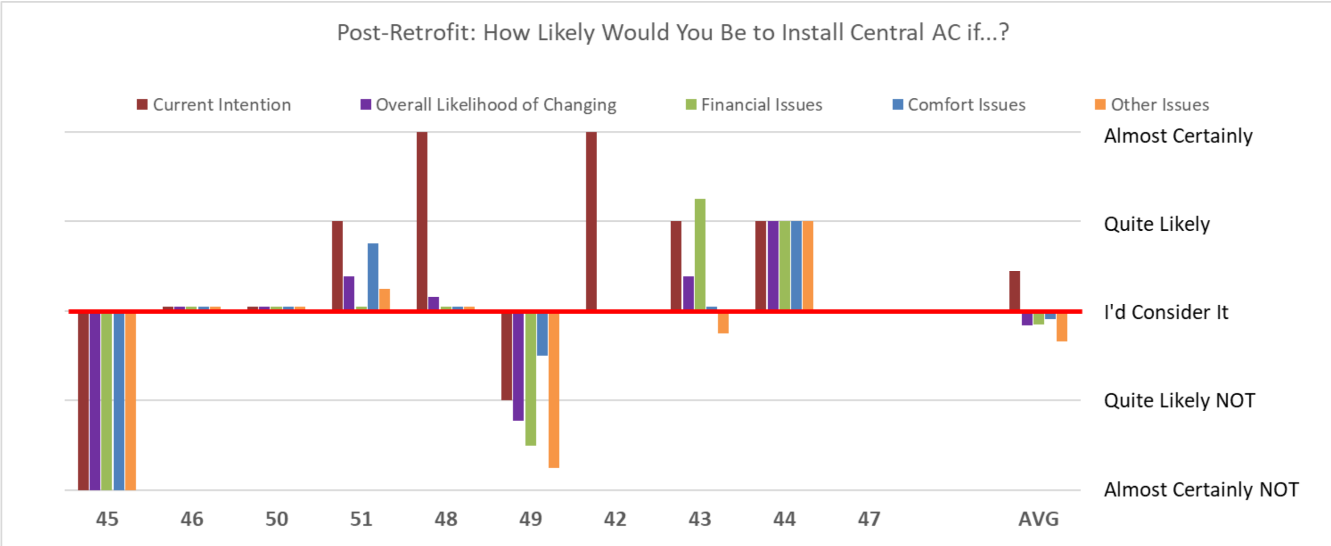
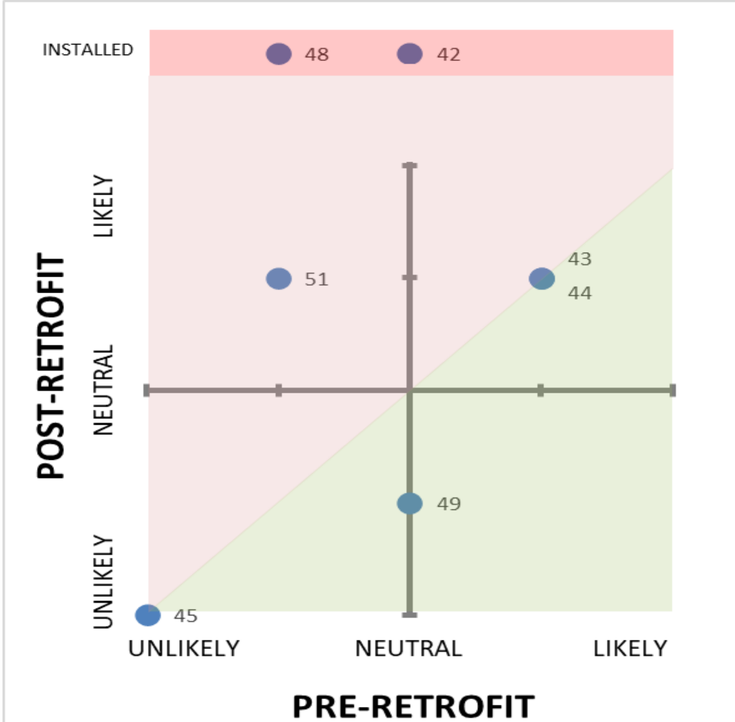


Table 57: Change in Likelihood of Adding Air Conditioning

Site	Pre	Post	Change	Notes
42	Considering	Installed AC	Installed AC	Installed AC. They had a baby and ventilation was not able to keep the house cool enough.
43	Somewhat Likely	Somewhat Likely	No Change	Now somewhat likely to install AC, but not more than before.
44	Somewhat Likely	Somewhat Likely	No Change	Occupant is waiting until it's time to replace heating system as they would like to move to a heat pump system for both heating and cooling.
45	Very Unlikely	Very Unlikely	No Change	Now very unlikely to install AC, but not less than before.
46	Very Unlikely			No Post Survey
47				No Pre or Post Survey
48	Somewhat Unlikely	Installed AC	Installed AC	Installed AC. They were unlikely to install it, but their heating system failed and they wanted a heat pump. They do not expect to use cooling much.
49	Considering	Somewhat Unlikely	Less Likely	Now somewhat unlikely to install AC, and even less than before.
50	Somewhat Unlikely			No Post Survey
51	Somewhat Unlikely	Somewhat Likely	Much More Likely	Now somewhat likely to install AC, and much more likely than before. They had a child who was sensitive to heat.
AVG	2 likely 2 neutral 5 unlikely 1 no response	2 installed 3 likely 0 neutral 2 unlikely 3 no response	2 installed 1 more likely 3 no change 1 less likely 3 no response	

Figure 50: Changes in Likelihood of Installing AC from PRE to POST Retrofit



Satisfaction Log

The Satisfaction Log, completed throughout the monitoring period, found the following:

- During the periods over the course of the demonstration where wildfires in the region caused very smoky conditions with poor air quality, most occupants reported that they were unable to use the NTV systems and remained uncomfortable. While they were no less comfortable than they would have been without the NTV system, an AC system would have allowed them to become comfortable while keeping indoor air quality at a reasonable level.
- Several occupants reported that the sound of the damper modulating was irritating. It was investigated and determined that the damper was cycling much too often. The irritating sound was significantly diminished by installing a time-delay relay on the damper. This was then installed at several of the sites.
- Four of seven sites who responded reported comfort problems during heat waves.
- Two sites reported that it took too long to cool off.
- Several reported problems with the fan turning on or off at unpredictable times.
- Overall, most comments were quite positive:

42	“Great! - I changed thermostats and need to chat but otherwise love it.”
44	“Temperature drop as measured by thermostat is slower than expected ~ 2F/hr. However, having cool air circulating provides immediate relief if you are sitting near a vent.”
45	“So far it's a slight benefit, but I'm not sure that the cost benefit is there. Will know more as we move through summer, if we can get it to work with ecobee....”

