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California Energy Commission

FINAL PROJECT REPORT

Residential Hydronic Heating and Cooling Applications by Air-to-Water Heat Pump Systems

Prepared for: California Energy Commission

Prepared by: Frontier Energy

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PREFACE

Project Overview

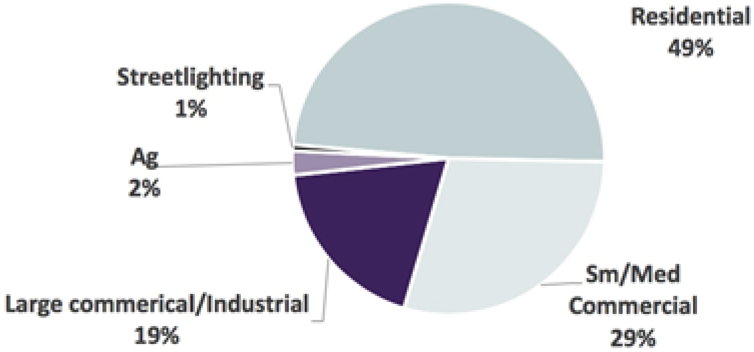
Sonoma Clean Power's (SCP) "Lead Locally" project (Project), funded through the California Energy Commission's (CEC) GFO-17-304 aims to identify strategies and technologies that can assist with the State's goals of doubling the efficiency of existing buildings by 2030. The Project includes applied research and technology deployment activities, each of which will propose innovations that could stimulate the energy efficiency market. With the applied research work, the team is investigating a series of innovative technologies that have the potential to be integrated into existing program models. Lessons learned from the applied research projects will be funneled directly to consumers, contractors, real estate professionals, and building officials through SCP and its local partner organizations. The technology deployment work will be 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) 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 customer 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 1 - SCP Customer Load for 2017.



Sonoma Clean Power Authority (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 does not, under any circumstance, disclose customer information for third-party telemarketing, e-mail, or direct mail solicitation. Aggregated data that cannot be traced to specific customers may be released at SCP's discretion.

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

Project Team, Roles and Responsibilities

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

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

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

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

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

Energy Docs and **Rick Chitwood** designs and installs the radiant panels, air-to-water heat pumps (AWHPs), and load reduction retrofits.

Chiltrix serves as the vendor for the AWHPs and provides informal design guidance and field test support throughout the project.

Huvco and Insolcorp serves as a vendor partner for daylight enhancement technologies and phase change materials, respectively, and provides informal design guidance and field test support throughout the project. Additional product vendors may join the Team and provide support as the Project proceeds.

ABSTRACT

This report documents the results of an applied research project to evaluate the energy performance, cost-effectiveness, and durability of two air-to-water heat pump systems with (1) radiant ceilings panels, or (2) hydronic fan coils, both systems installed in residential homes in Sonoma County, California. This project was part of Lead Locally, an initiative managed by Sonoma Clean Power and funded primarily by the California Energy Commission. The project consisted of field testing in three occupied homes and laboratory testing in Davis, California. The result from the project revealed potential energy savings for radiant ceiling panels, though potentially negative savings for hydronic fan coils. The costs to install the two AWHP systems were both too high to become cost-effective hence, neither system provide sufficient energy savings to justify the initial cost.

Keywords: Radiant ceiling panels, air-to-water heat pump, hydronic fan coil, indirect water heating, Retrofit, Lead Locally, Sonoma Clean Power

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EXECUTIVE SUMMARY

Introduction

This grant evaluated two air-to-water heat pump (AWHP) systems. First, radiant ceiling panels, and second, a hydronic fan coil system with indirect water heating. An AWHP is an “air conditioner” that can also work in reverse and provide heat during cold weather. Meaning, an AWHP can either pull energy from the outdoor air to heat water, or release energy to outdoor air to cool water. For this grant, the “conditioned” water is used to heat or cool the indoor space through either radiant ceiling panels or hydronic fan coils.

Radiant Panels

Radiant panel systems can be constructed in different ways, and can be designed to heat, cool, or both. The panels require surface area towards the living space and contain tubes in which a fluid (typically water) flows, or in some cases electrical wires (only suitable for heating). For hydronic radiant panels, tubes can transport heated or chilled water to either heat or cool the panels. Though these panel systems are intended to primarily heat or cool through the exchange of radiation with the indoor space and occupants, they also transfer energy to the condition space through convection. In this study, a radiant panel system suitable for retrofits was evaluated. The retrofit system included hydronic radiant ceiling panels holding cross-linked polyethylene (PEX) pipes with hot or chilled water from an AWHP.

Hydronic Fan Coils

Hydronic fan coil systems are most often seen in heating dominated climates, as they are easily integrated into existing hot water systems. They are also frequently used in multi-family buildings. In cooling climates and single-family homes, they are often paired with AWHPs to provide both heating and cooling. A three-function AWHP can used to provide space heating, space cooling, and domestic hot water. Thus, this study also evaluates integrating the hydronic heating and colling system with a water tank that serves the house with heated water. This setup is less common, and the cost-effectiveness is yet to be fully evaluated.

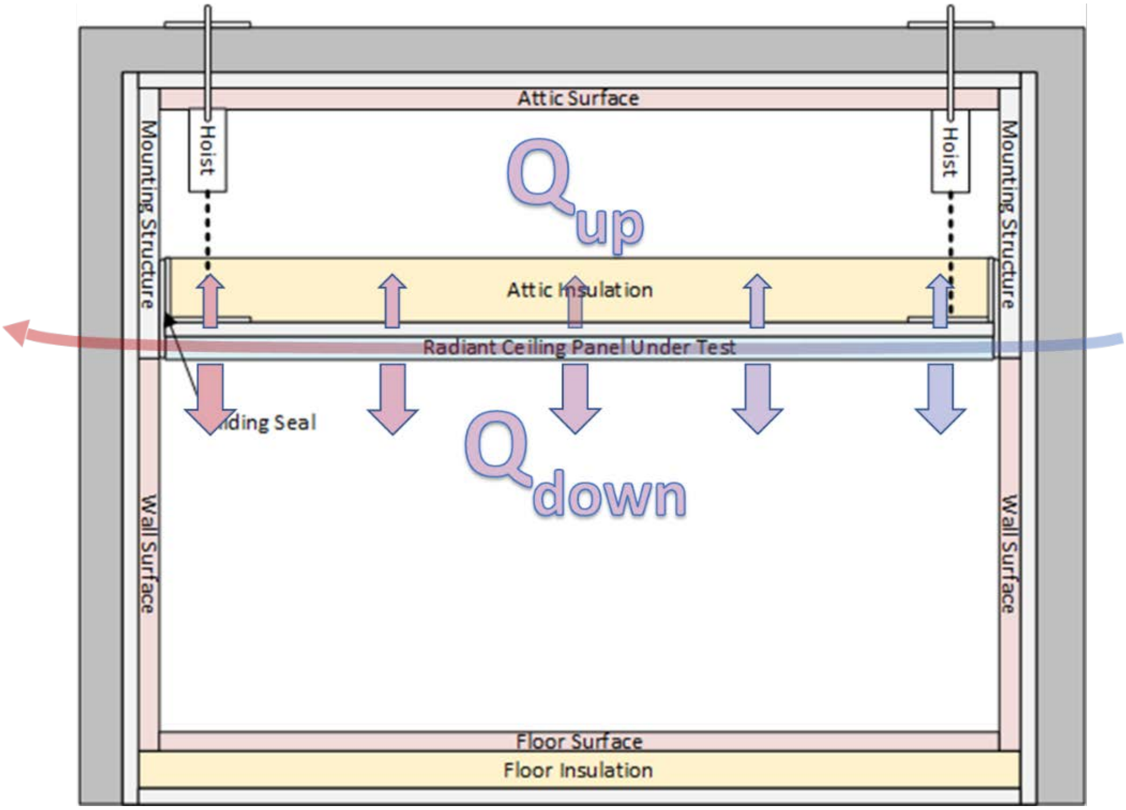
Laboratory Testing

Radiant systems experience conductive thermal losses, typically upwards to the attic space. For this reason, it is important to reduce these losses for the sake of energy use and indoor comfort. Similar to insulating and sealing duct systems, adding insulation between the radiant ceiling panels and the attic space has the largest impact on radiant ceiling losses.

The impact of these losses can be evaluated by calculating the delivery effectiveness, which is the ratio of the quantity of heating or cooling energy delivered to the conditioned space over the total energy provided to the system. Evaluating the thermal delivery effectiveness for a range of attic insulation levels would allow determining a minimum attic insulation level for use with radiant ceiling systems to include in Title 24.

The delivery effectiveness of the radiant panels was evaluated in the Frontier Energy’s Building Science Research Laboratory (BSRL), a 2200 ft^2 test facility in Davis, California. Figure ES 1 provides an illustration of how the radiant panel system was installed in the climate chamber, along with expected heat transfer flow directions.

Figure ES 1 - Diagram of the BSRL indoor environment chamber. The illustration also includes heat transfer from and to the radiant panel system. Q_{down} is the energy given to or taken from the interior space, and Q_{up} is the energy given to or taken from the attic.



The delivery effectiveness was evaluated for multiple design conditions. This was done by measuring the steady state downward heat transfer rate of the panels for a range of operating conditions as presented in Table ES 1.

The performance of the radiant panels and variations in combination of variables resulted in 16 different conducted tests. Using ASHRAE guidelines for radiant panels (ASHRAE, ASHRAE Handbook - HVAC System and Equipment - Chapter 6, 2012), the downward heat flux, Q_{down}, was calculated. Together with Q_{tot}, the delivery effectiveness, δ, was found. Table ES 1 presents the result of the 16 tests.

According to the laboratory data given by Table ES 1, δ varies between 50 to 77% for cooling mode and 54 to 66% during heating conditions. For both heating and cooling, it was found that the level of attic insulation had the highest impact on δ, which varied between either R-19 or R-49.

Table ES 1 - Laboratory result from testing the radiant panel system. All variables are presented together with the delivery effectiveness of the setup.

Insulation R-value ($ft^2 \cdot °F \cdot h/BTU$)	Indoor Temperature (°F)	Attic Temperature (°F)	Water Flow Rate (gpm)	Panel Supply Temperature (°F)	Return/Supply Temperature Difference (°F)	Delivery Effectiveness, δ (-)
19	76	140.0	0.50	50.0	-7.3	**53.1%**
49	76	140.0	0.50	50.0	-5.5	**76.7%**
19	76	140.0	0.50	55.0	-5.8	**47.8%**
49	76	140.0	0.50	55.0	-4.9	**66.0%**
19	76	140.0	0.75	50.0	-4.7	**56.7%**
49	76	140.0	0.75	50.0	-4.1	**75.8%**
19	76	140.0	0.75	55.0	-4.1	**49.3%**
49	76	140.0	0.75	55.0	-3.5	**66.9%**
19	68	55.0	0.50	95.0	5.2	**53.6%**
49	68	55.0	0.50	95.0	4.9	**61.2%**
19	68	55.0	0.50	105.0	7.0	**56.4%**
49	68	55.0	0.50	105.0	6.6	**64.7%**
19	68	55.0	0.75	95.0	3.5	**54.8%**
49	68	55.0	0.75	95.0	3.3	**63.2%**
19	68	55.0	0.75	105.0	4.8	**57.8%**
49	68	55.0	0.75	105.0	4.5	**66.2%**

Field Testing

All test sites were to be located within Sonoma and Mendocino counties and selected from existing SCP customers. Although the field tests were planned to be performed for radiant panels in five single-family homes, ultimately only one home was studied. Unfortunately, as the design and construction process unfolded at the first site, it quickly became evident that the cost of installation drastically exceeded expectations. The total installed cost was projected to be in excess of $100,000 per site. The project team determined that cost-effectiveness for the technology was impossible and, with the approval of the Energy Commission, decided to redirect project efforts to another similar technology. This resulted in only one home receiving the installation of the radiant panel system. Two of the other homes received a hydronic fan coil system with indirect domestic hot water heating, and one home received the mini-split heat pump technology being demonstrated under another Lead Locally task.

Six months of monitored baseline data was collected prior to the retrofits, followed by two years of monitored data collection post-retrofit.

Radiant Panels

The selected home for the installation of the radiant panels is an 1,812 square foot single story house, built in 1989 with three-bedrooms and two baths. Prior to the retrofit, the heating and cooling system consisted of a traditional central ducted HVAC system with natural gas furnace for heating. In addition to installing the AWHP and radiant panels, the building envelope performance was improved by installing R-49 insulation in the attic and caulking and spray foam interfaces (penetrations) between top plates and drywall to reduce air leakage. The duct work was removed.

Table ES 2 presents estimated average costs of natural gas during heating season, and costs of electricity during both cooling and heating season of 2020 and 2021. These rates are used to evaluate actual costs of energy for 2020 and 2021 compared to what they would have been if no retrofit measures were conducted.

Table ES 2 - Actual and estimated cost of energy post-retrofit, and under the scenario that no retrofit measure was undertaken.

Time Period	**No Retrofit (estimated)**							
	Degree Hours [H°F] (Pre-Retrofit Settings)		**Cooling (kWh)**	**Cost[a] ($/kWh)**	**Heating (kBtu)**	**Cost[c] ($/kBtu)**	**Total Cost**	
Start 1/1/2020 **End 12/31/2020**	12761	37741	1085	$0.26	17216	$0.0121	**$490**	
Start 1/1/2021 **End 12/31/2021**	8860	38799	753	$0.28	17698	$0.0143	**$464**	
Start 1/1/2031 **End 12/31/2031**	10811	38270	919	$0.33	17457	$0.0219	**$686**	
Time Period	**Post-Retrofit**							
	Degree Hours [H°F] (Post-Retrofit Settings)		**Cooling (kWh)**	**Cost[a] ($/kWh)**	**Heating (kWh)**	**Cost[b] ($/kWh)**	**Total Cost**	**Annual Savings**
Start 1/1/2020 **End 12/31/2020**	36579	23938	2007	$0.26	1462	$0.26	**$902**	**-$411**
Start 1/1/2021 **End 12/31/2021**	28540	23729	543	$0.28	1315	$0.28	**$520**	**-$56**
Start 1/1/2031 **End 12/31/2031**	32560	23834	1275	$0.33	1388	$0.33	**$881**	**-$195**

[a] *Cost of electricity during cooling season of 2020 and 2021* (PG&E, Tariffs, 2022)*, and cost of electricity for 2031 based on California statewide escalation rates* (Energy and Environmental Economics, 2019)*.*

[b] *Cost of natural gas during heating season of 2020 and 2021* (PG&E, Tariffs, 2022)*, and cost of natural gas for 2031 based on California statewide escalation rates* (Energy and Environmental Economics, 2019)*.*

[c] *Cost of electricity during heating season of 2020 and 2021* (PG&E, Tariffs, 2022)

Table ES 2 also provides an estimate of cost of energy for 2031, based off California statewide escalation rates (Energy and Environmental Economics, 2019). Unfortunately, the estimated annual savings in cost of energy from heating and cooling are negative for both 2020 and 2021 respectively. For 2033, cost savings are also negative and are based on average energy demand for cooling and heating during 2020 and 2021.

The total cost to install the radiant panel system at the test site was about $114,500, including labor, equipment, and material. Since the cost savings from installing the radiant panels are found negative and the installation cost is high, no assessment of present value, return of investment or simple payback time is conducted.

Hydronic Fan Coils

An AWHP system with hydronic fan coils and indirect water heating was installed at two test sites (site A and site B). Both homes are built with a crawlspace, have one-story, and are single-family homes with three bedrooms. In addition to installing the AWHP system, the building envelope performance was improved by installing R-49 insulation in the attic and caulking and spray foam interfaces (penetrations) between top plates and drywall to reduce air leakage. The duct work was also replaced.

Table ES 3 and Table ES 4 reveal an assessment of cost of energy for the two test sites. The assessment includes collected data, as well as predicted data if no retrofit measures were conducted, and future cost of energy based on statewide escalation rates (Energy and Environmental Economics, 2019). During 2020 and 2021, there are negative cost savings for test site A and test site B during 2020 compared to if no retrofit measures were conducted. There is a slight positive cost saving for test site B during 2021. The cost of natural gas and electricity are pulled from average rates during heating and cooling season for each year (PG&E, pge.com, 2022). Even future predicted costs generate negative cost savings according to Table ES 3 and Table ES 4.

Table ES 3 - Test Site A. Actual and estimated cost of energy post-retrofit.

Time Period	No Retrofit (estimated)						
	Degree Hours [H°F] (Pre-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kBtu)	Cost[c] ($/kBtu)	Total Cost
Start 1/1/2020 End 12/31/2020	14960	36734	238	$0.26	14014	$0.0121	**$231**
Start 1/1/2021 End 12/31/2021	10335	44359	164	$0.28	16923	$0.0143	**$288**
Start 1/1/2031 End 12/31/2031	12647	40546	201	$0.33	15468	$0.0219	**$405**

Time Period	Post-Retrofit							
	Degree Hours [H°F] (Post-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kWh)	Cost[b] ($/kWh)	Total Cost	Annual Savings
Start 1/1/2020 End 12/31/2020	12665	50271	100	$0.26	1190	$0.26	**$336**	**-$104**
Start 1/1/2021 End 12/31/2021	8561	60161	94	$0.28	1705	$0.28	**$504**	**-$216**
Start 1/1/2031 End 12/31/2031	10613	55216	97	$0.33	1448	$0.33	**$511**	**-$106**

a, b, and c referenced in Table ES 2

Table ES 4 - Test Site B. Actual and estimated cost of energy post-retrofit.

Time Period	No Retrofit (estimated)							
	Degree Hours [H°F] (Pre-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kBtu)	Cost[c] ($/kBtu)	Total Cost	
Start 1/1/2020 End 12/31/2020	24482	41861	650	$0.26	20720	$0.0121	**$420**	
Start 1/1/2021 End 12/31/2021	17458	23956	464	$0.28	11858	$0.0143	**$299**	
Start 1/1/2031 End 12/31/2031	20970	32909	557	$0.33	16289	$0.0219	**$540**	
Time Period	**Post-Retrofit**							
	Degree Hours [H°F] (Post-Retrofit Settings)		**Cooling (kWh)**	**Cost[a] ($/kWh)**	**Heating (kWh)**	**Cost[b] ($/kWh)**	**Total Cost**	**Annual Savings**
Start 1/1/2020 End 12/31/2020	31059	36193	956	$0.26	1741	$0.26	**$701**	**-$282**
Start 1/1/2021 End 12/31/2021	23317	28068	297	$0.28	703	$0.28	**$280**	**$19**
Start 1/1/2031 End 12/31/2031	27188	32131	627	$0.33	1222	$0.33	**$611**	**-$71**

a, b, and c referenced in Table ES 2

The cost to install the AWHP system with hydronic fan and indirect water heating was about $70,000 for each test site. From the assessment of the cost-effectiveness above, it's made clear that the total cost of labor, equipment, and material far exceeds any potential savings. In fact, with current rates, energy savings from installing the system may potentially be negative.

Conclusions

Several key conclusions were drawn from this applied research project:

- Field testing and lab testing indicate that the energy savings potential is small in the mild Sonoma County climate and even negative in most applications. For the radiant panel test site, the loss in cost of energy varies between $50 to $400 dollars annually during 2020 and 2021. During the same time period, the hydronic fan coil sites indicate losses in cost of energy from about $300 up to $20 in savings annually. The main reason for the lack of cost-effectiveness is a result converting from natural gas to electricity, since price of electricity is significantly higher than natural gas in relation to actual energy given.
- Lab testing indicates that the delivery effectiveness (efficiency) of the radiant panels is mainly influenced by the amount of attic insulation and temperature gradient between the panels and indoor space. Increasing R-value and difference between indoor ambient air temperature and radiant panel supply water temperature, increases efficiency.
- The cost of labor to install the two AWHP heating and cooling systems are too high to become cost-effective for the included test sites. The radiant panel system is more

expensive than the hydronic fan coil to install. About $115,000 for the radiant panels site versus $70,000 for the hydronic system. Because of small to negative savings, cost-effectiveness is beyond reach.

- Because of converting from natural gas to full electric, and the cost of natural gas compared to electricity, the two AWHP systems reveal better saving potential for cooling than heating. This implies that both AWHP heating cooling systems are assumed to generate better cost savings if installed in homes already using electricity for heating.
- To the homeowners, both hydronic systems are perceived as providing higher comfort post-retrofit and cost savings.
- Changes in user behavior and time spent inside the test homes were affected by the spread of SARS-COV-2 and the pandemic. The biggest changes happen almost immediately after the retrofit measures were conducted, which complicated the pre- versus post-retrofit energy and cost savings assessment. The occupants spent more time at home, and indoor comfort preferences changed for many homeowners. Changes 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.

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 applied research portion of Lead Locally focuses on several innovative technologies that will be evaluated through laboratory and field testing with the objective of expanding SCP's and other energy efficiency program administrators' portfolios of cost-effective retrofit options. These applied research projects are designed to remove uncertainty around the installed performance and cost of the technology, especially in combination with other retrofit measures, prior to broad deployment of the technology through the Lead Locally Energy Marketplace. Lead Locally will focus on adapting proven technologies and concepts to new applications by optimizing their performance in creative ways, providing building owners and contractors with the knowledge and tools they need to select the right applications, and installing the technologies in a manner that yields the expected energy savings. If at any point specific technologies prove nonviable for near-term application in Northern California, the remaining funding will be applied to more promising technology demonstration projects or technologies identified through the Energy Marketplace. The four applied research projects have been split into Phase 1 and Phase 2 technologies, allowing accelerated planning and preparation for the projects with the tightest timelines.

1.2 Purpose

The overall purpose of the Lead Locally Grant is to conduct a series of applied research projects and technology deployments and create an Energy Marketplace to increase and expedite energy savings and retrofits of residential and commercial buildings in Sonoma and Mendocino counties.

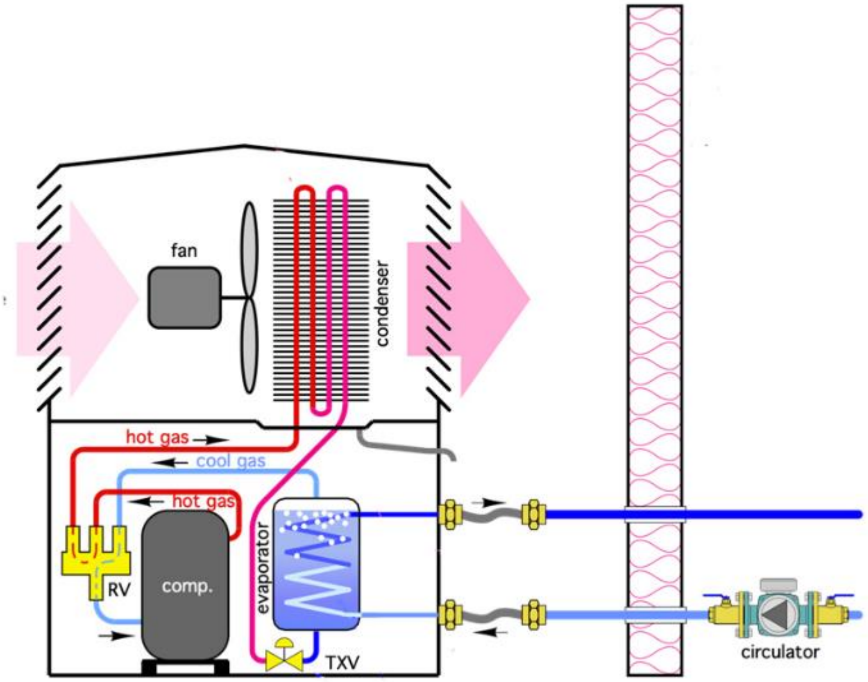
Through Phase 1 Research, Instrumentation, and Monitoring Plan, the purpose is to document the methodology that will be used by the project team to select, refine, characterize, and evaluate specific retrofit measures involving innovative building technologies or applications that present some level of performance or economic risk to building owners and occupants. Phase 1 technologies are on the critical path for Lead Locally and require an accelerated planning schedule to meet later program targets for deployment and technology transfer within the 3½ year timeframe of the grant.

1.3 Technology Overview

Locating ductwork in unconditioned attics and crawlspaces has been standard practice in California for at least 50 years due to low installation costs, but this approach typically results in significant distribution losses. The radiant ceiling panel system is one potential cost-effective retrofit method to reduce distribution losses, although it does require a transition from forced air space conditioning to more passive hydronic delivery. Recent work has shown that radiant ceiling panels with an energy efficient air-to-water heat pump (AWHP), can provide comfort superior to high performance forced air systems with ducts in conditioned space, while consuming comparable amounts of energy (Haile, Springer et al. 2018).

AWHPs consist of an outdoor unit that contains a compressor, heat exchanger coil, fan, and supply and return piping that connects to an indoor thermal distribution system. What is different compared to a traditional central air conditioner is that it uses water to convey heat to and from air handlers or other distribution components instead of refrigerant. The heat exchange to indoor components is from water to air instead of refrigerant to air. Figure 2 shows the basic components of the AWHP outdoor unit.

Figure 2 - Simplified diagram of the inner workings of an AWHP (Image credit: John Siegenthaller).



AWHP’s have been available in California for over ten years but are still not common. Below are some reasons why homeowners, designers, and contractors should become familiar with them:

- They can be used with ducted forced air distribution, radiant panels/floors, or both.
- They can provide heating, cooling, and water heating from one outdoor unit, often called “triple” or “three function” operation.
- They allow for zoned distribution without the problems associated with furnaces and air-to-air heat pump systems.

- “Monoblock” (or “monobloc”) systems are factory charged so there is no risk of refrigerant leakage from connections and field discharge of refrigerants. In addition, factory charging should result in precise levels of charge for the application, rather than the less precise field charging of conventional air conditioners and heat pumps.
- In most cases they can be installed without electric resistance heat for space heating or water heating, reducing energy use and peak electricity.

Meeting California’s 2045 zero carbon emissions goal (CEC, 2021) will require every existing home to replace gas furnaces and water heaters with heat pump-based systems. Many homes built before the 1980s have 100- or 125-amp electrical service which are less likely to support the installation of air-to-air heat pumps and heat pump water heaters, let alone electric cooking appliances and electric vehicles. The cost to upgrade an electrical service to 200 amps varies depending on whether the existing service is provided above or below ground. Above ground panel upgrades may cost as little as $2,000. For underground service, the cost will depend on whether the cable is in a conduit or directly buried and may exceed $7,000. A compilation of several sources cites an average cost of $4,256 (Energy and Environmental Economics, 2019).

AWHPs offer the additional following advantages for electrifying older homes:

- In many cases they may eliminate the high cost of upgrading the electrical service because they use a single compressor for space conditioning and water heating and can be used on the circuit previously assigned to the air conditioner condensing unit.
- With proper sizing they can be installed without inefficient electric resistance heating that is needed by air-to-air heat pumps for defrost cycle reheat and by heat pump water heaters for supplemental heat.
- They do not require adding a 240V circuit for the air handler as may be required for conventional air-to-air heat pumps.

During the course of this project, it was determined to shift focus from radiant ceiling panels to hydronic fan coils. Still, using the AWHP to provide chilled or hot water for space cooling and heating but now using a hydronic fan coil and ducted system to provide conditioned air. The reasoning behind this decision is explained in Section 2.6.

1.4 Objectives

The overall goals of the grant are to:

- Evaluate energy and cost savings of emerging technologies.
- Accelerate the rate of adoption of market-ready and advanced technologies.
- Design a viable, replicable, and scalable deployment strategy that overcomes barriers to retrofits.
- Streamline access to financing and incentives for energy efficiency projects.
- Maximize energy efficiency retrofit participation.
- Transfer program concepts and lessons learned to a robust set of program partners.
- Achieve a minimum 10% average (residential) and 20% average (commercial) reduction in on-site electricity consumption.

Overall grant objectives are to:

- Perform applied research experiments and quantify the cost-benefits of emerging or advanced technologies, including: grid integrated heat pump water heaters; radiant ceiling heating and cooling; air to water heat pumps; commercial daylighting retrofits; and residential attic Phase Change Material(s) (PCM).
- Identify the most promising technologies.
- Create an Energy Marketplace to promote the most promising technologies from the applied research phase and other existing technologies as solicited through the RFQ process and provide training for building professionals.
- Provide rich data sets from applied research, technology demonstrations, and analysis of customer electricity use and customer green button data.

The specific goals and objectives originally set for this project task were to determine the effectiveness of radiant ceiling heating and cooling systems compared to more traditional heating and cooling systems used in California and to evaluate the potential of these systems in more traditional rebate programs and/or deployment in the Energy Marketplace.

Frontier Energy aimed to:

- Recruit and enlist at least five houses in SCP service territory that meet the criteria defined in the research, instrumentation, and monitoring plan (Subtask 3.1) using the Energy Marketplace, direct mailing, homeowner associations, customer data analysis, or another marketing approach.
- Meet with the test house homeowners in a group setting to explain the technology, test plan, and responsibilities for all parties.
- Perform energy audits on all five homes to identify simple measures that can be performed to reduce space conditioning loads.
- Write energy audit reports documenting the condition of each house, characteristics of key energy consuming systems, building simulation results, and recommended retrofit measures.
- Implement building envelope retrofits identified through the energy audits.
- Install pre-retrofit instrumentation package and initiate real-time monitoring.
- Design the radiant ceiling heating and cooling equipment packages for each house, including system sizing, layout, and controls.
- Identify two test sites for which the air-to-water heat pump will provide water heating capability in addition to delivering hot and cold water to the radiant ceiling panels.
- Procure the equipment and material necessary for the retrofits.
- Retrofit each house with a radiant ceiling heating and cooling system and air-to-water heat pump, and two with an integrated water heating system.
- Perform post-retrofit commissioning of new equipment.
- Install additional instrumentation necessary for the post-retrofit period as defined in the Research, Instrumentation, and Monitoring Plan and EM&V Framework developed in Task 3.

- Monitor performance of the radiant ceiling heating and cooling systems and make adjustments as necessary to ensure proper operation.
- Respond to concerns expressed by homeowners throughout the test period.
- Develop a Program Participant Satisfaction Questionnaire for Homeowners to document satisfaction with the equipment, along with feedback on any more nuanced issues (such as noise or comfort) that may not have been captured by the instrumentation package.
- Ask homeowners to complete the questionnaire and then process the information, concerns, and feedback provided.
- Remove instrumentation from all five houses at the end of the test period.
- Prepare a Radiant Ceiling Heating and Cooling/Air to Water Heat Pumps Report. The report shall identify the outcomes of the research and data collection performed as part of the project. The report shall contain, at a minimum, a report of retrofit costs, an analysis of pre- and post-retrofit energy and cost savings over the 12-month testing period, an extrapolation of the data for the five installation sites to be representative of California's diverse climate zones, and results of the occupant surveys, thermostat setting data, circuit level monitoring, occupancy sensors, and window operation data.

1.5 Methodology

The applied research for this project was completed in two primary phases:

1. **Laboratory Testing** – Develop sizing methods for radiant panels by developing a dataset of downward heat transfer coefficients for a range of panel flow rates, inlet water temperatures, and design conditions.
2. **Field Testing** – Evaluate the laboratory-developed sizing method by retrofitting radiant systems to existing homes. The field tests will also quantify electricity and natural gas energy use impacts, retrofit costs, and payback periods for radiant ceiling panels. These results will also be compared to moving ducts into conditioned space, using the mini-split heat pump (MSHP) retrofit houses monitored under task 6.5.4. Through a series of post-installation surveys and monitoring, occupant behavior and satisfaction with the radiant ceiling panels will also be compared to ducted systems.

Each field test site included a well-established baseline that was compared to the retrofit case for the purpose of calculating energy saving.

Partners for this project included:

- **Frontier Energy Inc.** (Frontier), formerly Davis Energy Group (DEG), has over 35 years of experience evaluating residential technologies. Through a national workshop series presented in 1984, DEG helped inspire a resurgence of radiant technologies. Key Frontier Energy staff on this project include James Haile, P.E., Simon Pallin, PhD, and David Springer.
- **Energy Docs Home Performance** is a licensed General Building Contracting company in Redding, CA specializing in performing comprehensive home performance retrofits to existing homes. Mike MacFarland, owner of Energy Docs, has over twenty-five years of construction experience, as well as extensive research experience.

- **Rick Chitwood,** owner of Chitwood Energy Management, is an expert in energy-efficient residential building construction and a leader in building science-based design. Rick's work on research projects in California has contributed to each revision of the California Building Energy Efficiency Standards since 2001.

1.6 Success Criteria

The following topics were evaluated to determine overall project success: electricity savings, economic and non-energy benefits.

Electricity Savings

The radiant panels and hydronic fan coils were selected technologies because of being expected to notably improve the existing baseline site electricity consumption, moving it towards the portfolio level target of 10% site electricity reduction for the residential sector and 20% for the commercial sector.

Economic Benefits

The selected technologies were also evaluated in terms of their benefits and applicability for wider adoption across the entire SCP territory of customers and further across the State of California through IOU EE programs. This task defined success of the initial trials based on contractors' skills and capability gaps, allowing SCP to strategize development of a Workforce Education and Training delivery program to increase scaling through the Energy Marketplace. The development of territory-wide EE programs that include the successfully verified innovative technologies will have long-lasting positive economic benefits to the residents of Mendocino and Sonoma counties.

Cost-effectiveness of measures was evaluated from two different standpoints. Firstly, that of the homeowner whose home is being retrofitted, utilizing metrics such as simple payback and return on investment. Secondly, data was collated to support the evaluation of the overall program in conjunction with the CPUC framework for cost-effectiveness, which is needed for future inclusion of the measures in ratepayer funded Energy Efficiency programs.

Non-energy Benefits

The project team monitored and recorded baseline non-energy factors. Project completion included a comprehensive occupant acceptance procedure inclusive of a building owner questionnaire that identified any issues requiring further improvement prior to the measure being included in the Energy Marketplace.

CHAPTER 2: Radiant Panels with Air-to-Water Heat Pumps

2.1 Background and Operation

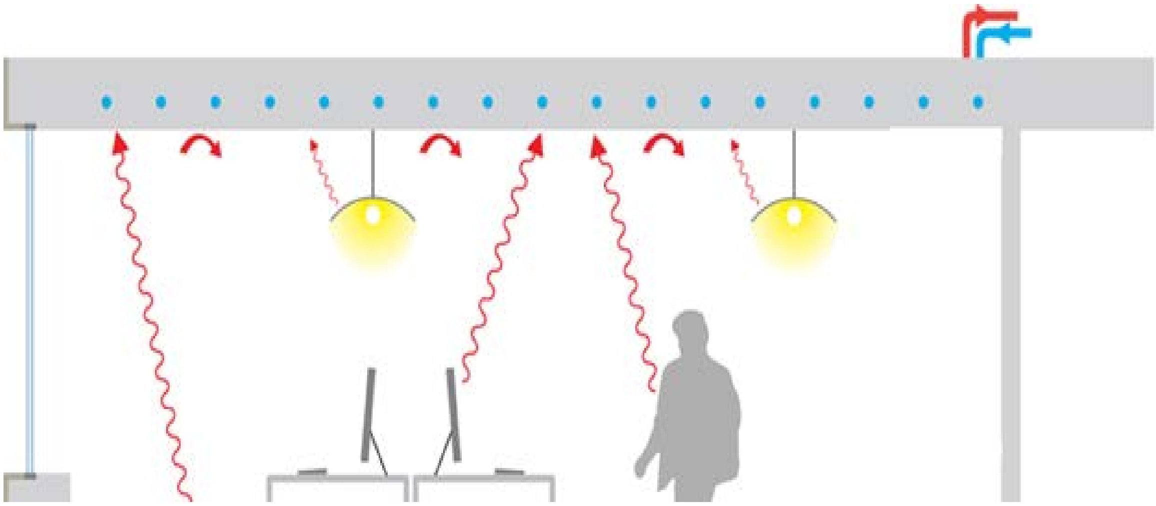
Traditional forced air systems distribute heated and cooled air through ducts (commonly in attics) into the conditioned space. In addition to duct thermal losses during operation (due to conditioned air losing energy to hot or cold attics) ducts also are leaky and result in direct loss of conditioned air to unconditioned space. Bringing ducts into the conditioned space will eliminate the negative impact of duct losses. In new construction, allowing for ducts installed inside the conditioned space is easier to implement than in most retrofit applications. Here, radiant panel systems offer an alternative solution to reduce distribution losses, while being less intrusive to install, and providing equal or superior comfort compared to forced air systems.

Radiant panel systems can be constructed in different ways, and can be designed to heat, cool, or both. The panels require surface area towards the living space and contain tubes in which a fluid (typically water) flows, or in some cases electrical wires (only suitable for heating). For hydronic radiant panels, tubes can transport heated or chilled water to either heat or cool the panels. Though these panel systems heat or cool through the exchange of radiation with the indoor space and occupants, they also transfer energy to the condition space through convection to a degree. In general, the larger the temperature difference between the fluid and the ambient indoor air temperature, the higher the ratio of radiant to convective heat exchange. The temperature of the fluid depends on various factors, such as indoor thermal loads, total radiant panel surface area, indoor relative humidity levels, the size of the tubes and the fluid flow rate. The indoor relative humidity is of minimal concern during the heating season, but during the cooling season it is important that the indoor air wet-bulb temperature never exceeds that of the panel surface temperature. In such case, water vapor may condensate on the panel surface. Even temperatures close to indoor air wet-bulb should be avoided since mold growth may initiate at a relative humidity of 80% (ASHRAE 2016). In most California applications, high indoor humidity is uncommon, however this should be reviewed as part of the design process.

To fully appreciate the advantages of radiant panels, one will benefit from brief understanding of the exchange of energy for which radiation presents. Radiation, or infrared electromagnetic radiation to be accurate, is a physical phenomenon that exists at the surface of all materials. In other words, everything emits radiation, always. The intensity of radiation emission depends on material properties and surface temperature of both the emitting surface and the surrounding absorbing surfaces. Materials with higher temperature emit more compared to materials with a relatively lower temperature. With that said, at any material surface there is a constant exchange of emitting and absorbing radiation. Simultaneously, there is an exchange on heat from convective and conductive heat transfer. The net heat flux will determine whether the temperature of the surface will increase, decrease, or remain the same. The concept of radiant panels during heating cycles is to emit radiation to surrounding objects and thus increase their surface temperature. While the radiant panels emit more radiation than they absorb, the temperature of the panels will drop. Therefore, a circulating fluid is required to maintain the temperature of the panels. The opposite is true during cooling. In this case, the panels are kept cooler than the surrounding environment, causing adjacent surfaces and objects to emit more radiation to the panel than that being absorbed. Thus, dropping in temperature.

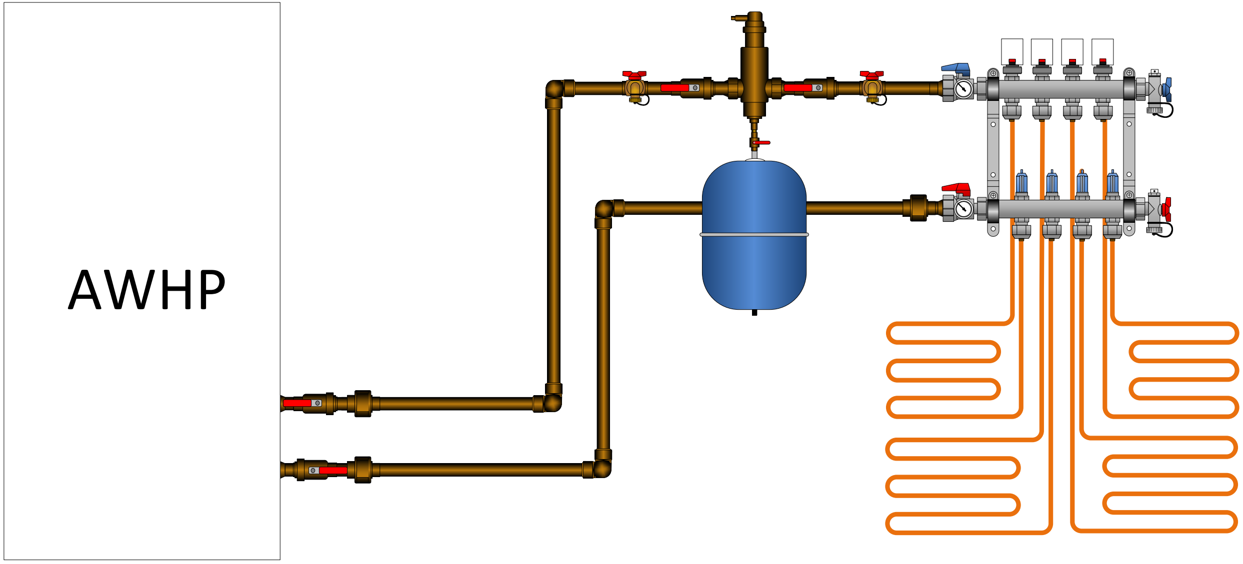
Figure 3 provides a representation of heat transfer effects in a room during a cooling cycle. As touched upon earlier, some heat/energy exchange occurs at the panel surface via natural convection. Ceiling panels are preferred over floor panels in cooling dominated climates since warmer air is more buoyant and naturally rises only to drop after being cooled by the panels. Because radiative heat transfer is more direct than convection, comfort can be delivered at higher cooling setpoints and lower heating setpoints, which can translate to energy savings and improved equipment efficiency.

Figure 3 - Conceptual exchange of energy from heating panels in a conditioned space during cooling cycles. Solid arrows represent convective heat transfer and curved arrows represent emitted radiation by surrounding objects (Image credit: Caroline Karmann, Center for the Built Environment at UC Berkeley).