48	"We continue to love it!" "It's great. We may look into getting a filter with higher filtration to use temporarily during the fires." "Last night (8/19) was the first time we left all the windows closed because of smoke from the fires. The system worked great because it finally was cool enough outside. It was wonderful to be able to keep out the smoke & noise by keeping the windows closed." "We continue to find it very helpful to have cool filtered air with the option to keep the bedroom windows closed."
49	"So far very well. We are sleeping better at night because it is cooler. I will be interested to see what our first utility bill is like now that the system has been running daily for a few weeks."
50	"Overall this recent heatwave tested the concept, and we have been much more comfortable in the house than before. "
51	"We are probably not going to turn the system on too often. It unfortunately does not provide any cooling relief for hours. No noticeable temperature difference happens until 3am when we are asleep anyway. We will just open windows and save on the energy cost. "

Conclusions

Summary of Results

Through installing and monitoring NTV cooling systems in ten homes in the SCP service territory, this project was able to demonstrate that it is a cost-effective measure that can make Sonoma homeowners more comfortable in their homes. Some of the findings from the demonstration include:

1. *Technology Issues*: Most installations went smoothly, although the contractor was uncomfortable with the custom-wiring required to add the relays to adapt the economizer controller for homes without AC, so the research team technician did this part of the installation for all sites. At one site, the framing of the attic did not allow for installation of the full economizer box, so the research team technician eventually developed a jury-rigged solution with a set of interlocked duct dampers installed in the outdoor air and return ducts. At another site, the Building Inspector judged that the alterations triggered Title 24 Energy Code, necessitating a $440 change order for remedial work.
2. *Energy Savings*: Analysis of utility bills confirmed that natural gas use did not increase between pre- and post-retrofit, suggesting that there was no heating penalty due to the presence of the economizer box and outdoor air duct. In fact, weather normalized energy actually went down on average by 8,500 kBtuper year or 20%, but this was likely due to changes in occupant behavior. Electric bills did increase, as expected. On average, annual whole-home electric energy use went up by about 610 kWh or 11%. The NTV fans consumed about 400 W when operating, and homes consumed on average about 300 kWh per year for the NTV fan. Overall net savings from avoiding installation of AC were 46% of cooling energy use and 4% of whole home energy use. On-peak cooling energy use was reduced from the AC scenario by 93%, while off-peak cooling energy use was increased by 44%. Off-peak home energy use was increased by 1%, but on-peak whole home energy use was reduced by 15%.

3. *Cost and Cost Effectiveness*: The average installation cost was over $3,500, which was significantly higher than the originally expected average of about $1,400, and the cost of the economizer box was slightly higher than expected: $980 vs. $750. It is expected that both the labor and material costs could be reduced by about 10% in a mature market. As expected, there is an energy-bill penalty for installing NTV, although a larger penalty for installing AC. The net savings from avoiding installing an air conditioner are positive. Savings are higher using TOU rates, as expected, although it makes a smaller difference than expected. The overall SPT is essentially zero since the measure has a negative incremental cost in most cases. The measure is economical on day one and requires no time to pay back.
4. *Homeowner Satisfaction*: The on-site temperature measurements indicate that in almost all cases, indoor temperatures were lower in the post-retrofit dataset, indicating that NTV is providing a comfort benefit. Comparing pre- and post-surveys of occupants, two occupants remained firmly in the position that they were not likely to install AC, and most hypothetical changes would not sway them. One home reported that they were less likely to install AC than before the study and one reported that they were more likely than before to install AC. Two sites actually did install AC over the course of the study. Two households had babies over the course of the study, and one chose to add AC because of that, and the other reported that they are now more likely to install AC. Also, the other home that installed AC did it because their heating system failed and they wanted to replace it with a heat pump. Another home reported that when it is time to replace their heating system, they will replace it with a heat pump, and are therefore somewhat likely to install AC. Most occupants reported that the system did not provide comfort during heat waves, but were quite happy with the system and reported that overall their comfort improved significantly.

Lessons Learned

The installed NTV systems operated well and generally satisfied occupants. There were some general lessons learned throughout this demonstration:

- Integrating with existing systems is complicated. In one case the system did not fit within attic framing and a jury-rigged system was installed. At several, use with certain smart thermostats caused confusion. At some sites the damper seemed to be short-cycling and operating too often, requiring addition of a time-delay relay. All of these types of issues make this a complex retrofit and require that the contractor takes great care to integrate the system well, and in some cases come back to address unanticipated issues. Because the contractor who installed the systems in this demonstration was uneasy with the wiring, they did not deal with most of these issues. The manufacturer of the economizer box expressed an interest in modifying their controller to include the adaptations that were found to be necessary in the demonstration in order to use the system for homes without AC. This should be encouraged.