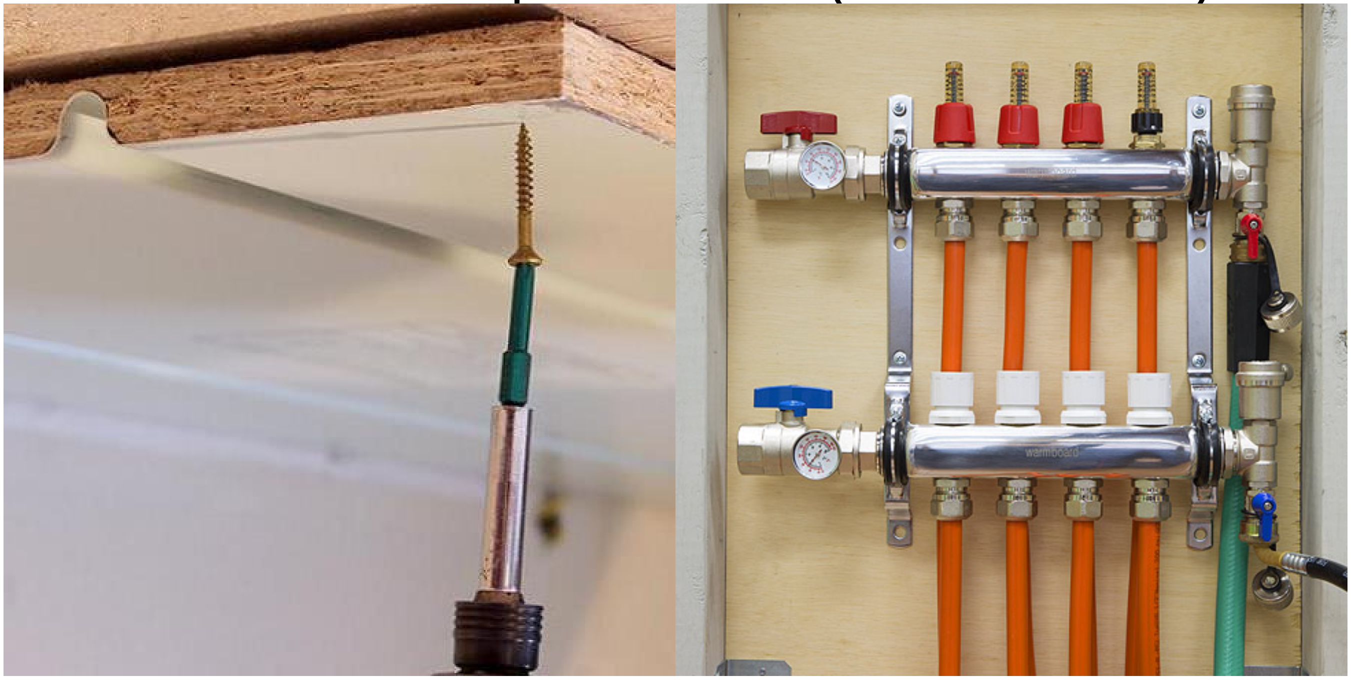
Radiant ceiling panels are heated using either a heated fluid or electric resistance cables, but can only be cooled using a chilled fluid, typically water in the 50 to 60°F range. Because radiant ceiling panels often cover most of the ceiling area in a building and have a large heat transfer surface, radiant systems deliver comfort at more moderate temperatures than hydronic fan coils, which use water temperatures around 140-160°F in heating and around 45°F in cooling. The moderate temperature translates to improved equipment efficiency, particularly with AWHPs as the heated and chilled water source.

Figure 4 - Diagram of evaluated hydronic system. The system includes an AWHP, fan coil, buffer tank, pump, and radiant panels.



In this study, a radiant panel system suitable for retrofits was evaluated. The retrofit system included hydronic radiant ceiling panels holding cross-linked polyethylene (PEX) pipes with hot or chilled water from an AWHP, as depicted in Figure 4. Radiant ceiling panels were installed in every room, with circuit flows balanced at a home-run manifold (similar to the model presented in right-hand picture of Figure 5). To ensure satisfying indoor air quality, bath fans were installed to provide ASHRAE 62.2 compliant ventilation. An EnergyStar certified dehumidifier was also installed to provide emergency dehumidification.

Figure 5 - (Left) Radiant panels holding the ½ inch PEX tubing and allow for modular channel patterns, (Right) A manifold distributes the heated or chilled water to all the radiant panels of the home (Warmboard reference).



The AWHPs used in this project were manufactured by Chiltrix. Chiltrix is a United States manufacturer based out of Chesapeake, VA and has significant experience in HVAC and solar energy engineering. Chiltrix develops and manufactures a wide range of DC-Inverter driven hydronic equipment, including air conditioners and heat pumps and various refrigeration heat recovery and water heating products.

The Chiltrix CX34 uses a variable speed compressor, pump, and fan to vary system capacity based on a desired entering water temperature and water temperature difference across the heat exchanger.

To provide the simplest controls for the field test systems, Chiltrix ductless fan coil units (FCUs) were used with the Chiltrix CX34. Chiltrix FCUs come in nominal delivery capacities ranging from 0.25 to 1 ton. All Chiltrix FCUs have DC-inverter driven variable speed fans. FCU sizes and types were chosen dependent on the needs of each individual field test site.

2.2 Monitoring Approach

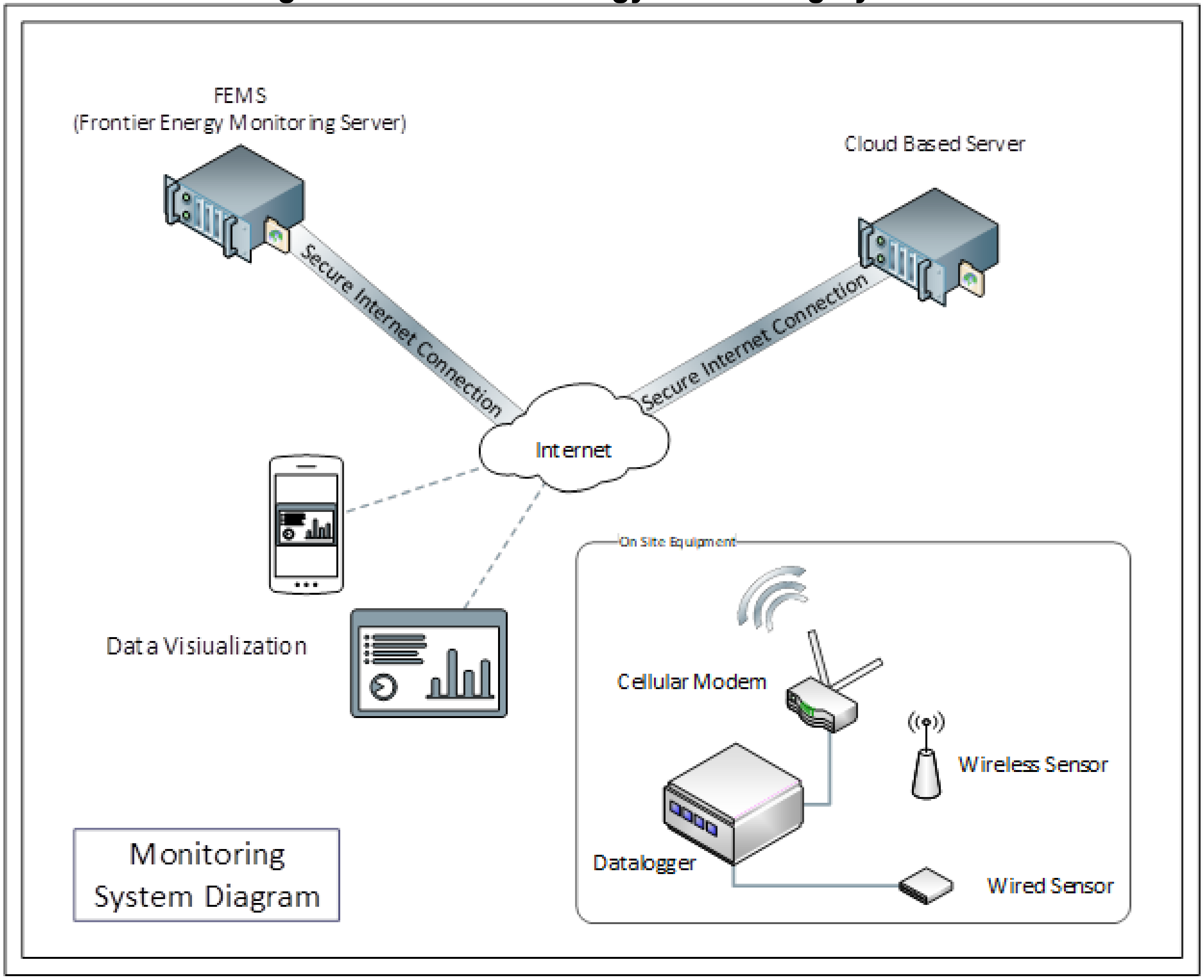
Field test data was monitored for all test sites (baseline and post-retrofit) for the length of time necessary to ensure performance is observed under the full range of weather conditions, typically between six months and one year. For most test sites, the collection of performance data post-retrofit lasted for two years, which reinforces the documented energy performance.

The specific monitoring approaches were tailored to the systems and research goals at each building, though basic methods and devices was kept as uniform as possible across field monitoring efforts. Figure 6 provides a high-level diagram of the monitoring methods and systems.

To the greatest extent possible, the monitoring systems and sensors used in the baseline monitoring periods continued to be used in the retrofit monitoring periods at each site. Data was collected from both wireless and wired sensors by one or more dataloggers. The dataloggers were securely transmitting data over the internet through a dedicated cellular modem, independent from the site internet service.

Two basic types of dataloggers were used: customizable and programmable dataloggers (e.g. dataTaker, Campbell Scientific, etc.) and dataloggers that were part of residential and commercial energy management systems (EMS) (e.g. SiteSage, inView, and Ecobee). All custom dataloggers and most EMS dataloggers provides some on-site data storage to prevent data loss due to internet connection failures and power outages.

Figure 6 - Frontier Energy Monitoring System.



EMS dataloggers sent data over a secure connection to a cloud server operated by the respective EMS providers. These EMS systems provide additional benefit to field test site owners and occupants, who were provided access to any available EMS features. Some EMS systems also provide data visualization both at an aggregate level for use in the Energy Marketplace and at an individual site level to assist with equipment commissioning and troubleshooting.

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

The FEMS enables set up to retrieve data in any file format from any datalogger at any specified interval. Data from EMS dataloggers are automatically downloaded through a secure login to the EMS cloud server and typically retrieved daily. Custom dataloggers communicate directly with the FEMS over a secure connection, uploading data files directly to the FEMS secure FTP server. The FEMS provides secure storage for all retrieved data by project and by site. In addition to retaining the raw data files, the FEMS automatically combines all data for each site into a site-specific binary data file for use in analyses. Direct access to the FEMS is kept limited to specific personnel for security and reliability reasons. Access to data collected by the FEMS was provided to other Team members via Frontier Energy's SharePoint service as necessary.

2.3 Laboratory Tests

Characterizing the performance of radiant ceiling panels is important to differentiate between products and design systems. Delivery effectiveness is the ratio of the quantity of heating or cooling energy delivered to the conditioned space over the total energy provided. There are no existing methods for determining radiant panel delivery effectiveness, such as ASHRAE Standard 152 provides for air-to-air systems (ASHRAE, 2004). An estimate of delivery effectiveness is necessary to properly size panels for a particular building. There are several laboratory testing standards for radiant panels, but none of these provide a method to estimate delivery effectiveness that is accessible to contractors and designers and compatible with existing industry practice.

In the absence of usable and accessible standards for evaluating radiant panel systems, radiant systems are typically evaluated by comparing the performance of the AWHP to the comfort performance of the whole system using ASHRAE Standard 55 and ACCA Manual RS (Haile, Springer et al. 2016). ACCA RS is a set of criteria for acceptable deviations from thermostat setpoints, allowable temperature differences between rooms in a house and floors (e.g. first to second floor), and allowable humidity ranges (1997). ASHRAE Standard 55 is a more complex standard that considers operative temperature, relative humidity, air velocity, and clothing (ASHRAE, 2010).

The delivery effectiveness of the radiant panels was evaluated in Frontier Energy's Building Science Research Laboratory (BSRL). The BSRL is a 2200 ft^2 test facility in Davis, California, that has been used since 2003 for testing equipment, fabricating prototypes, and maintaining field monitoring systems. The laboratory has been used for the evaluation of heat recovery systems, evaporative cooling technologies, tankless water heaters, furnaces and fan coils, and ventilation cooling systems. Improvements made in 2017 included construction of two large environmental chambers (see Figure 7) that can be used for the testing of residential and commercial HVAC technologies, water heating equipment, and building envelope components such as phase change materials (PCMs). A 10-ton variable speed packaged unit is currently used for conditioning the air in the larger test chamber and introducing the desired thermal loads on outdoor equipment. An additional radiant heating and cooling capability was added to the smaller chamber as part of Lead Locally to simulate both indoor and semi-conditioned spaces and allow testing of subtler thermal phenomena such as heat transfer rates for PCMs. An AWHP and tankless gas water heater are available for providing heated and chilled water for testing hydronic coils, radiant panels, and drain water heat recovery devices. A LabVIEW setup was used to monitor and control equipment during experiments.

Figure 7 - Environmental test chambers at the Frontier Energy – Davis lab facility (Credit: Joshua McNeil)

BSRL has two environmental simulation chambers: one larger chamber for simulating outdoor conditions and one smaller chamber for simulating indoor conditions. The conditions inside the chambers are controlled using a prototype high-performance commercial HVAC unit developed by Frontier Energy's predecessor, Davis Energy Group, called the HyPak. Controls and data logging are currently provided on an ad hoc basis using dataTakers and ADAM modules communicating with a computer using Modbus.

Of the laboratory resources available to the project team, BSRL was decided as the best option for the required laboratory testing of radiant panels and AWHPs. The environmental chambers afford the opportunity to precisely simulate design conditions at a steady state, allowing development of heat transfer coefficients for the radiant panels. BSRL is also in closest proximity to the project team, is the only facility available to the team with environmental chambers large enough for the radiant panel tests that is located in California and is the most conducive to the modifications necessary for conducting the radiant panel tests.

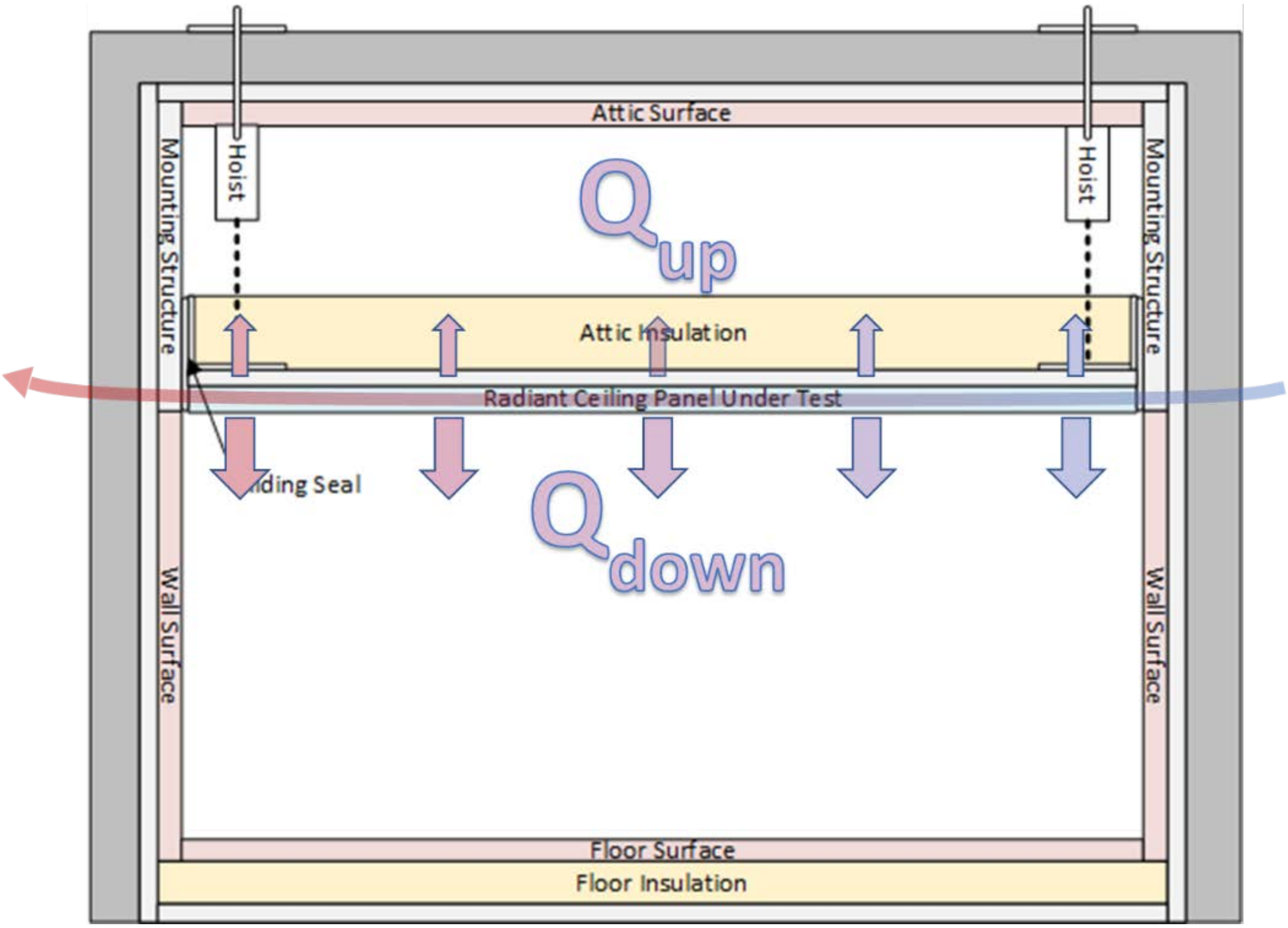
Modifications to BSRL systems and the instrumentation in the environment chambers required to perform the laboratory work included the following:

- Temperature controlled surfaces on all interior surfaces of the indoor environment chamber.
- A simulated attic section in the indoor environment chamber, which will include a removable ceiling for adjusting the insulation level at the back of the panel under test.
- Fine-resolution and high-sample rate data acquisition systems and instrumentation.

A National Instruments CompactDAQ system and high-performance liquid cooled industrial computer with a redundant data backup system was used for data acquisition and controls.

Figure 8 provides an illustration of how the radiant panel system was installed in the climate chamber, along with expected heat transfer flow directions.

Figure 8 - Diagram of planned modifications to the BSRL indoor environment chamber. The illustration also includes heat transfer from and to the radiant panel system. Q_{down} is the energy given to or taken from the interior space, and Q_{up} is the energy given to or taken from the attic.



The middle horizontal surface was the radiant ceiling panels under test. This horizontal surface was lowered using remote controlled electric hoists, allowing adjustments to the level of insulation in the simulated attic, then returned to original position while testing. The attic and indoor air temperatures were controlled using small hydronic fan coils.

Test Matrix

The goal of the radiant ceiling panel laboratory testing was to determine the delivery effectiveness, δ, i.e., downward heat transfer rate, Q_{down}, over total energy given or absorbed by the hydronic system, Q_{tot}. The energy given to or taken from the attic, Q_{up}, to the radiant panel system is considered as the loss (see Figure 8). Thus, the delivery effectiveness can be defined as:

$$\delta = \frac{Q_{down}}{Q_{tot}} = \frac{Q_{down}}{Q_{down}+Q_{up}}. \tag{1}$$

The delivery effectiveness was evaluated for multiple design conditions. This was done by measuring the steady state downward heat transfer rate of the panels for a range of operating conditions:

- Attic insulation R-values of 19 and 49.
- Panel entering water temperatures from 50 to 55°F in cooling and 95 to 105°F in heating.
- Water flow rates between 0.5 and 0.75 gpm.
- In cooling, attic air temperature was maintained at 140 while the indoor space was maintained at 76. In heating, attic air temperature was maintained at 55 while the indoor space was maintained at 68.

These conditions were selected because they are what is typically seen in the field. While R-30 attic insulation has been a requirement for some time, many houses still exist with R-19 and many houses have aging or poorly installed insulation. R-49 was selected as it represents a relatively high R value installed in new homes and as a retrofit. Panel supply water temperatures are typical for radiant ceiling systems, and the flow rates are typical for a single radiant circuit (with multiple circuits per installation, and often two or more circuits per zone).

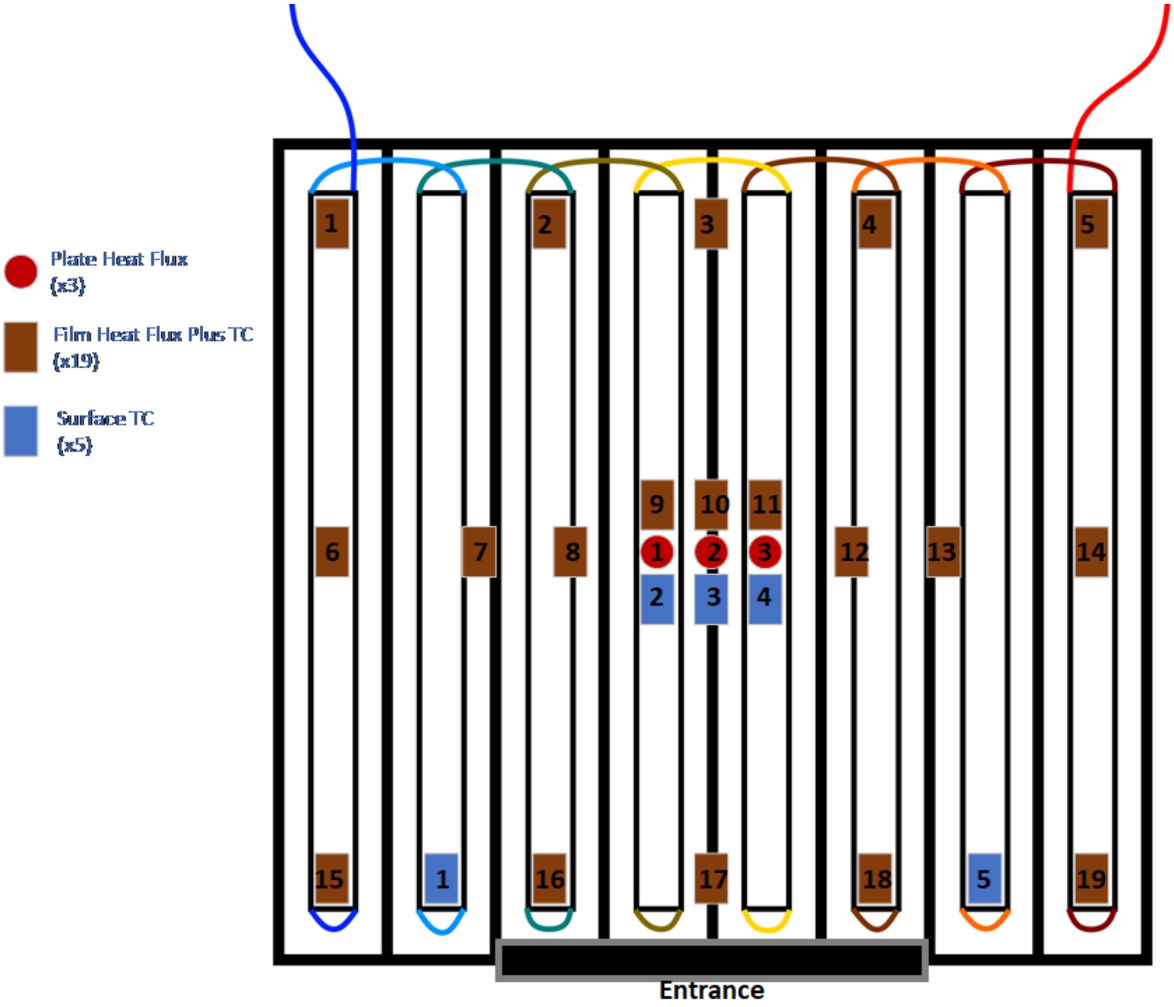
Data points collected included:

- Panel inlet and outlet water temperatures.
- Water flow rates.
- Surface temperatures of all surfaces at multiple locations.
- Ambient air temperatures and humidity in both the simulated attic and interior spaces.
- Heat flux at the interior panel surface and at the back of the panel.

Heat flux readers and thermocouples were strategically located at the ceiling surface, just underneath the board embedded PEX pipes. The layout and placement of sensors are presented in Figure 9.

Sensor data was collected at a high resolution, providing sufficient data to determine the downward heat transfer rate for each condition.

Figure 9 - Schematic layout of heat transfer and temperature sensors for the radiant panel laboratory test setup.



The general test procedure conducted during the testing:

1) Adjust level of insulation above the panels.
2) Set attic space temperature and surface temperatures to simulate the design condition.
3) Set entering water temperature.
4) Set flow rate.
5) Wait for steady-state conditions, defined as no variation in ceiling supply temperature, ceiling flow rate, attic air temperature, indoor air temperature, and all heat fluxes and surface temperatures for at least one hour.
6) Repeat steps 4 through 5 for each flow rate.

7) Repeat steps 3 through 6 for each entering water temperature.
8) Repeat steps 2 through 7 for each design condition.
9) Repeat steps 1 through 8 for each insulation level.

Steps 2 through 8 was fully automated. The BSRL data logging and control system was programmed with target values for inlet water temperature, flow rate, and interior space surface temperature. Once steady state was achieved, BSRL systems maintained steady state for one hour.

Lab Results

The combination of variables resulted in 16 different setups and conducted tests. Initially, the plan was to use both the thermocouples and the heat flux sensors to determine the downward heat flux to the interior chamber space. However, upon reviewing the retrieved data from the heat transfer sensors, it was determined to only use the surface temperature readings from the thermocouples.

Readings from select surface thermocouples were averaged together to obtain the panel surface temperature. Two additional tests were conducted, one in heating and one in cooling mode, to use infrared temperature sensors to verify the average surface temperatures provided by the surface thermocouples.

The downward heat flux, Q_{down}, was calculated based on ASHRAE guidelines (ASHRAE, ASHRAE Handbook - HVAC System and Equipment - Chapter 6, 2012). Using Q_{down}, together with Q_{tot}, the delivery effectiveness, δ, was found. Table 1 presents the result of the 16 tests. During cooling mode, δ varies between 50 to almost 76%. While, for heating the range is smaller; between 54 to 66%.

Table 1 - Laboratory result from the radiant panel system. All variables are presented together with the delivery effectiveness of each setup. Upper half presents data during heating mode, and lower half during cooling.

Insulation R-value (ft^2·°F·h/BTU)	Indoor Temperature (°F)	Attic Temperature (°F)	Water Flow Rate (gpm)	Panel Supply Temperature (°F)	Return/Supply Temperature Difference (°F)	Delivery Effectiveness, δ (-)
19	76	140.0	0.50	50.0	-7.3	**53.1%**
49	76	140.0	0.50	50.0	-5.5	**76.7%**
19	76	140.0	0.50	55.0	-5.8	**47.8%**
49	76	140.0	0.50	55.0	-4.9	**66.0%**
19	76	140.0	0.75	50.0	-4.7	**56.7%**
49	76	140.0	0.75	50.0	-4.1	**75.8%**
19	76	140.0	0.75	55.0	-4.1	**49.3%**
49	76	140.0	0.75	55.0	-3.5	**66.9%**
19	68	55.0	0.50	95.0	5.2	**53.6%**
49	68	55.0	0.50	95.0	4.9	**61.2%**
19	68	55.0	0.50	105.0	7.0	**56.4%**
49	68	55.0	0.50	105.0	6.6	**64.7%**
19	68	55.0	0.75	95.0	3.5	**54.8%**
49	68	55.0	0.75	95.0	3.3	**63.2%**
19	68	55.0	0.75	105.0	4.8	**57.8%**
49	68	55.0	0.75	105.0	4.5	**66.2%**

Table 2 illustrates the impact of all variables on δ. In other words, how much the variation in variable values will impact the effectiveness of the radiant panel system. During the laboratory tests, the attic insulation was either R-19 or R-49. According to δ, the attic insulation impacted the effectiveness the most. Secondly, the supply water temperature. A lower supply temperature, thus a higher temperature gradient between the panels and the indoor chamber space, generates higher efficiencies. This is believed to be a result of an increased radiation exchange between the panels and the surrounding materials, because of a higher temperature induced convective heat transfer. The water flow rate seems to have some impact, but only slightly compared to the other variables. Table 2 also presents the temperature difference between supply and return to the radiant panels. This gradient is an indicator of how much energy is leaving or entering the hydronic system. Though, it doesn’t tell in which direction energy flows and where to or from.

During cooling mode, the attic temperature was kept at 140°F and indoor chamber space at 76°C.

Table 2 - Impact of testing variables on efficiency during cooling mode. According to the result, the attic insulation has the highest impact on delivery effectiveness during cooling.

Insulation R-value (ft²·°F·h/BTU)	Water Flow Rate (gpm)	Panel Supply Temperature (°F)	Return/Supply Temperature Difference (°F)	Delivery Effectiveness, δ (-)
19	0.50	55.0	5.8	**47.8%**
19	0.75	55.0	4.1	**49.3%**
19	0.50	50.0	7.3	**53.1%**
19	0.75	50.0	4.7	**56.7%**
49	0.50	55.0	4.9	**66.0%**
49	0.75	55.0	3.5	**66.9%**
49	0.75	50.0	4.1	**75.8%**
49	0.50	50.0	5.5	**76.7%**

Just as for Table 2, Table 3 illustrates the impact of the variables on δ , but during heating mode. Far left of the table is the variation in attic insulation, which again is found most influential on the system efficiency. During the laboratory tests, the attic insulation was either R-19 or R-49. And again, supply temperature also proved influential. A higher temperature gradient between the panels and the indoor chamber space, generates higher efficiencies. The impact of flow rate seems to have some impact, but only slightly compared to the other variables.

During heating mode, the attic temperature was kept at 55°F and indoor chamber space at 68°C.

Table 3 - Impact of testing variables on efficiency during heating mode. According to the result, the attic insulation has the highest impact on delivery effectiveness during heating.

Insulation R-value (ft²·°F·h/BTU)	Water Flow Rate (gpm)	Panel Supply Temperature (°F)	Return/Supply Temperature Difference (°F)	Delivery Effectiveness, δ (-)
19	0.50	95.0	5.2	54%
19	0.75	95.0	3.5	55%
19	0.50	105.0	7.0	56%
19	0.75	105.0	4.8	58%
49	0.50	95.0	4.9	61%
49	0.75	95.0	3.3	63%
49	0.50	105.0	6.6	65%
49	0.75	105.0	4.5	66%

To summarize the findings from the 16 tests, it’s found that the delivery effectiveness increases with increasing attic insulation R-value. Likewise, a higher temperature gradient between supply temperature to the radiant panels and the indoor air will improve efficiency.

2.4 Field Site

Although, the field tests were planned to be performed in five single-family homes, ultimately only one home was studied. Though, multiple test sites were considered essential to reduce the impact from occupant behavior and comfort considerations which were assumed to possess significant effect on the operation and perceived performance of radiant systems, the installation cost was higher than anticipated resulting in changes to the study design.

All test sites were to be located within Sonoma and Mendocino counties and selected from existing SCP customers. Candidates for the installation were selected based on home, system, and occupant characteristics. For the residential sites, selection criteria required that all test sites be single family (detached) homes, single story, less than or equal to 2,000 sq. ft. of conditioned space, be ten years old or older, and contain no known asbestos. For the system, the requirements specified that the systems include existing ducted (functional) central heating and cooling, ducts located in an (unconditioned) attic space, preferably electric heating, and be at least 10 years old. Finally, the current owners had to be full time occupants and not expecting to move within two years, non-smokers, not employed in the energy industry, and not retirees.

Six months of monitored baseline data was to be collected prior to the retrofits, followed by one year of monitored data collection post-retrofit. Data collected was focused on system performance, as well as occupant comfort and behavior. 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.

Four sites were selected based on the defined criteria above. Unfortunately, as the design and construction process unfolded at the first site, it quickly became evident that the cost of installation drastically exceeded expectations. The total installed cost was projected to be more than $100,000 per site. The project team determined that cost effectiveness for the technology was impossible and, with the approval of the Energy Commission, decided to redirect project efforts to another similar technology. This resulted in only one home receiving the installation of the radiant panel system. Two of the other homes received a hydronic fan coil system with indirect domestic hot water heating, and one home received the mini-split heat pump technology being demonstrated under another Lead Locally task. The cost analysis and reasoning behind this decision is further described in Section 2.5.

As outlined in the monitoring plan of the “Lead Locally” project, if a technology doesn’t perform well in the application, SCP will recommend investing remaining funds into promising alternative technologies identified through the Energy Marketplace vendor solicitation. The technology selected to be investigated in lieu of the radiant panel system is presented in Section 2.5. and Chapter 3.

The home that received radiant ceiling panels is a 1,812 square foot single story house, built in 1989 with three-bedrooms and two baths. Prior to the retrofit, the heating and cooling system consisted of a traditional central ducted system with gas furnace and electrical air conditioning.

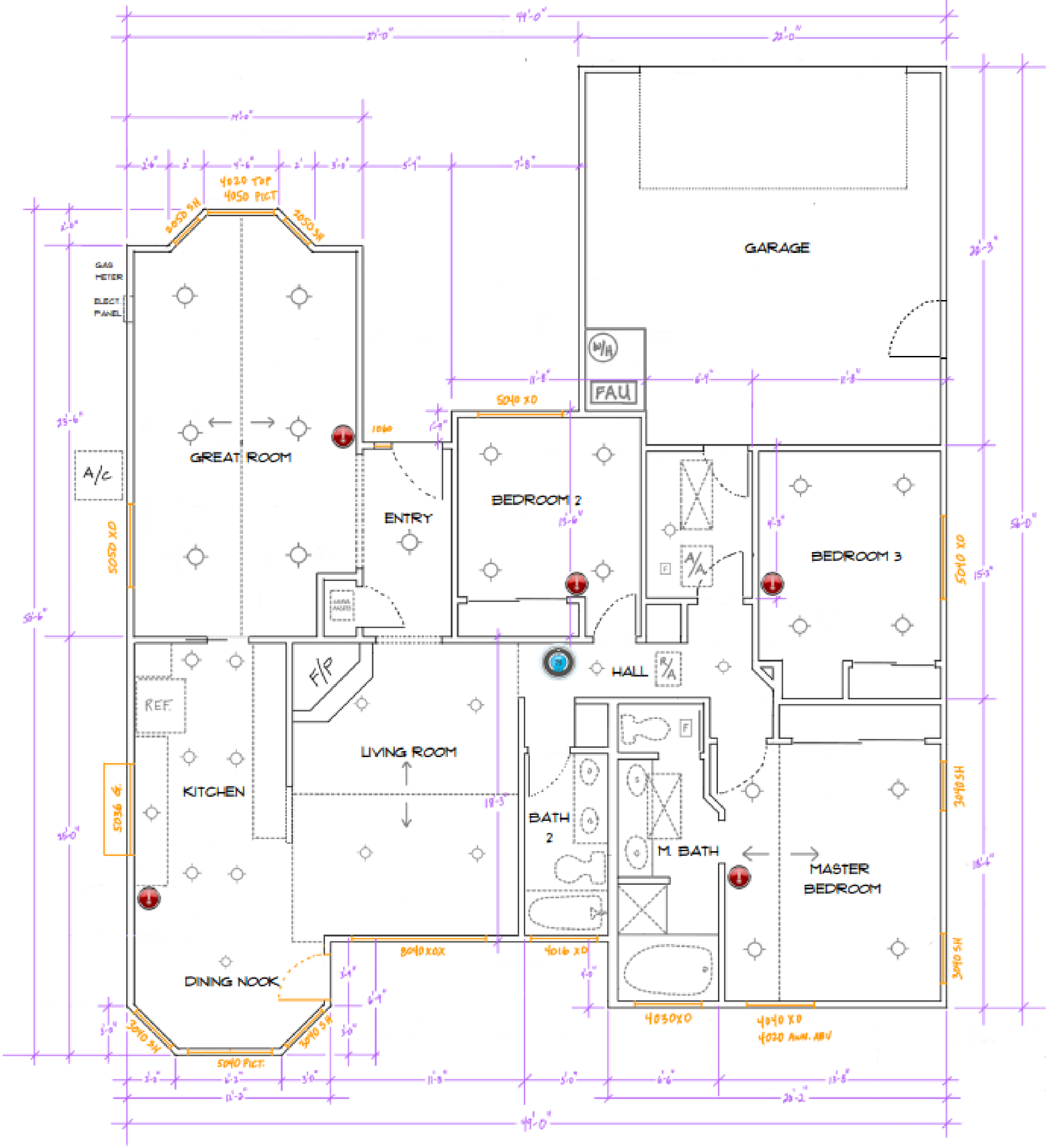
Figure 10 - Selected home to install the radiant panel system.

Figure 11 - Baseline and pre-retrofit heating and cooling system.

In order to make an assessment on return of investment and improved performance from installing the radiant panels, baseline monitoring was set in place for approximately 6 months, see Figure 11. Between March 25th of 2019 and October 6th of 2019, indoor temperature, relative humidity, as well as existing heating and cooling system electrical and gas use were recorded. An Ecobee thermostat was used to log indoor temperatures in each room, relative humidity, occupancy, setpoint, and equipment operation time. Another data logger recorded the electrical energy use of the condensing unit and the furnace/AHU separately from a

WattNode True-RMS energy meter, and the gas use of the furnace through a 1 pulse per cubic foot EKM gas meter.

Figure 12 - Floor plan of the test home. The red symbols indicate locations of the temperature sensors and the blue symbol where the thermostat is mounted.



The data logger recorded data from sensors at a 15 second interval. Temperature and occupancy in every room, as well as setpoint and equipment operation time were recorded every five minutes through the Ecobee thermostat. See Figure 12 for sensor placement. In addition, the thermostat recorded relative humidity and controlled the whole house dehumidifier to provide emergency dehumidification to avoid condensation on the radiant panel surfaces during cooling. Weather conditions were retrieved from a nearby weather station and recorded with site data.

On October 7th, the installation of the retrofit ceiling panels began, and construction was finished October 25th of 2019.

Figure 13 - The installation of the radiant panels was somewhat disruptive and required the homeowners to leave the house unoccupied during the weeks of installation. The panels were mounted on the outside of the existing ceiling drywall (left). Furniture and flooring were protected during the installation (right).

Figure 14 **- The great room from upper left to lower right: pre-retrofit, panel install, finished retrofit, post-retrofit thermal image.**

Figure 15 - Manifold located in garage where furnace previously stood.

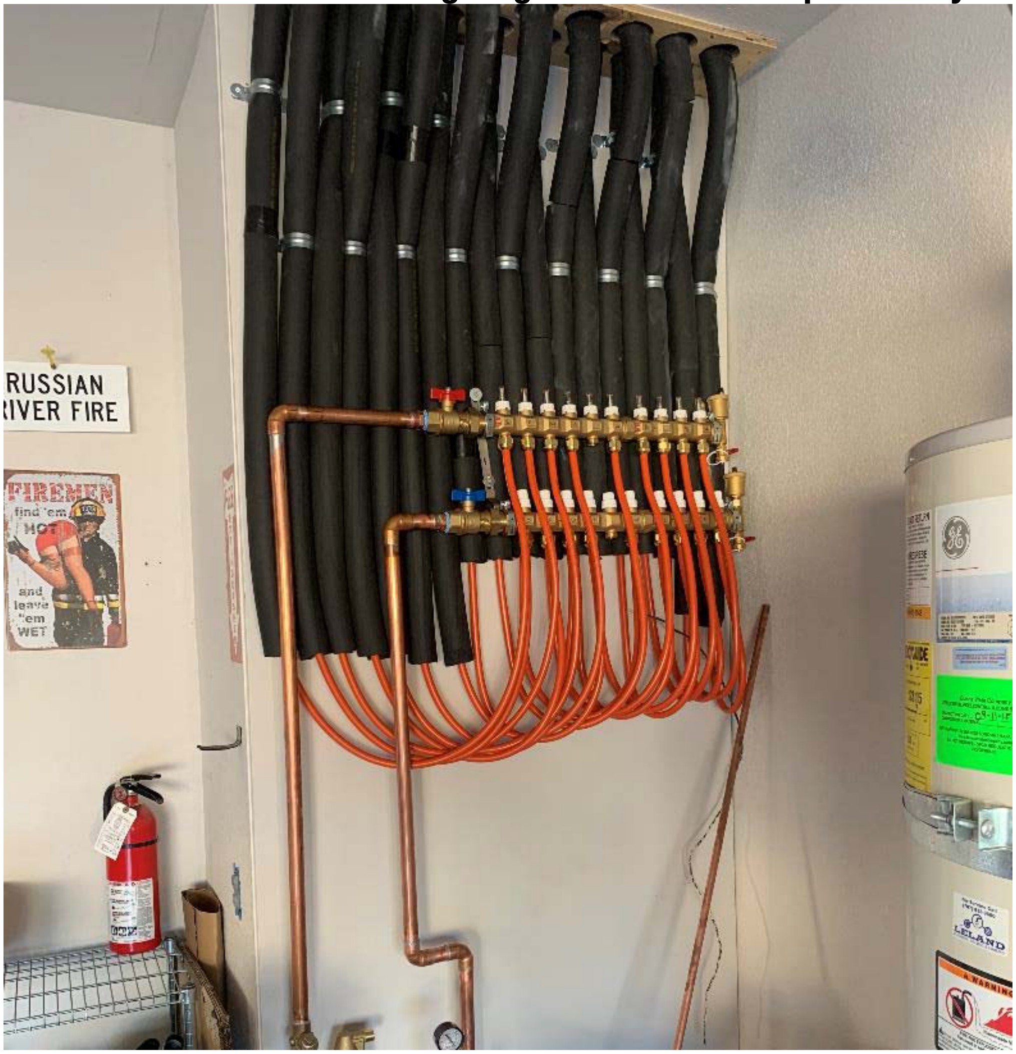


Figure 16 - Installing tubing into the channels of the radiant panels.

For the test site, radiant panels from Warmboard® were installed. Because of the intrusiveness of the installation, the house was left unoccupied until completion. The following measures were taken.