- Sonoma is an area that has unfortunately been increasingly prone to wildfires and unhealthy smoky air. There was one significant smoke event during the demonstration, and most occupants reported that they were unable to use the NTV systems, and remained uncomfortable. While they were no less comfortable than they would have been without the NTV system, an AC system would have allowed them to become comfortable while keeping indoor air quality at a reasonable level. Some occupants did report that it was preferable to operate the NTV system—which brings in filtered air—than to open windows. It is possible that with appropriate filtration, NTV could be a good alternative even during wildfire season. In fact, if it could flush out the home at times of relatively high air quality, it could be a beneficial measure for many homes.
- Code interpretations will have to be considered more closely. At one site, the Building Inspector judged that the alterations triggered Title 24 Energy Code requirements (duct modification over 40'), and required additional work (a duct test, additional alterations such as installing a 24" wide elevated attic catwalk, installing a 30" x 30" service platform for the FAU to provide future access to the unit, and to splice into an existing electrical line and install a junction box, new light switch, and light, and verify carbon monoxide detector in common area), necessitating a $440 change order. The interpretation of the research team is that the added duct work is not handling conditioned air, and the added equipment does not fit into the definition of a new space conditioning system, and Title 24 requirements should not be triggered.
- Finally, the fact that two of the households had babies during the course of the study, and that others either installed or plan to install a heat pump illustrate how complex the decision is whether or not to add AC. In particular, as heat pumps become more prevalent (with encouragement from entities such as SCP), we may find that AC becomes more prevalent and the role of NTV becomes diminished.

Conclusions

This is a relatively low-cost retrofit that can be marketed as a niche product to homeowners with relatively small homes (whose furnace fans provide an airflow well matched to the size of the damper assembly, and whose airflow is likely to be large enough to provide sufficient cooling effect), central heating systems with the air handling unit in the attic, and no AC. Marketing of this system should emphasize that it can be an alternative to installing AC, but that it cannot promise that occupants will be comfortable at all times, or that bills will be reduced. Rather, it can provide an improvement in comfort compared to what they have now, at a lower cost than installing central AC.

Because it is cheaper than AC in most cases, and saves on energy costs, it is automatically cost effective. But in this demonstration, it cost only about $400 less to install than a central AC system, and saved only $129/year, so economics are not likely to drive its adoption. It does not provide comfort at the same level as AC, so it will be hard to convince the majority of homeowners.

However, many users in this demonstration liked the system, and appreciated that it allowed them to be more comfortable and to avoid installing a new AC system. It was clearly cost effective and saved energy. Notably, using NTV instead of AC reduced whole building peak period energy use by 15%. NTV should be evaluated on a case-by-case basis. If it is installed by qualified HVAC contractors who are familiar with making modifications to existing systems, including making ducting alterations in the attic and integrating with existing thermostats, and marketed to homeowners who are environmentally inclined but also desire to improve comfort, it is a promising technology. Although not explicitly evaluated in this project, NTV is a well-established measure for homes with air conditioning, and economizers are recommended for all but the smallest packaged units in commercial buildings, and these applications should also be encouraged.

CHAPTER 4: Conclusions and Recommendations

4.1: Energy Savings and Cost-Effectiveness Summary

The seven retrofit technologies that were demonstrated under Lead Locally showed a range of performance and cost effectiveness across the 50 test sites. A summary of the energy savings and cost-effectiveness for all test sites that yielded reliable results is shown in Table 58. Similar results are presented in Table 59 for the technologies in general, assuming mature market costs and typical building applications. Several demonstrated significant energy and cost savings, and the initial investment could be recovered within 10 years. This includes heat pump water heaters replacing electric resistance, commercial induction cooking, heat recovery dishmachines, and nighttime ventilation in lieu of air conditioning. Others achieved site energy savings that either did not translate into utility bill savings or the savings was insufficient to make the investment cost-effective within a reasonable time period. Examples include ducted mini-splits, aerosol envelope sealing, phase change materials in drop ceilings, residential induction cooking, and HPWHs replacing gas furnaces. Relative to the 10% energy savings goal for residential buildings, ducted mini-splits achieved this target on average, while aerosol sealing, phase change materials, and induction cooking met the target for certain sites. For commercial buildings, induction cooking and heat recovery dishmachines demonstrated significant savings but did not approach the 20% target as individual measures. However, with appropriate incentives, careful choice of application (including new construction and in combination with PV systems), or end-of-life replacement, all technologies show significant promise.

Table 58: Individual Site Energy Savings and Cost-Effectiveness Summary

Site #	Technology	Building type	Actual cost of measure (equipment + installation)	Annual electricity savings (site kWh)	Annual gas savings (site kBtu)	Annual total energy savings (site kWh)	% energy savings (whole building kWh)	Annual TOU utility bill savings ($)	Simple payback (years) (actual)
1	Aerosol Envelope Sealing	Residential	$3,892	931	100	946	6.5%	$295	13.2
2	Aerosol Envelope Sealing	Residential	$6,969	60	10,800	3,228	11.7%	$246	28.3
3	Aerosol Envelope Sealing	Residential	$4,209	49	8,800	2,631	14.9%	$188	22.3
4	Aerosol Envelope Sealing	Residential	$4,933	7	2,100	626	2.9%	$44	112.7
5	Aerosol Envelope Sealing	Residential	$4,457	0	0	0	0.0%	$0	No Payback
6	Aerosol Envelope Sealing	Residential	$1,207	97	100	118	1.4%	$31	39.6
7	Aerosol Envelope Sealing	Residential	$1,207	220	100	234	2.6%	$68	17.7
8	Aerosol Envelope Sealing	Residential	$1,167	210	100	227	2.3%	$65	17.9
9	Aerosol Envelope Sealing	Residential	$1,167	101	100	115	1.3%	$31	37.3
10	Aerosol Envelope Sealing	Residential	$4,417	7	100	42	0.5%	$3	1280.2
14	Exhaust Heat Recovery Dishwashers	Commercial	$4,000	2,920	0	2,689	8.0%	$1,147	3.5
16	Exhaust Heat Recovery Dishwashers	Commercial	$4,000	8,030	0	7,390	8.0%	$2,979	1.3
17	Heat Pump Water Heaters	Residential	$4,000	-2,032	23,100	4,748	8.4%	$157	25.5
18	Heat Pump Water Heaters	Residential	$4,000	-1,399	13,900	2,667	4.7%	$121	33.1