- Removal of entire existing heating and cooling system, including ductwork.
- Removal of existing attic insulation
- Mounting radiant panels underneath existing ceiling surface, installing PEX-AL-PEX tubing, covering with gypsum board, drywall mud/sand, and finish up with matched paint.
- Routing plumbing for the panels through the attic to a central location for valves and controls, where the buffer tank was installed.
- Caulk and spray foam ceiling plane to seal gaps around penetrations and joist/drywall interfaces.
- New blown-in attic insulation with R-49 cellulose insulation.
- Replacing bathroom exhaust fans with new exhaust fans that provide ASHRAE 62.2 compliant continuous ventilation.
- Remove duct work in crawls space and install a vapor retarder on the ground.
- Installing ducted dehumidifier to mitigate any condensation concerns (AprilAire 1850Z).
- Installing the air-to-water heat pump (Chiltrix CX34).
- Installing the buffer tank.
- Commissioning and testing the new system.

Further information about the installation process and guidelines can be found in the Air-to-Water Heat Pump Design and Installation Guide (Energy, 2021).

A blower door test was executed both before and after the outlined measurements above. The first test revealed a total home air leakage rate of 2,134 cfm at a 50 Pascal pressure difference. Same test after the retrofit measures were completed revealed an air leakage rate of 1,470. With a total house air volume of 14,500 ft^3, the measurements convert to 8.8 ACH50 before the installations and improvements of the building envelope, and 6.1 ACH50 after the retrofit measures were completed.

Figure 17 - PEX pipes were mounted inside the precut channels of the radiant panels.

The installed data loggers and acquisition system collected information on performance from the end of October in 2019 to the end of December in 2021.

The monitoring equipment was decommissioned in February of 2022.

Post-installation survey

The homeowner completed a survey more than a year after the radiant panel system was installed. The first part of the survey included questions related to comfort, control, and quality of equipment. The homeowner 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 satisfied with the comfort questions related to temperature, feeling of drafts, perceived air quality, noise, and general comfort. Likewise, the

HVAC system control was perceived satisfying, except for thermal responsiveness of system. The quality, visual appearance, and ease of maintenance were rated highly.

The second part of survey included usage. The homeowner replied that they changed thermostat setpoints pre- and post-retrofit. They noted that the indoor environment is somewhat slow to respond to thermostat and control changes. However, the system worked satisfyingly if not make changes too often. The homeowners also commented that they love not having air blowing through the vent system and constantly turning on and off. They also pointed out that the radiant panel system results in a lower energy in general.

The third part of the survey was related to household and time spent indoors. No changes were made to the number of people living in the house but that in March 2020, they spent significantly more time indoors due to the pandemic of COVID-19.

Finally, the survey ended with questions related to the program, support, staff, and contractors, and participating in the project. Here, the response was mainly “very satisfying” to the homeowners.

The full post-retrofit survey is provided in Appendix A.

2.5 Performance Assessment and Cost Evaluation

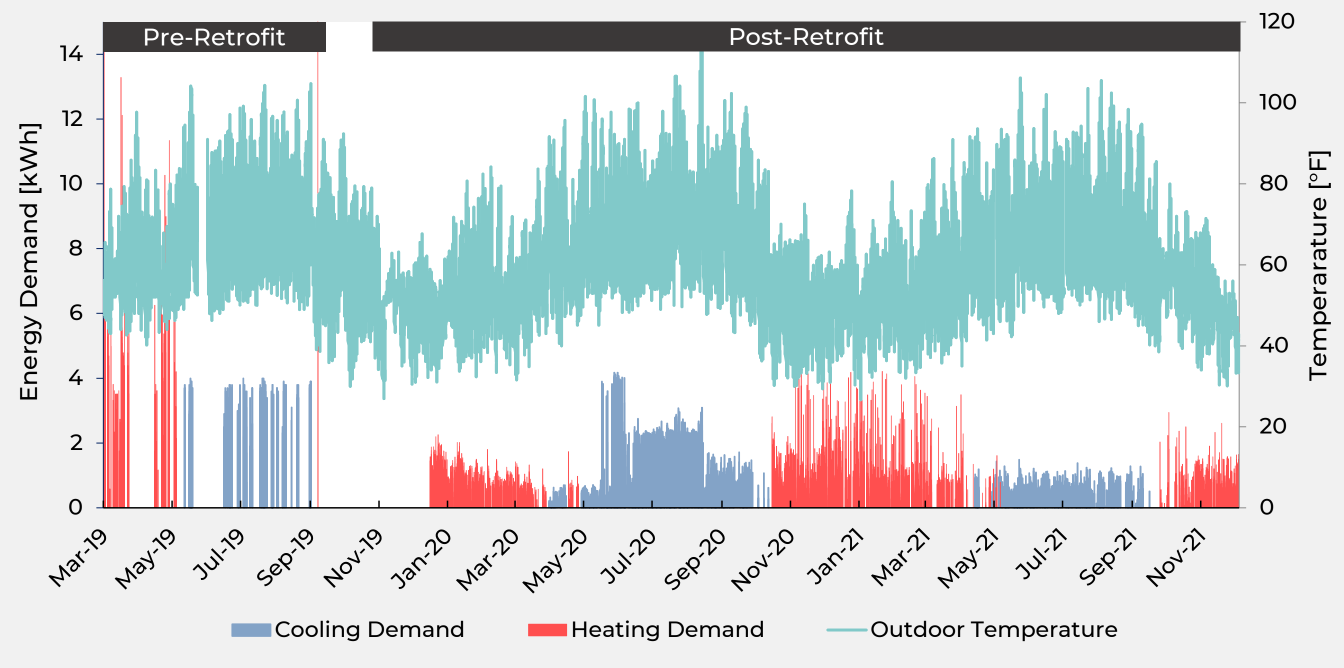
Pre- and post-retrofit performance

Unfortunately, a comparison in performance and energy usage pre- and post-retrofit is quite problematic for the test site. The complexity is not a result of the radiant panel system per se, but rather a cause of a change in energy source for heating. Pre-retrofit, the furnace uses natural gas for heating, while post-retrofit, the AWHP uses electricity. Since, the price of natural gas is different than electricity, a side-by-side comparison is not possible without converting the natural gas usage pre-retrofit from kBtu to kWh. However, this approach makes the comparison incomplete unless energy usage is converted to cost, which will allow for a monetary comparison. The initial assessment will focus on energy usage. Here, natural gas usage pre-retrofit is converted to kWh. Later, the cost of energy will be introduced to evaluate cost-effectiveness.

The assessment in this section focuses on cost of energy and expected changes from installing the radiant panel system. Any changes in operational carbon emissions are not evaluated.

The baseline data for the test site was collected between March 25th of 2019 and October 6th of 2019 and is presented in the far left of Figure 18. Here, cooling and heating energy demand is depicted together with the variation in outdoor ambient air temperature. Figure 18 presents the use of natural gas in means of kWh.

Figure 18 - Cooling (blue) and heating (red) energy demand pre- and post-retrofit. The outdoor temperature (green) during the time of data collection is also depicted. Here, heating pre-retrofit is expressed in kWh.



The impact of variation in outdoor climate pre- and post-retrofit is accounted for using a method based on heating and cooling degree hours. Degree hours are applied to normalize the weather data and allow for a comparison between the baseline and post-retrofit performance data. For cooling degree hours, ASHRAE 169 suggests summarizing all hours during a year when the outdoor temperature exceeds 65°F and below 50°F for heating degree hours (ASHRAE, 2021). This approach makes sense if comparing weather data or estimating building heating and cooling energy demand. However, the drawback is that this approach obviously assumes that heating always occurs when the outdoor air temperature is below 50°F and that cooling always happens at temperatures higher than 65°F. In reality, whether heating or cooling is required mainly depends on three variables: (1) the thermostat setpoints, (2) building envelope and HVAC system characteristics, and (3) comfort preferences. These variables account for heating and cooling loads induced by the outdoor air temperature and exterior environment, but also for anything that acts as a heat sink or source to the interior; for example, solar radiation through windows, air infiltration, or heat generated by appliances, lighting, and people. Consequently, whether cooling or heating is required depends on several significant variables other than outdoor air temperature.

Instead of using pre-defined base temperatures for heating and cooling degree hours, this study uses a method to calculate actual degree hours from site specific data. In other words, the actual outdoor air temperatures are applied for when heating or cooling occur. Using available information on thermostat setpoints, occupancy presence and energy demand, these baseline temperatures are defined. Pre-retrofit, the average lowest outdoor air temperature for when cooling is required is found at 75.8°F and highest 56.8°F for heating. After the retrofit, the overall heat balance of the building is different because of adding more insulation in the attic and making the building more airtight. Also, the user behavior has proven different. Due to COVID-19 pandemic, the tenants spend more time inside the house. In addition, the heating and cooling system is replaced by the radiant panels and thus the efficiency and perceived comfort are different compared to pre-retrofit. The average lowest outdoor air temperature used to calculate degree hours for cooling drops to 63.9°F and the highest average temperature for when heating is needed drops to 53.1°F after the retrofit is completed. The datapoints used to calculate average lowest outdoor air temperatures for when cooling is needed and average highest outdoor temperature for when heating is needed are presented in Figure 19.

Figure 19 - Lowest daily temperatures for when cooling and heating is needed. The data points help to determine base line temperatures used to calculate heating and cooling degree hours.

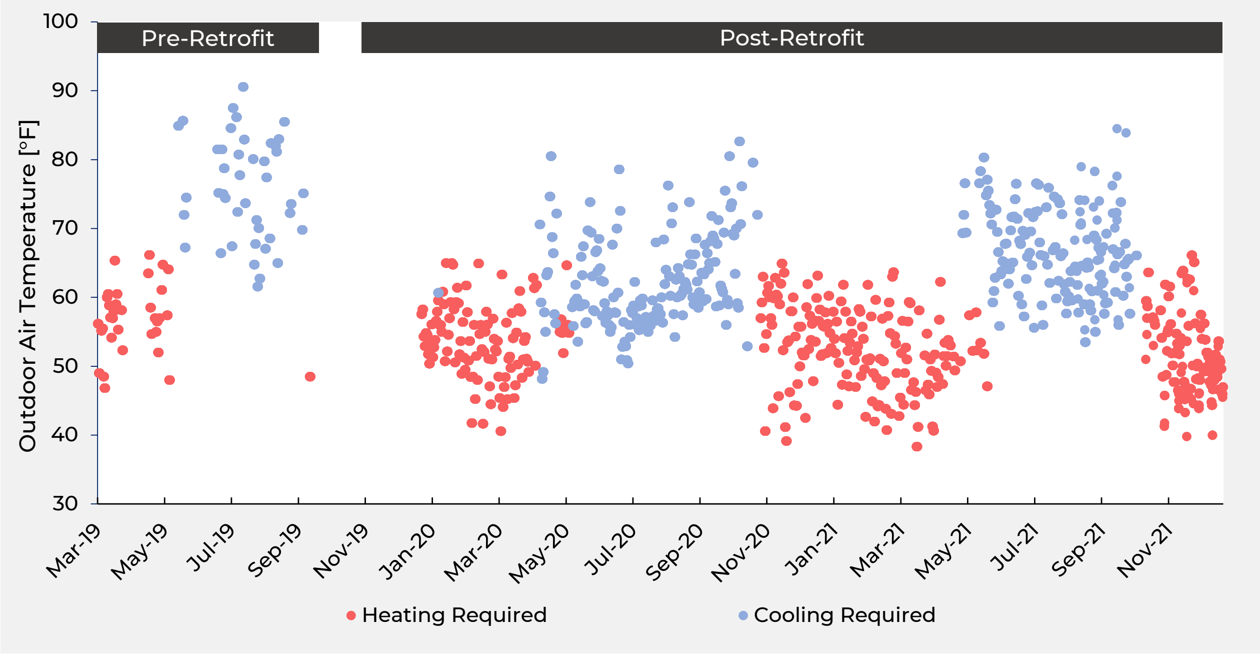


Table 4 presents actual degree hours based on temperatures presented above and energy usage for the test site during the period between March 25th and October 10th in 2019 (pre-retrofit), and for the full year of 2020 and 2021 (post-retrofit).

Table 4 - Heating and colling degree hours and energy usage pre- and post-retrofit for the test site with the installed radiant panels. A usage ratio is presented that reflect on the relation between usage and degree hours. Heating usage pre-retrofit is presented in both kBtu and kWh.

Time Period	Degree Hours [h°F]		Usage [kWh]		Usage Ratio [kWh/(h°F)]		Savings [-]	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
Start 3/25/2019 End 10/6/2019	9,310	7,285	792	974 / *3,323* *(kBtu)*	0.085	0.134 / *0.456* *(kBtu/h,F)*	-	-
Start 1/1/2020 End 12/31/2020	36,579	23,938	2,007	1,462	0.055	0.061	**35%**	**54%**
Start 1/1/2021 End 12/31/2021	28,540	23,729	543	1,315	0.019	0.055	**78%**	**59%**

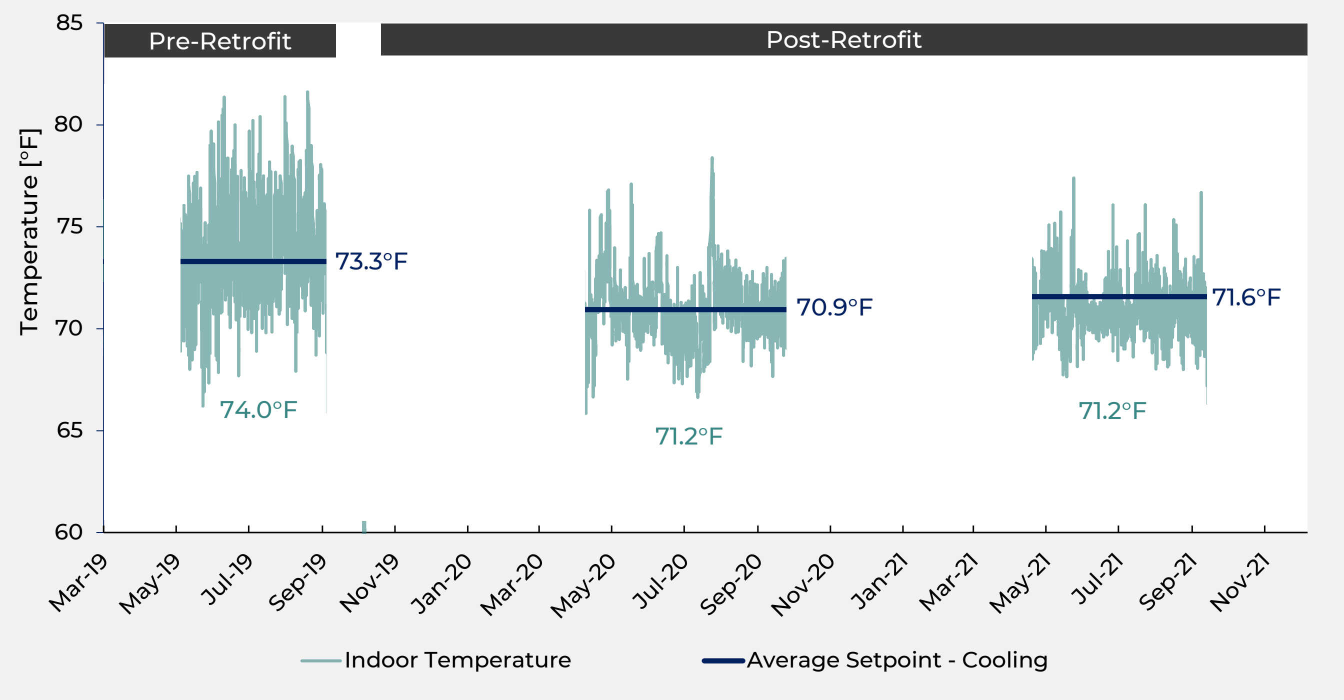
Table 4 provides energy usage pre- and post-retrofit. Hence, the radiant panel system consists of an AWHP using electricity only, the gas usage prior to the installation is presented in both kBtu and converted to kWh. This simplifies a side-by-side comparison pre- and post-retrofit.

Table 4 also presents an energy usage ratio for heating and cooling demand. The ratio is defined as a normalized indicator of energy utilization per degree hour and can be used to estimate energy savings at different climate conditions with different cooling and heating degree hours. For cooling, the usage ratio is 0.085 kWh per degree hour prior to the retrofit. Post-retrofit, the usage ratio drops to 0.055 during the first year after the installation, and then to 0.019 for the second year. The reason for the difference in performance between the first and second year is assumed to be related to the peak in cooling energy use during June 2020, as seen in Table 4. Also, there was a change in settings for when the dehumidifier runs between the two years. This setting resulted in a higher energy demand during 2020 compared to 2021. The purpose of the dehumidifier is to make sure that condensation never occurs on the surface of the radiant panels. In 2020, the dehumidifier ran at 10% lower indoor relative humidity, which can also explain the higher cooling demand in 2020 compared to 2021. For heating, the savings are more consistent between the two years after the installation of the radiant panels. Pre-retrofit, the usage ratio is 0.134 kWh per heating degree hour. Post-retrofit, the usage drops to approximately 0.058 between the two years, which coincides with an 56% reduction in heating demand. Here, it’s important to again understand heating demand pre-retrofit is converted from kBtu to kWh. Meaning, there may be a reduction in energy, but not necessarily in cost.

Major variables on energy demand include human comfort levels and preferences. For the test site, there were no restrictions given on temperature range and limits for the thermostat. Thus, the homeowners were free to adjust the setpoint temperatures as they pleased. Figure 20 and Figure 21 depict annual average thermostat setpoints for heating and cooling. The variation in indoor temperature collected from a temperature sensor close to the thermostat is also presented.

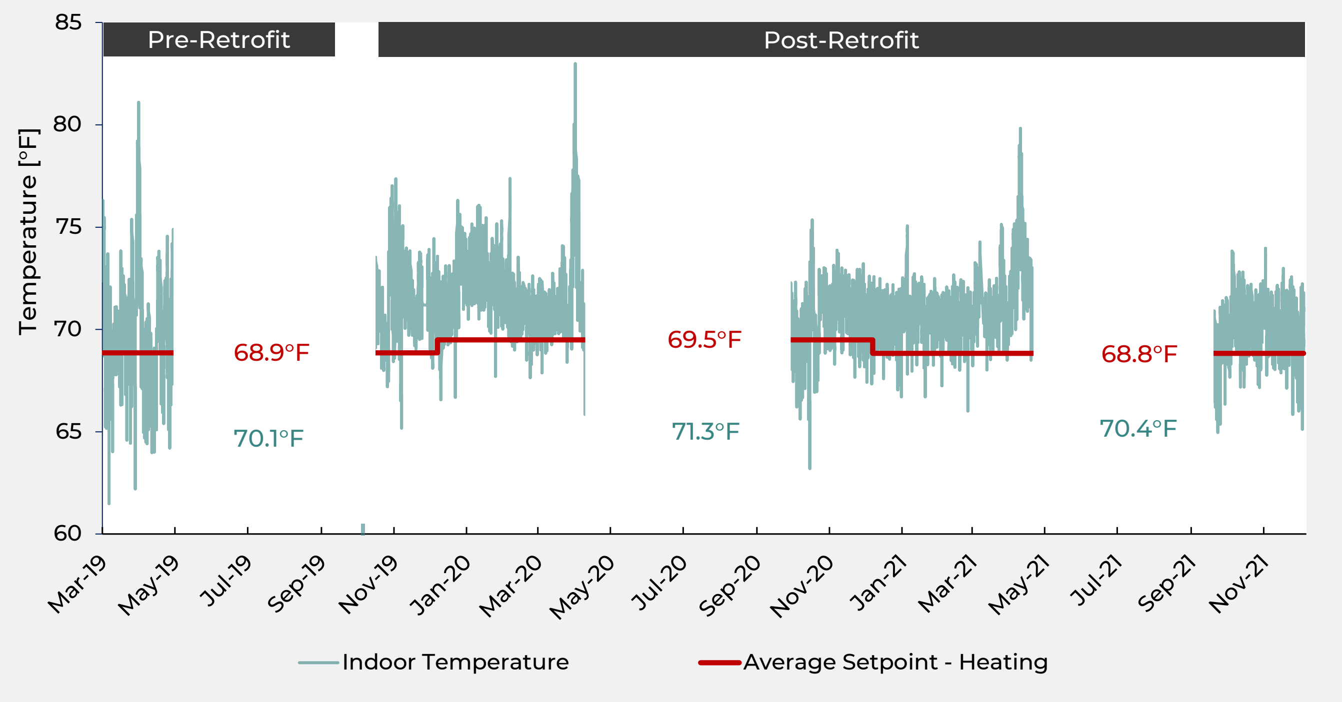
As seen in Figure 20, the average cooling thermostat setpoint is higher before the installation of the radiant panels than post-retrofit. This is assumed to be a result of the homeowners spending more time inside the house because of the start of the COVID-19 pandemic in March 2020. A change in variation of the indoor temperature can also be visualized in Figure 21 during the same period. Pre-March 2020, the indoor temperature seems to fluctuate more. The fact that the cooling thermostat setpoint was set significantly higher pre-retrofit (74.0°F, as seen in Figure 20) results in a higher average indoor temperature and thus lower overall cooling demand. That implies that the estimated savings in cooling demand presented in Table 4 are assumingly on the conservative end and can be expected higher.

Figure 20 - Average thermostat setpoint during cooling (blue horizontal line), and variation in indoor temperature during the time of cooling (green). The average indoor temperature during the cooling season is also presented.



Though, the same trend in more fluctuating temperature pre-retrofit is seen for heating (Figure 21) as well, the time for which data was collected is not substantial enough to draw conclusion similar to that of cooling.