19	Heat Pump Water Heaters	Residential	$4,000	-2,404	190	3,165	5.6%	$103	38.8
20	Heat Pump Water Heaters	Residential	$4,000	-1,449	167	3,751	6.6%	-$69	No Payback
21	Heat Pump Water Heaters	Residential	$4,000	2,749	0	4,660	8.2%	$625	6.4
22	Heat Pump Water Heaters	Residential	$4,000	-3,060	102	-59	-0.1%	-$104	No Payback
23	Heat Pump Water Heaters	Residential	$4,000	-1,027	86	1,495	2.6%	$67	59.7
24	Heat Pump Water Heaters	Residential	$4,000	-2,929	155	1,612	2.8%	$115	34.8
25	Heat Pump Water Heaters	Residential	$4,000	-2,885	148	1,436	2.5%	$96	41.7
28	Induction Cooking	Residential	$3,000	440	0	440	8.9%	$74	40.5
29	Induction Cooking	Residential	$3,000	612	0	612	12.3%	$107	28.0
30	Induction Cooking	Residential	$3,000	112	0	112	2.3%	$19	157.9
31	Induction Cooking	Residential	$3,000	-149	0	-149	-3.0%	-$24	-125.0
32	Induction Cooking	Residential	$3,000	227	0	227	4.6%	$39	76.9
34	Induction Cooking	Commercial	$5,500	-10,585	1679	38,511	0.8%	-$700	No Payback
35	Ducted Mini-Split Heat Pump	Residential	$26,016	939	9	1,205	19.0%	-$233	No Payback
36	Ducted Mini-Split Heat Pump	Residential	$26,016	-230	37	849	6.6%	-$15	No Payback
37	Ducted Mini-Split Heat Pump	Residential	$26,016	-517	0	-517	-6.1%	-$134	No Payback
38	Ducted Mini-Split Heat Pump	Residential	$26,016	-1,612	48	-201	-1.7%	-$19	No Payback
39	Ducted Mini-Split Heat Pump	Residential	$26,016	-300	108	2,865	63.6%	$53	494.6
40	Ducted Mini-Split Heat Pump	Residential	$26,016	-283	42	958	7.8%	-$22	No Payback
41	Ducted Mini-Split Heat Pump	Residential	$26,016	-29	6	141	1.9%	-$1	No Payback
42	Nighttime Ventilation (Versus AC)	Residential	-$672	244	0	244	3.6%	$129	0.0

43	Nighttime Ventilation (Versus AC)	Residential	-$233	244	0	244	3.6%	$129	0.0
44	Nighttime Ventilation (Versus AC)	Residential	-$804	244	0	244	3.6%	$129	0.0
45	Nighttime Ventilation (Versus AC)	Residential	$780	244	0	244	3.6%	$129	6.0
46	Nighttime Ventilation (Versus AC)	Residential	-$602	244	0	244	3.6%	$129	0.0
47	Nighttime Ventilation (Versus AC)	Residential	-$1,013	244	0	244	3.6%	$129	0.0
48	Nighttime Ventilation (Versus AC)	Residential	-$418	244	0	244	3.6%	$129	0.0
49	Nighttime Ventilation (Versus AC)	Residential	$106	244	0	244	3.6%	$129	0.8
50	Nighttime Ventilation (Versus AC)	Residential	$484	244	0	244	3.6%	$129	3.8
51	Nighttime Ventilation (Versus AC)	Residential	-$2,766	244	0	244	3.6%	$129	0.0
57	Phase Change Materials	Commercial	$5,863	811	315	10,053	9.2%	$744	7.9
59	Phase Change Materials	Commercial	$4,298	-5,389	310	3,693	1.5%	-$1,242	No Payback
60	Phase Change Materials	Commercial	$6,080	1,261	458	14,683	15.9%	$1,108	5.5

Table 59: Generalized Site Energy Savings and Cost-Effectiveness Summary

Technology	Building type	Projected long-term cost of measure (equipment + installation)	Annual electricity savings (site kWh)	Annual gas savings (site kBtu)	Annual total energy savings (site kWh)	% energy savings (whole building kWh)	Annual TOU utility bill savings ($)	Simple payback (years) (projected long-term)
Aerosol Envelope Sealing	Residential	$3,362	168	7,300	818	6.0%	$97	34.6
Heat Recovery Dishmachines	Commercial	$4,000	5,475	0	5,039	8.0%	$2,063	2.4

Heat Pump Water Heaters (Existing Gas WH)	Residential	$4,000	-2,148	15,200	2,352	4.6%	$61	65.8
Heat Pump Water Heaters (Existing Electric WH)	Residential	$4,000	2,749	0	4,660	8.2%	$625	6.4
Induction Cooking	Residential	$3,000	248	0	249	5.0%	$43	69.8
Induction Cooking	Commercial	$5,500	-10,585	167,900	38,511	0.8%	-$700	N/A
Ducted Mini-Split Heat Pump	Residential	$26,016	-290	3,600	757	13.0%	-$53	N/A
Nighttime Ventilation (Versus AC)	Residential	-$514	244	0	244	3.6%	$129	Immediate
Phase Change Materials	Commercial	$4,109	-1,106	36,100	9,476	8.9%	$203	20.2

4.2: Key Findings

Key findings and lessons learned from each technology demonstration project, along with overall conclusions, are described in the following sections.

Ducted Mini-Split Heat Pumps (13% Whole-House Energy Savings)

- The MSHP systems designed and installed for this study did not demonstrate cost-effectiveness as a retrofit option. The two main reasons were the cost of labor and converting from natural gas to electricity. When converting from gas to electricity, a technology must be very energy efficient to overcome the additional cost of electricity. However, there could be carbon emission savings and other non-energy benefits from replacing the furnace with a heat pump.
- None of the seven test sites had PV systems. In applications with PV systems in place, the MSHP systems designed for this research project may become cost-effective as a retrofit. Applications in new construction could also show more positive results.
- The start of the COVID-19 pandemic in early 2020 complicated the cost-effectiveness analysis considerably. The occupants spent more time at home, and indoor comfort preferences were tighter for many homeowners, resulting in higher heating and cooling energy than would have occurred otherwise.
- The MSHP systems installed at the seven test sites resulted in very positive feedback from the homeowners, with high satisfaction related to system performance, energy efficiency, and perceived comfort.

GIHPWH (4.6% and 8.2% Whole-House Energy Savings when Replacing Gas and Electric Resistance Water Heaters Respectively)

- GIHPWHs are a viable technology for the residential retrofit market because they show strong energy savings and positive cost savings even when replacing gas water heaters, and the grid interaction component coupled with smart occupant water usage behavior can successfully avoid the consequences of peak demand pricing.
- The grid interaction capability was shown to reduce the operating costs of HPWHs significantly.
- The sites that had the longest paybacks often ran the largest number of loads of laundry or dishes during peak periods, and tended to be the sites with the highest number of occupants. This suggests that the storage tank size of 80 gallons might be insufficient for households with more than 5 members.
- One important installation issue for this technology is the choice of location. Unfortunately, as a retrofit technology, the location of a water heater is difficult to change. However, placing a HPWH in a cold garage or in an unheated room is known to lessen its COP, so new construction contractors and designers need to be aware that placing HPWHs in conditioned spaces or in rooms known to get hot will improve their

performance. Alternately, evaporator inlet and/or outlet ducting can be installed to improve temperature conditions.

- HPWHs share a barrier with all electric technologies poised to replace many gas appliances in that they can involve significant upgrades to a building's electrical system, including upgrading the utility service capacity and installing a new circuit breaker panel. During this project's participant screening process, only homes with adequate reserve electrical capacity were chosen. This may be an even greater concern for larger HPWHs installed in commercial or multifamily buildings with limited electrical service.

Induction Cooking (5% and 0.8% Whole-Building Energy Savings for Residential and Commercial Buildings Respectively)

- Some energy savings came from effectively decommissioning pilot lights in a commercial setting.
- Generally, stovetops in residences don't see enough energy usage for the incremental efficiency gains from switching from gas to induction to be able to offset the increased cost of electricity, so this technology does not present homeowners with the ability to save money on their energy bills except when the home is powered by solar.
- Induction stovetops are widely available for both the commercial and residential markets and are as easy to install as gas ranges. Standalone units are plug-and-play, and countertop-embedded units require running wire from a breaker as opposed to running gas pipe from the building's main.
- The most significant barrier to widespread adoption is public education. The narrative around electric stovetops is still dominated by peoples' negative experiences with resistance coils. There is anecdotal evidence that many people think gas ranges offer a superior cooking experience to any electric products and need to have the visceral experience of cooking with induction. This is one of the reasons for the rise in popularity of induction cooktop lending programs among electric utilities.

Exhaust Heat Recover Dishmachines (8% Whole-Building Energy Savings)

- Exhaust heat recovery dishmachines have the potential to save significant amounts of energy in commercial foodservice facilities.
- For undercounter and door-type models, the barriers to wide-spread adoption are the significant up-front cost of dishmachines, which generally keeps old conventional-efficiency machines working in facilities well past their intended working lifetimes, and the additional time per wash cycle, which can present some throughput problems for higher volume facilities or facilities which have rush periods.
- For a typical restaurant, the dishwasher can represent up to 75% of the total hot water load, which means that it's one of the main drivers of the hot water system design. Installing a cold-feed only dishmachine at a site with a gas water heater presents an opportunity to significantly downsize a hot water system in terms of pipe length and diameter as well as the size of the water heater. Upgrading to an exhaust heat recovery dishmachine is therefore an important step towards upgrading a gas water heating

system to an electric heat pump water heating system because it will reduce the hot water load on the water heater enough so that commercially available heat pumps can keep up with demand.

Aerosol Envelope Sealing (6% Whole-House Energy Savings)

- The AeroBarrier sealant was highly effective in reducing infiltration, on average sealing the envelope by 83.3% and reducing the whole home infiltration by 57% as seen from the blower door measurements taken before and after the sealing for the ten test sites.
- The reduction in envelope leakage from AeroBarrier often translated to ample energy savings for the technology to be cost-effective. The average gas and electricity savings found for the ten test sites were 2,210 kBtu/year and 168.2 kWh/year respectively. The optimal energy savings for these technologies offered $121 savings per year in utility bills leading to an average payback period of 25.5 years. However, energy savings depended on the magnitude of leaks in parts of the home that weren't addressed by AeroBarrier, such as leaky window frames, leaky floors, or a leaky duct system. It also appeared that the middle floor apartment units saw minimal energy savings from the aerosol sealing in the Sonoma County climate.
- Aeroseal proved to be very effective when sealing duct systems at the test sites. Reductions in duct leakage ranged from 20% for the site that received manual duct repair prior to the Aeroseal, and 76% - 93% were seen among the two apartment units, leading to an average improvement of 70%.
- Many of the sites responded that they found aerosol particles around their home, such as in their door jambs, on door latches, around electrical outlets, and on their flooring. It is recommended that contractors spend more time cleaning the site prior to leaving so the brunt of the cleaning does not fall upon the homeowner or tenant.
- It is important for contractors to be well-versed in combustion air ventilation and ASHRAE 62.2 requirements to ensure the process does not lead to any safety hazards.

PCM in Commercial Applications (8.9% Whole-Building Energy Savings)

- The results for PCM in commercial applications indicate that for sites similar to those selected for the demonstration project, the technology leads to an average of 8.9% whole-building energy savings and a simple payback period of 20 years.
- There appears to be significant energy savings for PCM installed in drop ceilings, especially if the melting point is properly aligned with the temperature of the ceiling during the cooling months.
- Comfort improved in certain cases according to the business owners, but it was only quantifiable when there was no air conditioning.
- The Templok product appears to be durable based on observations one year after the retrofit.
- The weight of the product caused a number of concerns with business owners prior to installation, and in one case it appears that some of the ceiling tiles have cracked or deformed due to the weight. Further documentation of the structural analysis

performed by the vendor would be helpful, along with additional guidance on installation best practices.

- The installation process seemed to be quick and efficient for most business owners and contractors.
- Based on the results of this study, the Templok technology seems very promising for further deployment in the right applications. Incentives may be necessary to ensure cost-effectiveness for business owners, perhaps 50% of material costs to reduce the 20-year estimated payback to 10 years.