Figure 21 - Average thermostat setpoint during heating (red), and variation in indoor temperature during the time of heating (green). The average indoor temperature during the heating season is also presented.



The estimated energy savings for the test site is presented in Table 5. Here, the difference in usage ratio pre- and post-retrofit is used to calculate a savings ratio. The savings ratio is multiplied with the cooling and heating degree hours to calculate estimated energy savings. According to Table 5, the energy savings for heating and cooling add up to about 4,000 kWh annually on average between 2020 and 2021. Though, it is assumed that the radiant panel heating and cooling system contributes to most of the savings, there were improvements made to the building envelope which, to some extent, contributed as well. For example, the ceiling insulation increased to R-49 and the airtightness of the building was significantly improved by the retrofit measures.

Table 5 - Estimated energy savings the test site using annual average of 2020 and 2021, and estimate energy savings for Santa Rosa, CA. The heating and cooling degree hours represents a Typical Metrological Year (TMY).

Time Period	Degree Hours [H°F]/[D°F]		Savings Usage Ratio [kWh/(H°F)]/[kWh/(D°F)]		Estimated Savings [kWh]	
	Cooling	Heating	Cooling	Heating	Cooling	Heating
Test site, average of 2020 and 2021	32560	23834	0.048	0.075	**1566**	**1798**
Santa Rosa, CA TMY, 2008	18228	30566	0.048	0.075	**877**	**2306**

For a general comparison, the estimated savings from the test site is applied to a typical metrological year (TMY) of Santa Rosa, California. Here, the same saving usage ratios from the test site are applied but multiplied with cooling and heating degree hours for the selected

TMY. The comparison is general, thus heating and degree hours are calculated based on standard baseline temperatures of 65°F for cooling and 55°F for heating. The estimated reduction in energy use from applying the saving ratios from the test site comes down to roughly 900 kWh for cooling and 2,300 kWh for heating annually.

Electricity Savings

Although it may seem unrealistic to draw concrete conclusions from only one test site, measured performance pre- and post-retrofit indicate energy savings from installing the AWHP and radiant ceiling panels.

Since the existing home uses natural gas for heating pre-retrofit, the actual savings in cost is unclear until rates and cost of energy are included.

Prior to the retrofit, natural gas was used for heating, while electricity has been used after the retrofit measures. Utilizing the usage ratio for natural gas from pre-retrofit of 0.456 kBtu/(h·°F) multiplied with the actual heating degree hours of 2020 and 2021, of 23,938 and 23,729 h·°F, the estimated usage becomes 10,919 (109.2 therm) and 10,824 kBtu (108.2 therm) respectively.

Table 6 presents average costs of natural gas during heating season, and costs of electricity during both cooling and heating season of 2020 and 2021. The estimated costs are used to evaluate what the actual costs of energy were for 2020 and 2021 and what they would have been if no retrofit measures were conducted.

Table 6 - Actual and estimated cost of energy post-retrofit, and under the scenario that no retrofit measure was conducted. The cost analysis also includes what the savings may look like in 10 years from 2021, based on predicted California statewide escalation rates. The cooling and heating demand for 2031 is based on averages from the years of 2020 and 2021.

Time Period	No Retrofit (estimated)						
	Degree Hours [H°F] (Pre-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kBtu)	Cost[c] ($/kBtu)	Total Cost
Start 1/1/2020 End 12/31/2020	12761	37741	1085	$0.26	17216	$0.0121	**$490**
Start 1/1/2021 End 12/31/2021	8860	38799	753	$0.28	17698	$0.0143	**$464**
Start 1/1/2031 End 12/31/2031	10811	38270	919	$0.33	17457	$0.0219	**$686**

Time Period	Post-Retrofit							
	Degree Hours [H°F] (Post-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kWh)	Cost[b] ($/kWh)	Total Cost	Annual Savings
Start 1/1/2020 End 12/31/2020	36579	23938	2007	$0.26	1462	$0.26	**$902**	**-$411**
Start 1/1/2021 End 12/31/2021	28540	23729	543	$0.28	1315	$0.28	**$520**	**-$56**
Start 1/1/2031 End 12/31/2031	32560	23834	1275	$0.33	1388	$0.33	**$881**	**-$195**

[a] Cost of electricity during cooling season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of electricity for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).

[b] Cost of natural gas during heating season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of natural gas for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).

[c] Cost of electricity during heating season of 2020 and 2021 (PG&E, Tariffs, 2022)

Table 6 also presents the difference in cost of energy between actual and estimated (if no retrofit was conducted). Unfortunately, the radiant panel system results in an energy cost penalty for 2020 and 2021 despite using less energy. For a future estimate, Table 6 also presents predicted cost of energy for 2031, based off California statewide escalation rates (Energy and Environmental Economics, 2019). The predicted savings in cost for 2031 are also negative and are based on average energy demand for cooling and heating during 2020 and 2021.

The main reason to why the cost savings are not as notable as the drop in energy demand, is because the cost of natural gas is significantly less than electricity compared to generated energy. Since the installation of the radiant panel system results in less energy use, an existing home using electricity for heating may be a better fit for the technology and may generate positive cost savings.

Economic Benefits

Not only did the installation of the radiant panel system generate negative savings in cost of energy, but also the initial cost associated with the installation was high. The breakdown of labor hours and cost are presented in Table 7. Just for labor, the cost reaches almost $84,000. As seen in the table, and worth pointing out, many different trades were involved in the installation. This calls for organized work schedules and time management, which if not carefully planned for, can result in additional costs. Further considerations and reflections are discussed in the Success Criteria and Conclusion section at the end of Chapter 2. Table 7 include site and project specific costs of labor, such as crawlspace vapor barrier, and to some extent, off-site management.

Table 7 - Cost of labor to install the radiant panels at the test site.

LABOR BREAKDOWN			
DESCRIPTION	**TOTAL HRS**	**Cost Rate**	**Subtotal**
Attic air sealing	24	125	$3,000.00
Attic insulation	16	125	$2,000.00
Clean up	16	125	$2,000.00
Commissioning	16	150	$2,400.00
Crawlspace vapor barrier	36	125	$4,500.00
Drywall hang	48	125	$6,000.00
Drywall tape, float & texture	38	150	$5,700.00
Radiant panel hang	50	150	$7,500.00
Electrical	8	150	$1,200.00
Framing, furring, backing	12	150	$1,800.00
Interior protection	16	150	$2,400.00
Mechanical (ventilation, dehumidifier)	30	150	$4,500.00
Miscellaneous	3	150	$450.00
Painting	32	125	$4,000.00
Planning	4	150	$600.00
Plumbing (radiant contractor)	80	172.4	$13,788.27
Radiant tubing install	80	137.5	$11,000.00
Vacuum existing attic insulation	17	125	$2,125.00
Off-site labor & mgmt.	60	150	$9,000.00
LABOR TOTAL			**$83,963.27**

The cost of materials and equipment is presented in

Table 8. Here, the major costs are associated with the boards holding the PEX tubing, the plumbing parts, and the AWHP. The manufacturer of the AWHP claims an energy efficiency rating (EER) for cooling of 23 and coefficient of performance (COP) for heating of 3.92 (Chiltrix, 2022).

Table 8 - Cost of materials and equipment of installing the radiant panels at the test site.

EQUIPMENT AND MATERIALS BREAKDOWN				
QTY	**DESCRIPTION**	**UNIT**	**EXTENSION**	**EXT WITH TAX**
1	Chiltrix CX34	$4,385	$4,385	$4,746.76
1	Dehumidifier	$1,200	$1,200	$1,299.00
1	Electrical wiring, breakers, disconnects	$300	$300	$324.75
1	Plumbing parts, pipe insulation, fittings misc.	$5,000	$5,000	$5,412.50
125	Warmboard-R	$65	$8,090	$8,757.43
80	Rehau Rauplate	$4	$329	$356.14
1	FSK roll R-8 (knee walls)	$200	$200	$216.50
2	Panasonic bath fans	$160	$320	$346.40
1	Ecobee thermostat	$300	$300	$324.75
1	Controls	$200	$200	$216.50
24	Cans foam	$15	$360	$389.70
163	Cellulose insulation r-50	$8	$1,304	$1,411.58
1812	Reinforced cs vapor barrier 12 mil	$0	$634	$686.52
1812	Pins and tape for vapor barrier	$0	$453	$490.37
6	Tubes caulk, sealants	$7	$42	$45.47
1	Rolls tapes, adhesives, plastic, mask	$150	$150	$162.38
1087.2	Color matched paint	$1	$707	$764.98
1	Personal protective equipment	$200	$200	$216.50
42	Drywall, 4x8 type x lite sheets 1/2"	$10	$420	$454.65
1	Drywall prep coat primer sealer- 4.8 gals	$38	$38	$41.14
1	Drywall joint compound, tape, screws.	$150	$150	$162.38
12	Electrical cans, fixtures in ceiling	$30	$360	$389.70
1	HERS verification	$450	$450	$487.13
1	Project permit	$250	$250	$270.63
2	Shoemaker cans, return air grille (dehumidifier)	$50	$100	$108.25
12	Roof and sidewall vents	$20	$240	$259.80
1	Insulation removal equipment rental	$350	$350	$378.88
1	Insulation disposal costs	$450	$450	$487.13
1	Attic blow equipment	$500	$500	$541.25
1	Garbage disposal dumpster rental	$750	$750	$811.88
	EQUIPMENT AND MATERIAL TOTAL			**$30,561.01**

The total cost from Table 7 and Table 8 is about $114,500. Though some items can be claimed as site and project specific, the total cost is expected to land over $100,000. Since the cost savings from installing the radiant panels are found negative and the installation cost is high, no assessment of present value, return of investment or simple payback time is conducted.

2.6 Success Criteria and Conclusion

The intention was to evaluate radiant panels in terms of their benefits and applicability for wider adoption across the entire SCP territory and further across the State of California through IOU EE programs. Initially, the installation of radiant panels was planned for five homes. Throughout the first installation, it was made clear that the total cost of labor, equipment, and material far exceeded planned costs. Based on the performance assessment and cost evaluation of the radiant panel system, Frontier Energy, together with the CEC, recommended a shift in project focus to include other promising HVAC technologies. It was determined that the lack of cost-effectiveness would limit the technology’s potential for significant market adoption in Sonoma County, and elsewhere in Northern California, within the period of performance for the EPIC grant. Specifically, the barriers to cost-effectiveness and/or market adoption include, but are not limited to, the items noted below.

- Relocation during installation - Occupants are forced to find an alternative living while the panels are being installed.
- Cost – Based on the breakdown in installation and material costs, and estimated negative cost savings, the installation of the radiant panels system in existing homes is not financially reasonable. However, existing homes using electricity for heating may generate positive cost savings.
- Humidity Control – During cooling, the surface temperature of the panels shall never drop below the air dew point temperature, nor cause any adjacent surfaces to do the same. Thus, depending on climate conditions, relative humidity and temperatures sensors are required to regulate water inlet temperature to the panels, or to regulate indoor relative humidity using a dehumidifier (which consumes energy and adds heat to the indoor space).
- Recessed Lighting, duct work, and architectural features – Radiant panels installed in existing buildings may require special attention and design around penetrations through the ceiling plane and depending on architectural features. On this point, any future installation that penetrates the panels will require detecting the location of the tubes to prevent rupture and/or malfunction of the panels.
- Structural reinforcement – Depending on ceiling joist dimensions and spacing, the joist system may require reinforcement to support the additional weight associated with the radiant panels and the water that runs through the embedded pipes.
- Knowledgeable and trained installer – Radiant ceiling panels, as installed at the test site of this study, require experienced installers, and will involve various trades.
- Water leaks – Water pipes running through the building envelope always represent a risk. Leaks may occur in the pipes or in couplings and connections. Depending on

exterior climate and location of the running pipes, freezing may occur and cause rupture during a power outage.

Other takeaways from the case study related to (a) communication and outreach, (b) scoring and evaluation/suitability, and (c) technology and structure of project.

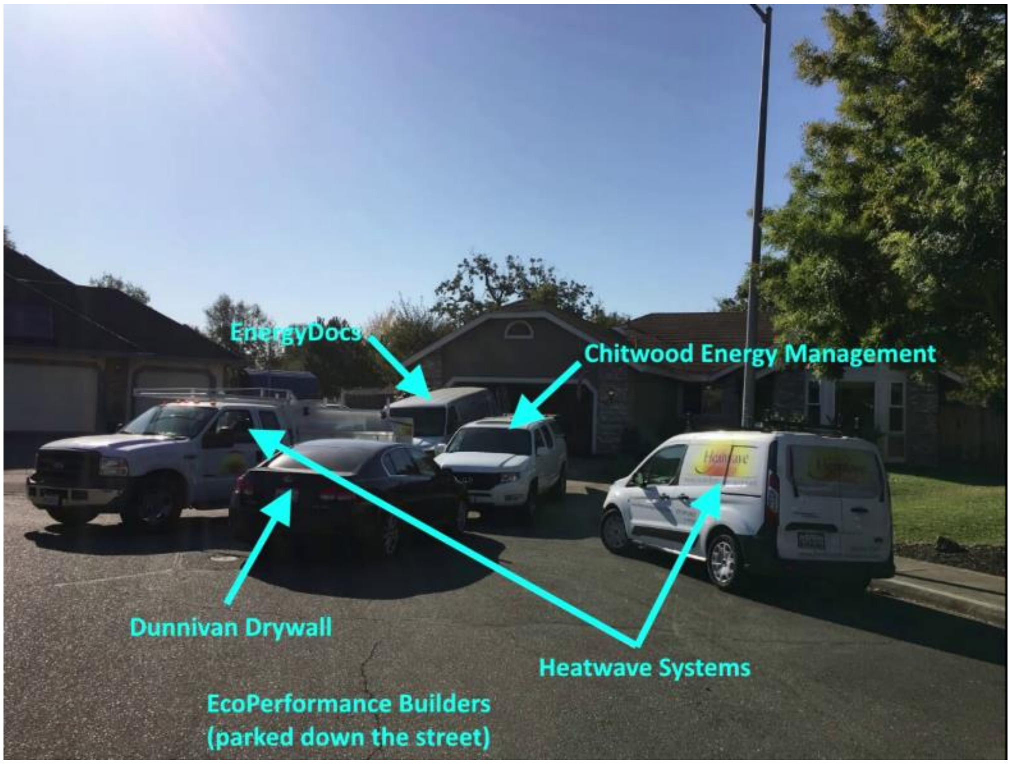
- Communication and outreach – (Pros) Great homeowner interests in participating in the study. Communication was easy to understand and approachable thanks to emails, SCP website, press release, Lead Locally facts sheets, and social media channels. Dedicated Lead Locally customer call center services and follow up with engineers by phone or site visit to address specific technical questions. (Cons) COVID-19 caused delays in material, construction, and site visits, and excluded elderly or more vulnerable homeowners from the pool of potential test sites. Cold calls were also not successful. In some cases, there were split incentives where tenants were interested, but not building owners. The duration of the project was sometimes perceived as an inconvenience and too disruptive to daily life.
- Scoring and evaluation/suitability – (Pros) The participation survey was simple and user friendly. One-on-one staff support to further assess home eligibility for technology installation and retrofit. Site visits worked well and allowed verification for compatibility with technology and identification of potential issues. The scoring approach was consistent, unbiased, appropriately weighted criteria for data integrity and customer inclusivity. (Cons) COVID-19 complicated or prevented site visits to assess eligibility. Some homeowners were unresponsive and because of the evolving pandemic, decided to decline participation.
- Technology and structure of project – (Pros) The Leal Locally program allowed to evaluate the cost-effectiveness of AWHPs coupled with radiant panels in existing homes. The test showed significant energy saving potential post-retrofit. Comprehensive monitoring allowed for collection of robust energy and performance data. (Cons) The total cost of installation and unexpected implementation challenges proves the radiant panels not to be a cost-effective retrofit measure. Limited residential market-readiness and experience between trades on installing the radiant panel system as evaluated.

Finally, a few notes worth discussing to make radiant panels more cost-effective.

- Cost of labor – The cost of labor was roughly three times higher than the cost of material and equipment. This indicates that the radiant panel system is complicated to install in existing homes. Radiant panels require skilled and experienced installers, both of which drive up the cost of labor. Preferably, the radiant panels should be designed to require less trades. Five contractors were needed to complete the work at the test site, representing five trades: carpentry, insulation, HVAC, plumbing, and drywalling, see Figure 22. This required significant coordination and logistics. In one day during the last week of the retrofit, 10 laborers were on site at the same time. The radiant ceiling panels used in this project required finishing with gypsum board, mudded and sanded, and finally finished with texture and paint. If panels can be designed to be esthetically appealing without the finishing process, there is room for cost savings. Potentially, panels can come pre-piped where quick-connects between the panels would allow for significantly less installation time. The general contractor overseeing the work at the radiant panel test house believed that it could be possible for a single contractor to complete the work, but it would require months of labor for a single job, and more licensing and insurance than is economically feasible for most contractors. In California, a licensed Class B General Contractor (GC) would possess all the necessary licensing to perform all of the work involved. However, the insurance necessary to cover HVAC and plumbing together is too significant for one individual. If that Class B GC primarily does one type of work, or oversees subcontractors on a larger building project, there is no reason for that Class B GC to pay the extra insurance to cover all of the trades. This is an issue that will be difficult for the technology to overcome, even if the technology is manufactured in a way that is easier to install.

- Performance – To minimize upward energy losses from the radiant panels, high ceiling R-value is needed. To avoid addition of attic insulation, the panels can potentially be equipped with high-R insulation above the running PEX tubes.

Figure 22 - A typical day at the house during the final week of retrofit work with all five contractors on site.



From the takeaways presented above, it was determined that serious barriers exist that are likely to prevent the radiant panel technology (as currently designed) from being cost-effective in the near term. Thus, Frontier Energy recommended that the four remaining sites planned to participate would not receive radiant panel retrofits, as similar costs of installation from the first test site were anticipated. Instead, Frontier Energy proposed that the remaining sites be retrofitted with either a hydronic fan coil-based system or a ducted mini-split system like those successfully installed in five pilot homes as part of the Technology Demonstration and Deployment task of this Lead Locally grant. It was decided that two of the test homes would be installed with a hydronic fan coil system and the other two would be installed with the ducted mini-split system, adding to a total of seven test homes for that technology.

The hydronic fan coil system would use the same air-to-water heat pump (AWHP) planned for the radiant ceiling panels, along with centralized fan-coil units in dropped ceilings and offer benefits similar to that of the AWHP plus radiant panel configuration. In comparison with radiant panels, the hydronic fan coil system was expected to be less complicated, less costly in terms of labor, and would not require homeowners to relocate during installation.

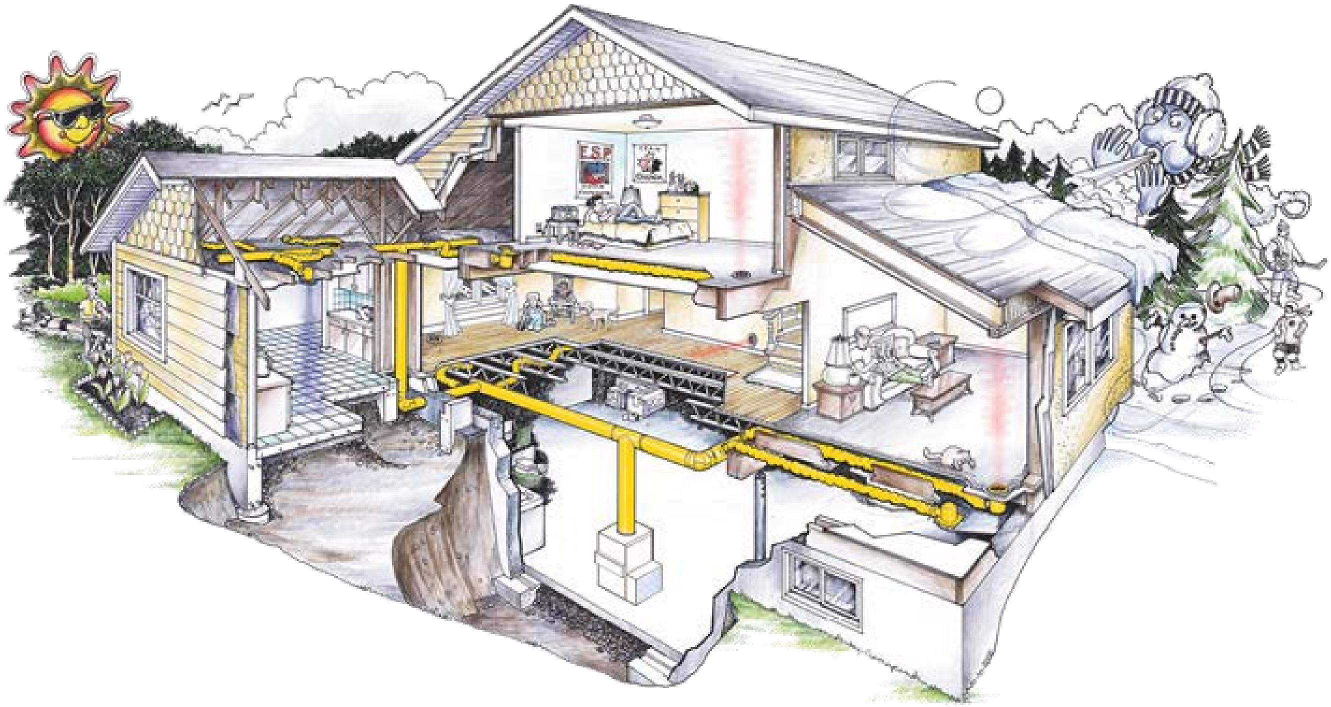
The performance and installation of the test homes with ducted mini-split heat pumps will be presented in the Tech Demo report of the project under Technology Demonstration and Deployment Verification.