Nighttime Ventilation (3.5% Whole-House Energy Savings Versus A/C)

- Nighttime ventilation (NTV) is a relatively low-cost retrofit that can be marketed as a niche product to homeowners with relatively small homes, central heating systems with the air handling unit in the attic, and no AC.
- Using NTV instead of AC reduced whole building peak period energy use by 15% based on our energy modeling results.
- Marketing of this system should emphasize that it can be an alternative to installing AC, but that it cannot promise that occupants will be comfortable at all times, or that bills will be reduced. Rather, it can provide an improvement in comfort compared to what they have now, at a lower cost than installing central AC.
- Because it is cheaper than AC in most cases, and saves on energy costs, it is clearly a cost-effective alternative to AC. But in this demonstration, it cost only about $400 less to install than a central AC system, and saved only $129/year, so economics are not likely to drive its adoption. It does not provide comfort at the same level as AC, so it will be hard to convince the majority of homeowners.
- However, many users in this demonstration liked the system and appreciated that it allowed them to be more comfortable and to avoid installing a new AC system.
- If it is installed by qualified HVAC contractors who are familiar with making modifications to existing systems, including making ducting alterations in the attic and integrating with existing thermostats, and marketed to homeowners who are environmentally inclined but also desire to improve comfort, it is a promising technology.

General Conclusions

- Lead Locally successfully demonstrated seven emerging retrofit technologies across a broad range of applications, learning a great deal about remaining technical and market barriers that must be addressed before broad deployment is likely in Northern California.
- All technologies performed well from a technical standpoint. The energy savings was a significant fraction of whole-building energy use for all technologies, and there were no customer complaints that weren’t resolved.
- Close collaboration between SCP, Frontier, manufacturers, and installers was essential for selecting quality sites with supportive building owners, ensuring the retrofits were

installed and monitored effectively, and addressing issues immediately once they were identified.

- Energy cost savings and cost-effectiveness varied greatly for different technologies and at different sites, ranging from -3% to 64% energy savings and from immediate payback to 1000 years. The specific application is a very important consideration, along with the remaining useful life of existing equipment. It is important to develop guidance for building owners to determine if they are a good candidate for each technology.
- Technologies that included fuel substitution were sometimes cost-effective if the improvement in efficiency overcame the higher cost of electricity. In applications with PV, the cost-effectiveness would be greatly improved.
- COVID-19 created several challenges for the project, affecting site recruitment and reliable calculation of pre-retrofit energy usage.
- Trained contractors are readily available for some technologies (such as induction cooking and HPWHs), but other require further infrastructure development to reduce installation costs (PCM, Aerobarrier, nighttime ventilation, ducted mini-splits).
- Based on post-retrofit surveys of building owners, they were generally satisfied or very satisfied with the technologies installed and their experience with the Lead Locally program.

4.3: Areas for Further Research

Several ideas for future research on the technologies demonstrated for Lead Locally became apparent as we executed the project:

- There is a broad range of possible mini-split heat pump retrofits. Only one design was tested for Lead Locally. Additional field studies of other options would be valuable to help determine the best design across a range of residential and small commercial applications.
- There is great potential to demonstrate cost-effective fully-electric kitchens. A full in-situ field retrofit study would improve our understanding of the cost-effectiveness and installation costs of fully electric kitchens.
- It would be valuable to repeat the exhaust heat recovery study with larger dishmachines. The energy savings from heat recovery on these larger machines would be significantly higher than the savings from the smaller undercounter machines and because throughput is set by the conveyor speed, they will have less of a throughput issue. More research is needed to determine the expected ROI and energy savings from this type of retrofit.
- From the three points of reference consisting of the initial leakage, initial post-retrofit leakage, and the leakage taken 11–19 months after the AeroBarrier installation, the effectiveness of air sealing degraded 27% on average. Further research is recommended to take multiple blower door measurements from one month to 3 years after the retrofit to determine to what extent and how rapidly the sealant degrades.

- Lab testing of the commercial PCM technology installed in drop ceilings would be helpful for determining optimal temperatures and actual energy savings under controlled conditions. The Lead Locally demonstration project and most of the published information is based on case studies that may or may not be representative of all applications and climate zones.
- Evaluation of potential for nighttime ventilation as a retrofit in combination with air conditioners would be a worthwhile project. Using nighttime ventilation in homes that do not have air conditioning had not been previously studied, and since there are many such homes in SCP territory, that was the sole focus of this study. However, combining nighttime ventilation with air conditioning is also expected to be a very beneficial retrofit in this region.

GLOSSARY

ACH50—Air changes per hour measured at a pressure of 50 Pascals. A metric used for expressing the air leakage of a building envelope.[12]

ADVANCED ENERGY CENTER—Sonoma Clean Power's customer center located in downtown Santa Rosa, which makes the latest clean energy technologies accessible all under one roof, with 0% financing, deep discounts, and a network of qualified contractors.[13]

AEROSOL ENVELOPE SEALING—The process of using an aerosol spray and pressure to seal a building, reducing air leakage.[14]

AEROSOL SEALING—The process of using an aerosol spray and pressure to seal a building and/or ventilation system, reducing air leakage.[15]

THE AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS (ASHRAE)—Founded in 1894, is a global society advancing human well-being through sustainable technology for the built environment. The Society and its members focus on building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the industry.[16]

ASHRAE 62.2—A standard for Ventilation and Acceptable Indoor Air Quality in Residential Buildings.[17]

12 DOE EERE "Infiltration meets ACH50 requirements" webpage https://basc.pnnl.gov/information/infiltration-meets-ach50-requirements

13 SCP Advanced Energy Center about webpage https://scpadvancedenergycenter.org/about

14 DOE EERE "Aerosol Envelope Sealing in New Construction" webpage https://www.energy.gov/eere/buildings/aerosol-envelope-sealing-new-construction

15 EERE "Aerosol Envelope Sealing in New Construction" webpage https://www.energy.gov/eere/buildings/aerosol-envelope-sealing-new-construction

16 ASHRAE about webpage https://www.ashrae.org/about

17 ASHRAE Standards 62.1 & 62.2 webpage https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

CFM25—The volume of air delivered per minute measured at a pressure of 25 Pascals.[18]

COMMERCIAL DISHMACHINES—Automated machines that can clean and sanitize a large quantity of kitchenware in a short amount of time by utilizing energy, hot water, soap, and rinse chemicals.[19]

DEFROST CONTROLLER—A device that periodically cycles cooling and heating periods to eliminate built up frost that may impede the operation of air conditioner components.[20]

DROP CEILING—A ceiling suspended from the floor or roof construction above.[21]

DUCTED MINI-SPLIT HEAT PUMP (DMSHP)— A term used to refer to variable capacity air-source heat pumps that are small (generally less than 1.5 tons of cooling) and paired to one or more ducted air handlers.[22]

ECONOMIZER (Air)—A ducting arrangement and automatic control system that allows a heating, ventilation and air conditioning (HVAC) system to supply up to 100 percent outside air to satisfy cooling demands, even if additional mechanical cooling is required.

ENERGY STORAGE—The practice of storing thermal energy in building components or systems to achieve load reduction.[23]

---

18 DOE "Air Distribution Retrofit Strategies for Affordable Housing" webpage https://www.nrel.gov/docs/fy14osti/61432.pdf

19 Energy Star "Commercial Dishwashers" webpage https://www.energystar.gov/products/commercial_dishwashers

20 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

21 Webster definition of "Suspended Ceiling" https://www.merriam-webster.com/dictionary/suspended%20ceiling

22 Green Building Advisor "Ducted Air-Source Heat Pumps from American Manufacturers" article https://www.greenbuildingadvisor.com/article/ducted-air-source-heat-pumps-from-american-manufacturers

23 DOE EERE "Thermal Energy Storage" webpage https://www.energy.gov/eere/buildings/thermal-energy-storage

FORCED AIR UNIT (FAU)—A HVAC system component containing a fan or fans and other necessary equipment to perform one or more of the following functions: circulating, filtration, heating, cooling, and mixing of air; usually connected to an air-distribution system.[24]

GRID INTERACTIVE—Systems that are designed to operate in response to signals from utilities or third-party aggregators to control operation.[25]

GRID-INTERACTIVE HEAT PUMP WATER HEATERS (GIHPWH)—HPWHs that are designed to operate in response to signals from utilities or third-party aggregators to control operation while still providing consistent and reliable hot water to the occupants.[26]

HEAT FLUX—The flow of energy per unit of area per unit of time. It is sometimes called thermal flux and also referred to as heat flux density or heat flow rate intensity. It has both a direction and a magnitude, so it is a vectorial quantity.[27]

HEAT PUMP WATER HEATERS (HPWH)—Systems that heat and usually store water as for domestic use. They do this by using electricity to move heat from one place to another instead of generating heat directly.[28]

INDUCTION COOKING—The use of an electromagnetic coil to create heat in compatible cookware.[29]

LEAD LOCALLY—A grant program managed by Sonoma Clean Power, primarily funded through the California Energy Commission. The program aims to develop strategies to double energy efficiency in existing buildings and measure the results of the prospective technologies, prior to launching future customer programs.[30]

MINISPLIT HEAT PUMP (MSHP)—An encased, factory-made assembly or assemblies designed to be used as permanently installed equipment to provide conditioned air to an enclosed space(s). It normally includes multiple evaporators, compressor(s), and condenser(s).[31]

---

24 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

25 CEC&S "Single Family Grid Integration" https://title24stakeholders.com/wp-content/uploads/2020/10/SF-Grid-Integration_Final-CASE-Report_Statewide-CASE-Team-Clean.pdf

26 CEC&S "Single Family Grid Integration" https://title24stakeholders.com/wp-content/uploads/2020/10/SF-Grid-Integration_Final-CASE-Report_Statewide-CASE-Team-Clean.pdf

27 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

28 DOE "Heat Pump Water Heaters" webpage https://www.energy.gov/energysaver/heat-pump-water-heaters

29 Energy Star "2021-2022 Residential Induction Cooking Tops" webpage https://www.energystar.gov/about/2021_residential_induction_cooking_tops

30 SCP "Energy-Saving Upgrades Available to Eligible Homes and Businesses" https://sonomacleanpower.org/news/energy-saving-upgrades-available-to-eligible-homes-and-businesses

31 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

NIGHTTIME VENTILATION (NTV)—An automated system to move fresh air throughout a building at night to reduce the temperature of its interior thermal mass, reducing daytime cooling usage.[32]

PEAK LOAD REDUCTION—Changes to the operation of building end uses to minimize the consumption of electricity during utility peak periods.[33]

PHASE CHANGE MATERIALS (PCMs)—Materials that absorb thermal energy as they melt, releasing the absorbed energy when ambient temperatures fall below the material's melting point. By accumulating energy during the day and releasing energy overnight, PCMs reduce building cooling costs and improve energy efficiency.[34]

PHOTOVOLTAIC SYSTEM (PV)—A system capable of generating a voltage as a result of exposure to visible or other radiation. Generally referred to as a solar panel.[35]

RETROFIT MEASURES—An action that is taken to reduce the energy or electricity use of a home or commercial building.[36]

ROOF-TOP UNITS (RTUs)—Packaged air conditioner mounted on a roof, the conditioned air being discharged directly into the rooms below or through a duct system.[37]

SIMPLE PAYBACK—The number of years for energy bill savings after a retrofit to cover its initial investment.[38]

SITE ENERGY—The energy consumed at a building location or other end-use site.

SONOMA CLEAN POWER (SCP)—A community choice aggregator that serves the residents and businesses in Sonoma and Mendocino counties, providing clean energy from more renewable resources, such as geothermal, wind, and solar.[39]

THERM—One hundred thousand (100,000) British thermal units (1 therm = 100,000 Btu).