CHAPTER 3:
Hydronic Fan Coils with Air-to-Water Heat Pump

3.1 Background and Operation

Hydronic fan coil systems are an emerging technology in California, with units available from major manufacturers, such as Carrier and Goodman. Figure 23 depicts an example of a ducted hydronic fan coil system. These technologies are most often seen in heating dominated climates, as they are easily integrated into existing hot water systems. They are also frequently used in multi-family buildings. In cooling climates and single-family homes, they are often paired with AWHPs to provide both heating and cooling. Smaller fan coil manufacturers, such as Hi-Velocity and iFlow, offer high efficiency units with smart-home features and optimized heat exchanger designs. The hydronic fan coil system implemented in place of the radiant delivery systems would use one (or more) of these high efficiency fan coils connected to a low static pressure duct system installed in conditioned space; this uncommon application of existing technologies qualifies this system design as an emerging technology.

Figure 23 - Illustration of an AHU with hydronic fan coils (Systems, 2022)

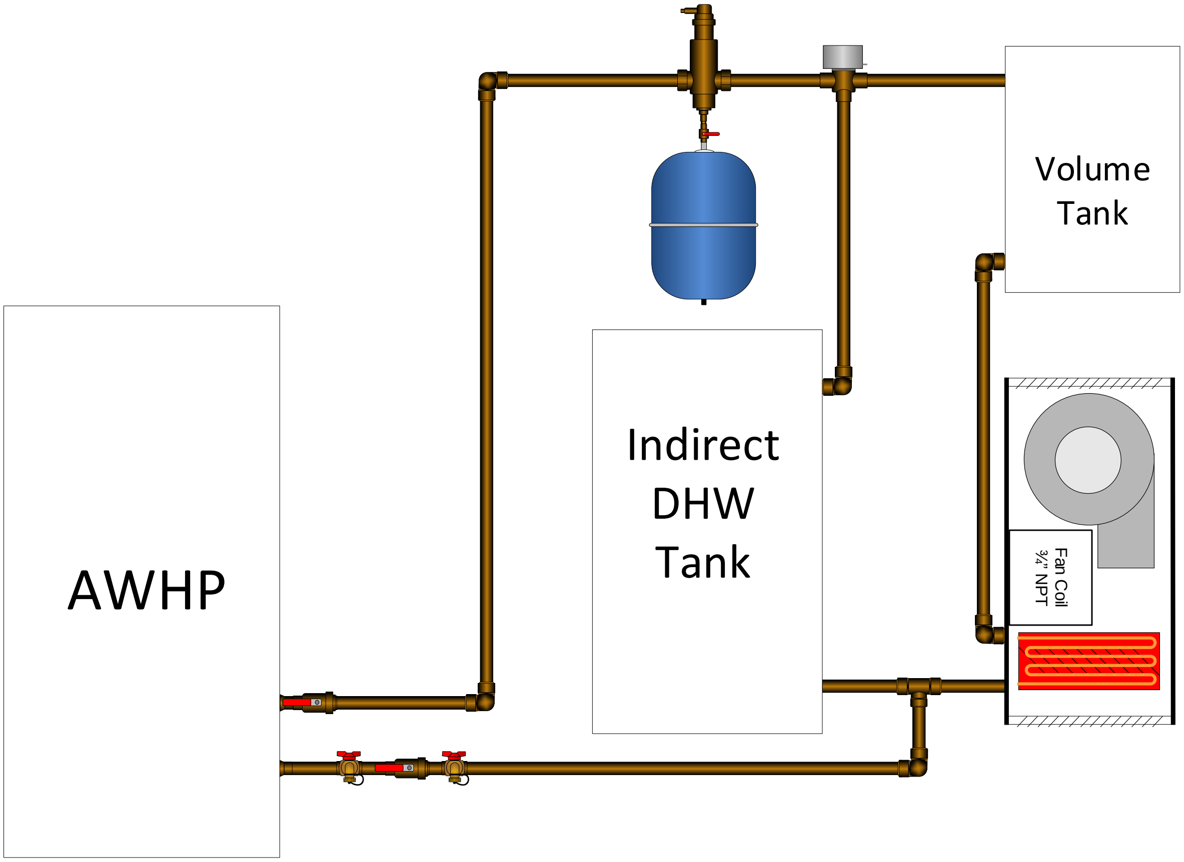


A three-function AWHP can used to provide space heating space cooling, and domestic hot water. Thus, this study also evaluates integrating the hydronic heating and cooling system with a water tank that serves the house with heated water. This setup is less common, and the cost-effectiveness is yet to be fully evaluated.

A combined heat pump system serving the hydronic fan coils and a water tank will require controls. Though control features for each AWHP vary, most can be controlled using “dry contact” inputs to initiate heating or cooling operation or to activate domestic water heating.

An order of priority must also be in place. For example, if the heat pump happens to be operating in cooling mode and receives a call for domestic water heating, the heat pump switches to heating mode and the 3-way valve (see Figure 24) is signaled to divert flow to the indirect water heater.

Figure 24 - Integrated domestic water heating and space conditioning.



3.2 Monitoring Approach

The monitoring procedure and data acquisition are presented in Section 2.2.

3.3 Laboratory Tests

No laboratory tests were conducted specifically targeting the AWHP system with hydronic fan coils and indirect water heating.

3.4 Field Sites

As discussed in Chapter 2, all test sites were located within Sonoma and Mendocino counties and selected from among SCP customers. Candidates for the installation were selected based on home, system, and occupant characteristics. For the house, it had to include single family (detached), single story, less or equal to 2,000 sq. ft. of conditioned space, and no known asbestos. For the system, the requirements were ducted functional central heating and cooling, ducts located in the attic space, preferably electric heating, and at least 10 years old.

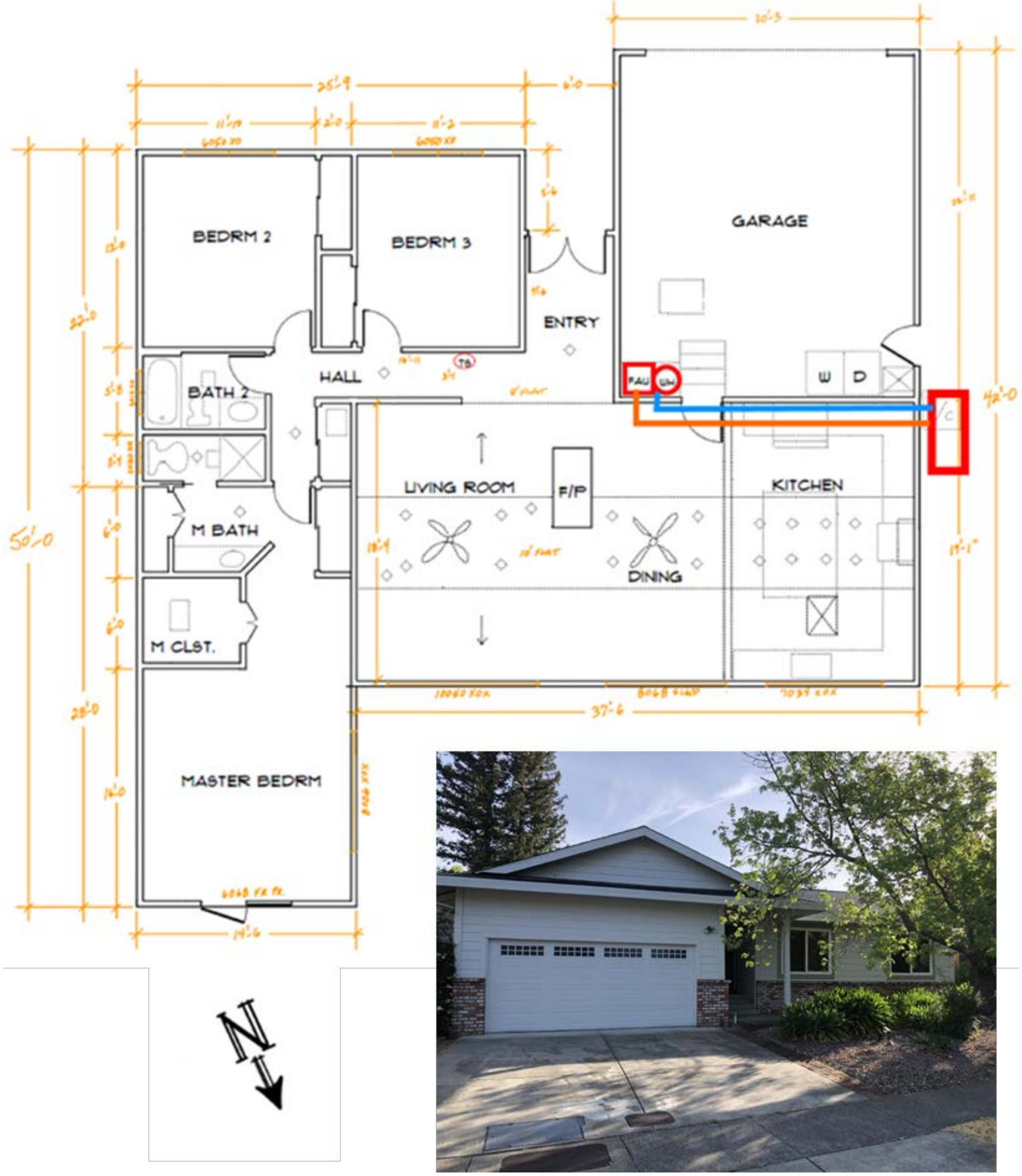
Finally, the current owners had to be full time occupants and not expecting to move within two years, non-smokers, not employed in the energy industry, and not retirees.

Six months of monitored baseline data was to be collected prior to the retrofits, followed by one year of monitored data collection post-retrofit. Data collected were based on system performance, as well as occupant comfort and behavior. 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.

Originally, the plan was to install radiant panels in five single-family homes, but four sites were selected based on the criteria above. Since the radiant panel was found to be a non-cost effective retrofit solution, two test sites (A and B) from the four candidates were selected for the installation of an AWHP with hydronic fan coils and integrated domestic water heating.

Test Site A

Figure 25 - Test site A. Air handler and indirect water heater tank are in the garage. The existing condensing unit, which was replaced with the AWHP is located next to the exterior door of the garage.



Test site A is a 1,700 square foot, crawlspace, one-story, single-family house with three bedrooms. Pre-retrofit, the house had a central ducted HVAC system with a gas furnace, and a gas water heater.

In order to make an assessment on return of investment and improved performance from installing the AWHP system, baseline monitoring was set in place for the period of March 23rd to November 5th,2019. The same monitoring equipment and data points as the radiant ceiling site were used for both hydronic fan coil sites. These are described in chapter 2.

Installation of the AWHP system occurred between November 6th, 2019 and November 22nd. During this time, the outdoor condensing unit was replaced with the AWHP, see Figure 26. The location of the new water tank and air handling unit (AHU) remained the same post retrofit, and the hydronic fan coil was installed with the AHU as depicted in Figure 27. All water lines between the new units were insulated according to code. The locations of the AWHP, AHU, and indirect water heating tank are depicted in Figure 25.

In addition to installing the AWHP system, building envelope improvements were also conducted. The attic insulation was replaced with R-49 blown-in insulation and efforts were made to caulk and foam gaps in the ceiling floor around penetrations and joist/drywall interfaces. In addition, the crawlspace was cleaned and installed with a ground surface vapor retarder.

Replacement ductwork at both sites had total air leakage of <10 CFM25 (lower than measurable by field verification and diagnostic testing methods required by Title 24), R-8 continuous duct insulation (code minimum), average total static pressure of 0.23 in. w.c. (fan airflows were rated at 0.6 in. w.c.), average fan efficacy of 0.28 W/CFM (Title 24 maximum is 0.58 W/CFM) and were installed in indirectly conditioned space.

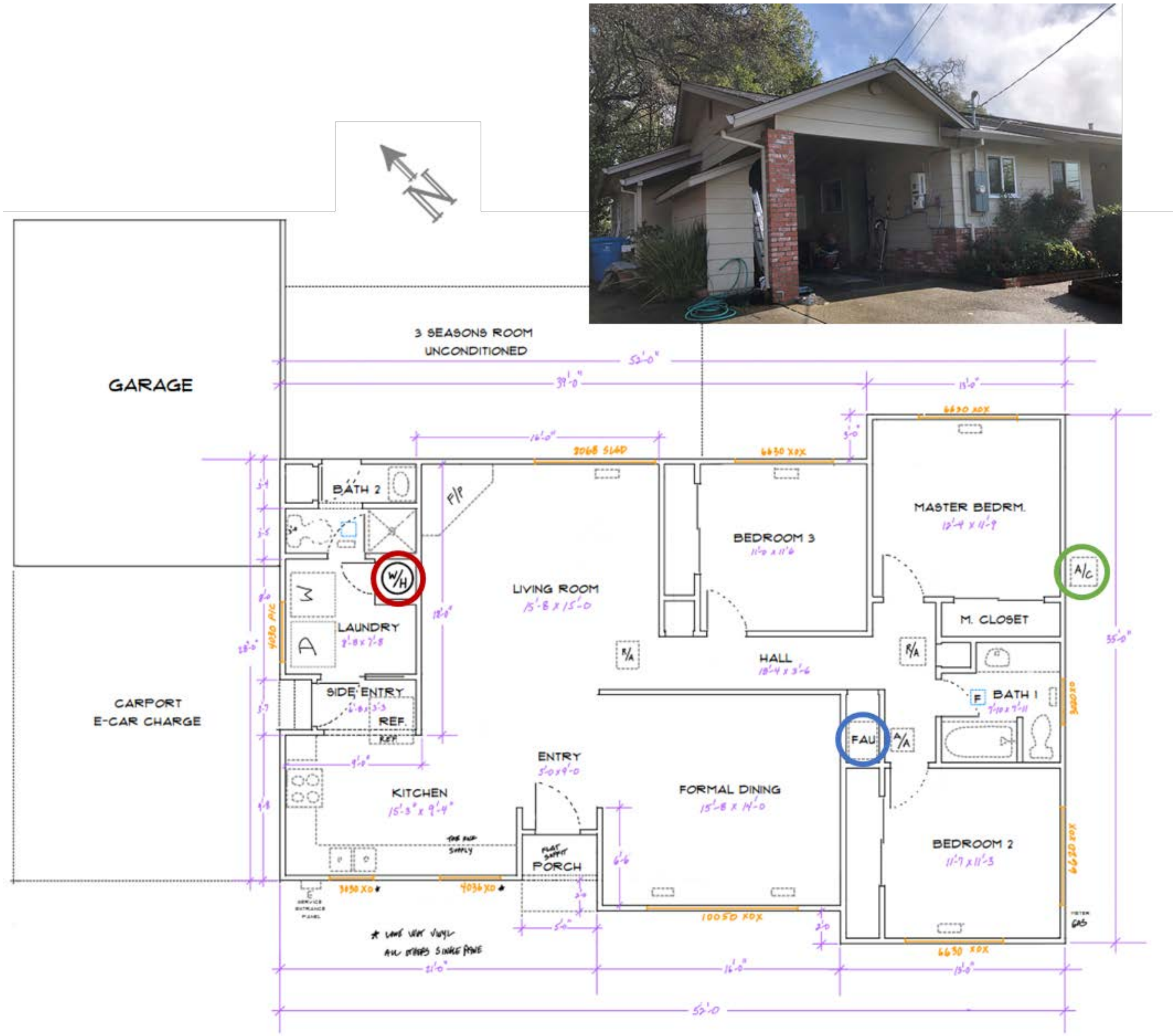
Two blower door tests to were conducted to measure the overall building airtightness before and after the retrofit measures. The initial test prior resulted in an air leakage rate of 2,001 cfm at 50 Pascals pressure difference. Post retrofit testing revealed an air leakage rate of 1,305 cfm. The total house air volume is 13,600 ft^3. Using the exchange rate as a mean of representing airtightness, the measurements read 8.8 ACH50 before the retrofit, and 5.8 ACH50 afterwards.

Figure 26 - Existing condensing unit prior to retrofit measure (left), and AWHP (Citrix CX34) as installed post retrofit (right).

Figure 27 - Existing gas water heater, gas furnace, and air handling unit (left). New indirect water heater tank, expansion and backup tanks, air handling unit and hydronic fan coil (right).

Test Site B

Figure 28 - Test site B. The location of the existing water heater is marked in red, the air handling unit in blue, and the outdoor unit in green.



Test site B is a 1,560 square foot, crawlspace, one-story, single-family house with three bedrooms. Pre-retrofit, the house had a central ducted HVAC system with a natural gas furnace and water heater. Figure 28 displays the floor plan of the house and the location of existing equipment prior to the retrofit.

The baseline reading and collection of energy performance data began on May 31st, 2019 and lasted until January 6th of 2020.

Installation of the AWHP system occurred between January 7th, 2020, and January 24th. The outdoor condensing unit was removed with the location used for the AWHP. The new water heater tank remained in the closet of the laundry room. This room also hold expansion and backup tanks, as seen in Figure 29.

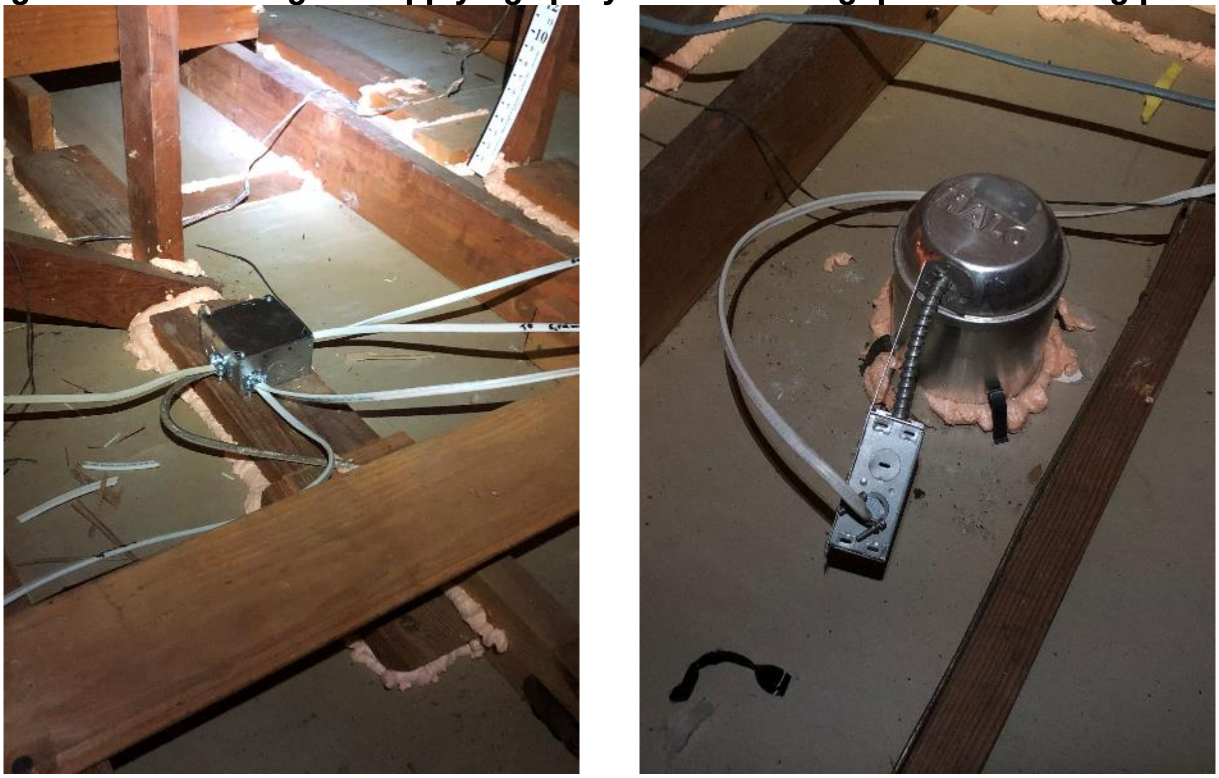
The hydronic fan coil was installed in the AHU closet, adjacent to the return grill, and the AHU was installed at the bottom of the closet with supply air directed towards the crawlspace. The setup is presented in Figure 30. All water lines between the new units were insulated according to code. The locations of the AWHP, AHU, and indirect water heating tank are depicted in the floor plan of Figure 28.

Figure 29 - Installation site of AWHP (left). Closet in laundry room holds indirect water heating tank, expansion, and backup tanks (right).

Figure 30 - Closet holding the air handling unit (bottom), and the hydronic fan coil (top).