---

32 Landsman, Jared "Performance, Prediction and Optimization of Night Ventilation across Different Climates " https://escholarship.org/uc/item/6n99w3bx

33 DOE EERE "Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction" https://www.energy.gov/eere/buildings/downloads/impacts-commercial-building-controls-energy-savings-and-peak-load-reduction

34 DOE EERE "Phase Change Materials for Building Applications (SBIR)" https://www.energy.gov/eere/buildings/articles/phase-change-materials-building-applications-sbir

35 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

36 DOE EERE "Retrofit Existing Buildings" https://www.energy.gov/eere/buildings/retrofit-existing-buildings

37 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

38 Science Direct definition of "Simple Payback Time" https://www.sciencedirect.com/topics/engineering/simple-payback-time#:~:text=Simple%20payback%20time%20is%20defined,renovation%20will%20cover%20the%20investment.

39 SCP "Who We Are" webpage https://sonomacleanpower.org/whoweare

TIME OF USE (TOU)—Utility rate plans that can reduce expenses by shifting energy use to partial-peak or off-peak hours of the day. Rates during partial-peak and off-peak hours are lower than rates during peak hours.

UNIFORM ENERGY FACTOR (UEF)—A measure of water heater overall efficiency. The higher the UEF value is, the more efficient the water heater. UEF is determined by the Department of Energy's test method outlined in 10 CFR Part 430, Subpart B, Appendix E.[40]

VARIABLE SPEED—An air conditioning system can use a variable speed compressor (variable capacity system) and or variable speed blower fan.[41]

WASTE HEAT RECOVERY—The recovery of heat that would otherwise be wasted from a system or process.[42]

WEATHER NORMALIZATION—The process of adjusting for the energy your building would have used under average weather. The weather in a given year may be much hotter or colder than a building's normal climate; weather normalization accounts for this difference.[43]

---

40 Energy Star "Water Heater Key Criteria" webpage https://www.energystar.gov/products/water_heaters/residential_water_heaters_key_product_criteria

41 DOE "Heat Pump Systems" webpage https://www.energy.gov/energysaver/heat-pump-systems

42 ASHRAE Terminology webpage https://xp20.ashrae.org/terminology/

43 Energy Star Portfolio Manager Technical Reference https://www.energystar.gov/sites/default/files/tools/Climate_and_Weather_2020_508.pdf

References

Aeroseal, L. (s.f.). *Aeroseal Duct Sealant Safety Data Sheet.* Obtenido de Aeroseal: https://aeroseal.com/sds/

Aeroseal, L. (s.f.). *DEV1667 - AeroBarrier X1 Sealant Safety Data Sheet.* Obtenido de Island AeroBarrier: https://www.islandaerobarrier.ca/wp-content/uploads/2019/02/AeroBarrier-X1-Sealant-Datasheet-and-SDS.pdf

Aeroseal, LLC. (s.f.). *AeroBarrier*. (Aeroseal, LLC) Recuperado el 10 de 11 de 2020, de https://aeroseal.com/aerobarrier/

ASHRAE. (2014). *Measurement of Energy, Demand, and Water Savings.* Atlanta, GA: ASHRAE.

CEC. (2019). *2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings.* Sacramento, CA: California Energy Commission. Obtenido de https://ww2.energy.ca.gov/2018publications/CEC-400-2018-020/CEC-400-2018-020-CMF.pdf

CEC. (February de 2019). *2019 Residential Alternative Calculation Method Reference.* Sacramento, CA: California Energy Commision. Obtenido de California Energy Commision: https://www.energy.ca.gov/sites/default/files/2020-10/2019%20Residential%20ACM%20Reference%20Manual_ada.pdf

Energy and Environmental Economics, I. (2019). *Residential Building Electrification in California - Consumer economics, greenhouse gases and grid impacts.* San Francisco: Energy and Environmental Economics, Inc.

Ferris, T., Froess, L., Meyer-Jones, T., Miller, J., Nittler, K., Roberts, J., . . . Wilcox, B. (2019). *2019 Residential Alternative Calculation Method Reference Manual.* Sacramento, CA: California Energy Commission, Building Standards Office.

Harrington, C., & Modera, M. (2012). *Laboratory Testing of Aerosol for Enclosure Air Sealing.* Golden, CO: National Renewable Energy Laboratory.

Hendron, R., & Chally, S. (2022). *Phase Change Materials in Residential Applications Final Report.* Sacramento, CA: California Energy Commission.

Hendron, R., Bradt, C., Grant, P., Lima, B., Pereira, J., McGoldrick, R., . . . Kuykendall, R. (2019). *Phase 2 Research, Instrumentation, and Monitoring Plan.* Sacramento: California Energy Commission.

Hendron, R., Bradt, C., Grant, P., Lima, B., Pereira, J., Roussev, Y., . . . Kuykendall, R. (2019). *Phase 2 Research, Instrumentation, and Monitoring Plan. California Energy Commission. .* Sacramento, CA: California Energy Commission.

Hendron, R., Bradt, C., Haile, J., Lima, B., Pereira, J., McGoldrick, R., . . . Kuykendall, R. (2018). *Phase 1 Research, Instrumentation, and Monitoring Plan.* Sacramento, CA: California Energy Commission.

James, B., & Delaney, P. (2012). Phase Change Materials: Are They Part of Our Energy Efficient Future? *2012 ACEEE Summer Study on Energy Efficiency in Buildings*.

Michigan, A. (s.f.). *AeroBarrier Michigan*. Recuperado el 10 de 11 de 2020, de https://abmichigan.com/

PG&E. (28 de February de 2022). *Tariffs*. Obtenido de pge.com: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.pge.com%2Ftariffs%2FRes_Inclu_TOU_210801-211130.xlsx&wdOrigin=BROWSELINK

Sonoma Clean Power Authority. (2019). *Technology Demonstration Program Implementation Plan.* Sacramento, CA: California Energy Commission.

U.S. Department of Energy. (2016). *Field Trial of an Aerosol-Based Enclosure Sealing Technology.* Washington, DC: U.S. Department of Energy. Obtenido de https://www.nrel.gov/docs/fy16osti/64741.pdf