Building envelope improvements were also implemented. The attic insulation was removed and replaced with R-49 blown-in insulation, caulk and spray foam were applied to seal gaps in the ceiling plane around penetrations and joist/drywall interfaces. Figure 31 shows gaps sealed with spray foam around a light canister and top plates/joists. In addition, the crawlspace was cleaned and installed with a ground surface vapor retarder.

Figure 31 - Caulking and applying spray foam to seal gaps in the ceiling plane.



Blower door tests were conducted pre and post retrofit. The air leakage rates were measured at a negative pressure difference of 50 Pascals. Prior to the retrofit, the measured air leakage was 2,757 cfm and 1,581 cfm post retrofit. With a total house air volume of 12,500 ft^3, these measurements correspond to 13.2 ACH50 pre-retrofit, and 7.8 ACH50 afterwards.

Various information was collected from the test site. Data loggers collected data from sensors reading inputs such as temperature and relative humidity. Heating, cooling and ventilation energy usage was recorded together operational modes of AWHP, AHU, and valves.

The installed data loggers and acquisition system collected information on energy performance from the start of the baseline period to the end of December in 2021.

The monitoring equipment was decommissioned in February of 2022.

This site and equipment presented significant challenges for the installing contractor. The hydronic coil used in Site A was an “A” coil (referring to its shape) while the coil used in Site B was a “slab” coil. This required mounting the coil horizontally and the AHU vertically in order to fit both in the closet. Additionally, even though the furnace closet was deep enough to accommodate both the fan coil and the DHW tank, one would have had to be installed behind the other, preventing access in the event of maintenance. Instead, the DHW tank and fan coil had to be installed in separate closets, as the baseline system was. This added complexity and required installing most of the other hydronic system components (expansion tanks, additional volume tank, switch valves, etc.) in the much smaller DHW closet.

Post-installation survey for Site A and B

The homeowner completed a survey more than a year after the AWHP system was installed. The first part of the survey included questions related to comfort, control, and quality of equipment. The homeowner selected a number between one and five to measure satisfaction, where one represented “Very Dissatisfied” and five “Very Satisfied”.

For test site A, the homeowners were very satisfied, or satisfied with the comfort questions related to temperature, feeling of drafts, perceived air quality, noise, and general comfort. Likewise, the HVAC system control was perceived satisfying, except for “Availability of options (ex. temperature, schedule, fan speed, etc.)”, which was given a “2”. The quality, visual appearance, and ease of maintenance were rated highly. For test site B, the homeowners were very satisfied, or satisfied on all topics mentioned above.

The second part of survey included usage. Here the homeowners of test site A, replied that they changed thermostat setpoints pre- and post-retrofit to 68°F for heating and 78°F for cooling. They also revealed that they leave windows open when the outdoor temperature is above 68°F during heating season. The homeowner of test site A also states that they would like the ability to override the system control priority of heating versus hot water. They also would like the ability to adjust fan speed and complained about the outdoor unit being loud and operating a lot during the winter. The homeowner uses a humidifier during periods of dry air and reveal that they would have wanted the option to choose finishes of the registers.

For test site B, the homeowners stated that they changed the thermostat setpoint to 71°F, and only opened the windows during swing season (spring and fall). The homeowners also discussed overriding the priority water heating has over the hydronic fan coils and provided an example of heating halting in the middle of the night to heat up the water heater tank, which were not going to use that night. They also mention overriding the DHW system during hot days when cooling should have priority.

The third part of the survey was related to household and time spent indoors. For both test sites, no changes were made to the number of people living in the house but that in March 2020, they started spending significantly more time indoors due to the COVID-19 pandemic.

Finally, the survey ended with questions related to the program, support, staff, and contractors, and participating in the project. Here, the response was mainly “very satisfying” to the homeowners of both test sites.

The full post-retrofit surveys for the two test sites are provided in Appendix A.

3.5 Performance Assessment and Cost Evaluation

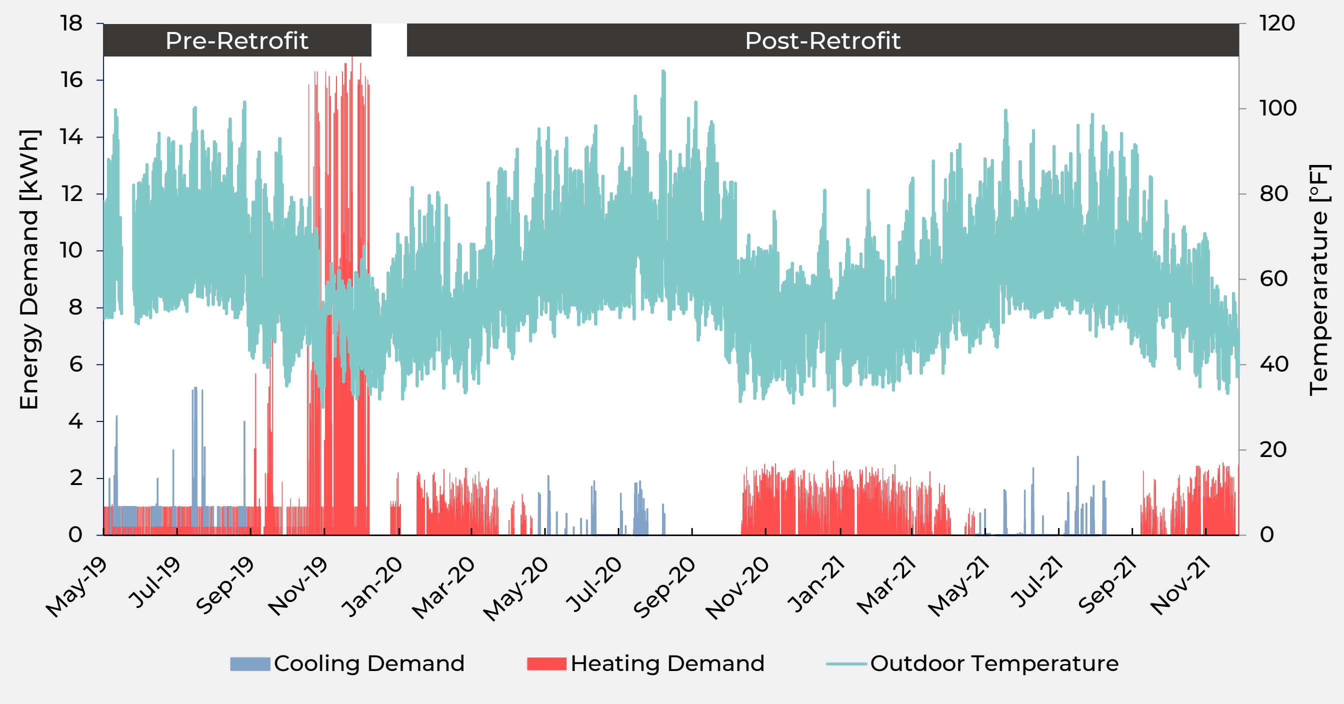
As for the radiant panels, a comparison in performance and energy usage pre- and post-retrofit is quite problematic for the two test sites. Pre-retrofit, the furnace uses natural gas for heating, while post-retrofit, the AWHP uses electricity. In order to allow for a side-by-side comparison, natural gas usage pre-retrofit must be converted from kBtu to kWh. Unfortunately, this approach also makes the comparison complicated since the cost of natural gas is less than electricity in relation to given energy. Thus, a full assessment and cost evaluation must include rates and cost of energy.

Remark, the assessment in this section focuses on cost of energy and expected changes from installing the radiant panel system. Any changes in operational carbon emissions are not evaluated.

Pre- and post-retrofit performance – Test site A

The baseline data for the test site was collected between May 31st of 2019 and January 6th of 2020 and is presented in the far left of Figure 32. Here, cooling and heating energy demand is depicted together with the variation in outdoor ambient air temperature. Figure 32 also shows the energy demand and outdoor temperature post-retrofit.

Figure 32 - Test site A - Cooling (blue) and heating (red) energy demand pre- and post-retrofit. The outdoor temperature (green) during the time of data collection is also depicted.



As applied in the performance assessment of the radiant panel test site, the impact of variation in outdoor climate pre- and post-retrofit is accounted for using heating and cooling degree hours. Again, degree hours are applied to normalize the weather data and allow for a comparison between the baseline and post-retrofit performance data. ASHRAE 169 suggests summarizing all hours during a year when the outdoor temperature exceeds 65°F and below 50°F for heating degree hours (ASHRAE, 2021); an approach which make sense if comparing weather data or estimating building heating and cooling energy demand. However, the drawback as mentioned earlier is that this approach obviously assumes that heating always occurs when the outdoor air temperature is below 50°F and that cooling always happen at temperatures higher than 65°F. In reality, whether heating or cooling is required mainly depends on three variables; (1) the thermostat setpoints, (2) building envelope and HVAC system characteristics, and (3) comfort preferences. Consequently, whether cooling or heating is required depends on a number of significant variables other than outdoor air temperature. Instead, the following assessment applies a method of calculating actual degree hours from site specific data. In other words, the actual outdoor air temperatures are applied for when heating or cooling occur. Using available information on thermostat setpoints, occupancy presence and energy demand, these baseline temperatures are defined. Pre-retrofit, the average outdoor air temperature for when cooling was required was found at 70.9°F and 58.3°F for heating.

Post-retrofit, the heat balance of the building is different because of building envelope retrofit measures, such as adding more insulation in the attic and improved overall airtightness. Also, the user behavior is assumed somewhat different. Due to COVID-19 pandemic, the tenants spent more time inside the house. The average outdoor air temperature to calculate degree hours for cooling drops to 72.4°F and increases to 61.1°F for heating after the retrofit is completed. The datapoints used to calculate average outdoor air temperatures for when cooling or heating is needed are presented in Figure 33. As found by the scatter plot, the outdoor air temperature range for when either heating or cooling is needed becomes narrower after the installation of the AWHP system.

Figure 33 - Test site A - Lowest daily outdoor ambient air temperatures for when cooling and heating is needed. The data points help to determine baseline temperatures used to calculate heating and cooling degree hours.

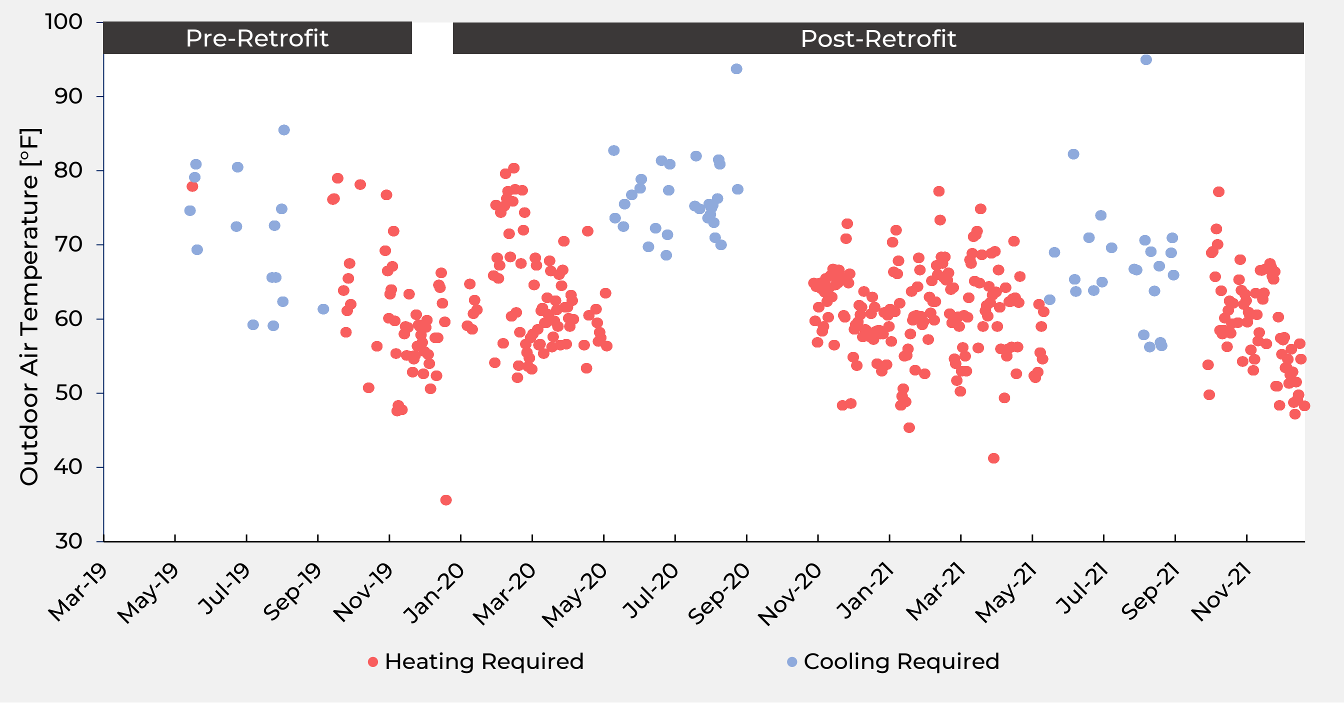


Table 9 presents actual degree hours based on temperatures presented above and the energy usage for the test site A during the period between May 31st and January 7th of 2020 (pre-retrofit), and for the rest of the year of 2020 and the year of 2021 (post-retrofit).

Table 9 - Test site A - Heating and colling degree hours and energy usage pre- and post-retrofit for the test site. A usage ratio is presented that reflect on the relationship between usage and degree hours.

Time Period	Degree Hours [H°F]		Usage [kWh]		Usage Ratio [kWh/(H°F)]		Savings [-]	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
Start 3/25/2019 End 10/6/2019	11,532	17,190	183	1922 / *6558* *(kBtu)*	0.016	0.112 / *0.381* *(kBtu/h,F)*	-	-
Start 1/1/2020 End 12/31/2020	12,665	50,271	100	1,190	0.008	0.024	**50%**	**79%**
Start 1/1/2021 End 12/31/2021	8,561	60,161	94	1,705	0.011	0.028	**31%**	**75%**

Table 9 also presents an energy usage ratio for heating and cooling demand. This ratio serves as a normalized indicator of energy utilization per degree hour and is useful to estimate energy savings. For cooling, the usage ratio is 0.016 kWh per degree hour prior to the retrofit. Post-retrofit, the usage ratio drops to 0.008 during the first year after the installation, and then slightly higher in 2021 to 0.011 kWh per degree hour. According to Table 4, the estimated energy savings for cooling compared to the baseline period vary roughly between 30 and 50%.

For heating, the savings are more consistent between the two years after the installation of the AWHP system. Pre-retrofit, the usage ratio is 0.115 kWh per heating degree hour. Post-retrofit, the usage drops to 0.024 for 2020 and 0.028 for 2021. The drop in usage corresponds to a decrease in heating energy demand of 75 to 79%.

Major variables on energy demand include human comfort levels and preferences. For the test site, there were no restrictions given on temperature range and limits for the thermostat. Thus, the homeowners were free to adjust the setpoint temperatures as they pleased. According to the survey, and the collected data, a temperature of 78°F was set for cooling and 66°F for heating. In the analysis, the setpoint preferences are assumed constant pre- and post-retrofit.

The estimated energy savings for test site A is presented inTable 10. Here, the difference in usage ratio pre- and post-retrofit is used to calculate a savings ratio. The savings ratio is multiplied with the cooling and heating degree hours to calculate estimated energy savings. According to Table 10, the electricity savings for heating and cooling add up to about 4,700 kWh annually on average between 2020 and 2021. This analysis converts kBtu pre-retrofit to kWh for a side-by-side comparison. Though, it is assumed that the AWHP system contributes to most of the savings, building envelope improvements also certainly had a beneficial impact.

Table 10 - Test site A - Estimated energy savings using annual average savings

usage ratio (post-retrofit usage subtracted from pre-retrofit), and estimate energy savings for Santa Rosa, CA from applying same saving ratios. The heating and cooling degree hours represents a Typical Metrological Year (TMY).

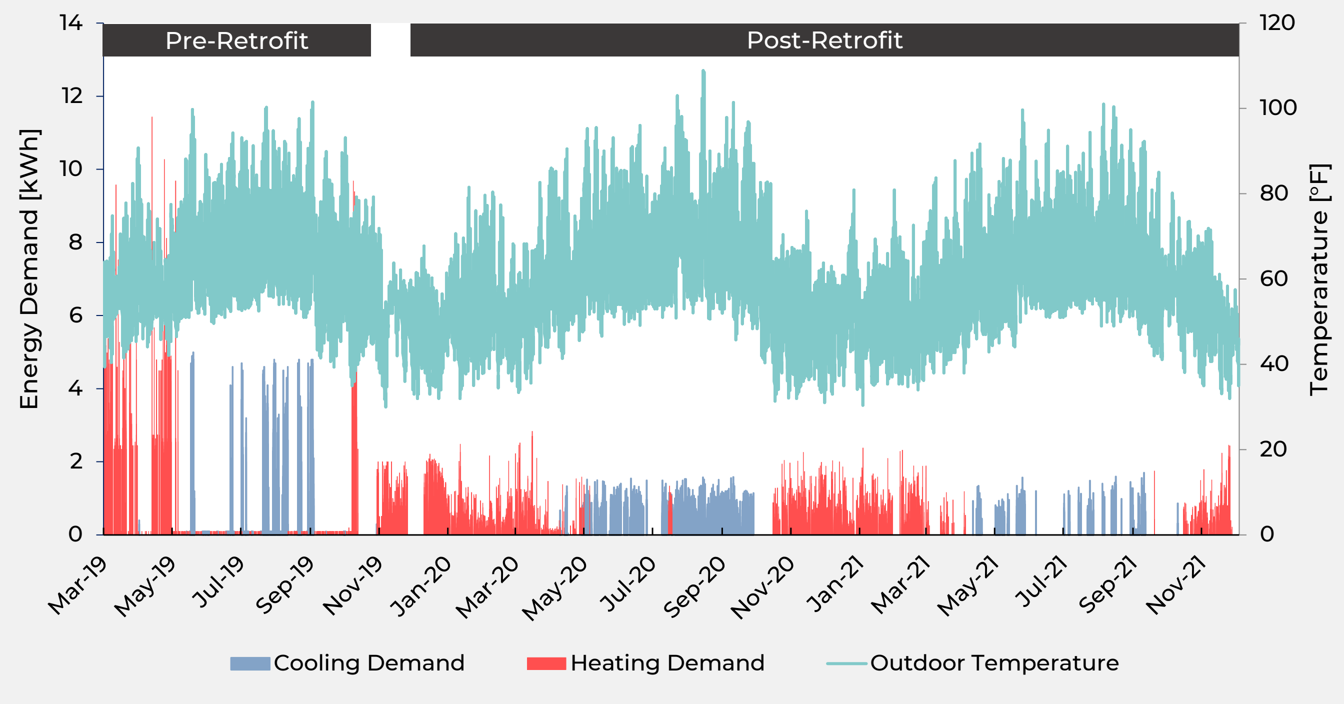
Time Period	**Degree Hours [H°F]/[D°F]**		**Savings Usage Ratio [kWh/(H°F)]**		**Estimated Savings [kWh]**	
	Cooling	**Heating**	**Cooling**	**Heating**	**Cooling**	**Heating**
Test site, average of 2020 and 2021	10613	55216	0.006	0.086	**69**	**4737**
Santa Rosa, CA TMY, 2008	18228	30566	0.006	0.086	**118**	**2622**

For a general comparison, Table 10 presents estimated energy savings from the test site if applied to a typical meteorological year (TMY) of Santa Rosa, California. Here, the same saving usage ratios from the test site are applied but multiplied with cooling and heating degree hours for the selected TMY. Heating and cooling degree hours are calculated based on standard baseline temperatures of 65°F for cooling and 55°F for heating. The estimated reduction in energy use is estimated at roughly 120 kWh for cooling and 2,600 kWh for heating annually. However, the predicted energy savings are dominated for heating and the existing home pre-retrofit used natural gas for heating. Because the cost of natural gas is lower compared to electricity in relation to energy given, it’s likely that the estimated savings in heating usage may result in an increase in energy cost.

Pre- and post-retrofit performance – Test site B

The baseline data for the test site was collected between March 23rd of 2019 and November 5th of 2019 and is presented in the far left of Figure 34. Here, cooling and heating energy demand is depicted together with the variation in outdoor ambient air temperature. The retrofit measures were completed by November 22nd of 2019. Figure 34 also shows the energy demand and outdoor temperature until the end of 2021.

Figure 34 - Test site B - Cooling (blue) and heating (red) energy demand pre- and post-retrofit. The outdoor temperature (green) during the time of data collection is



As for test site A, the impact of variation in outdoor weather pre- and post-retrofit is accounted for using heating and cooling degree hours.

Pre-retrofit, the average outdoor air temperature for when cooling was required was found to be 66.2°F and for heating, 56.1°F. As mentioned for test site A, the overall heat balance of the building is affected by the building envelope retrofit measures and improved overall airtightness, as well as any potential change in user behavior due to the COVID-19 pandemic. The average outdoor air temperature to calculate degree hours for cooling drops to 63.6°F and increases to 55.0°F for heating after the retrofit is completed. The datapoints used to calculate average outdoor air temperatures for when cooling or heating is needed are presented in Figure 35.

Figure 35 - Test site B - Lowest daily outdoor ambient air temperatures for when cooling and heating is needed. The data points help to determine base line temperatures used to calculate heating and cooling degree hours.

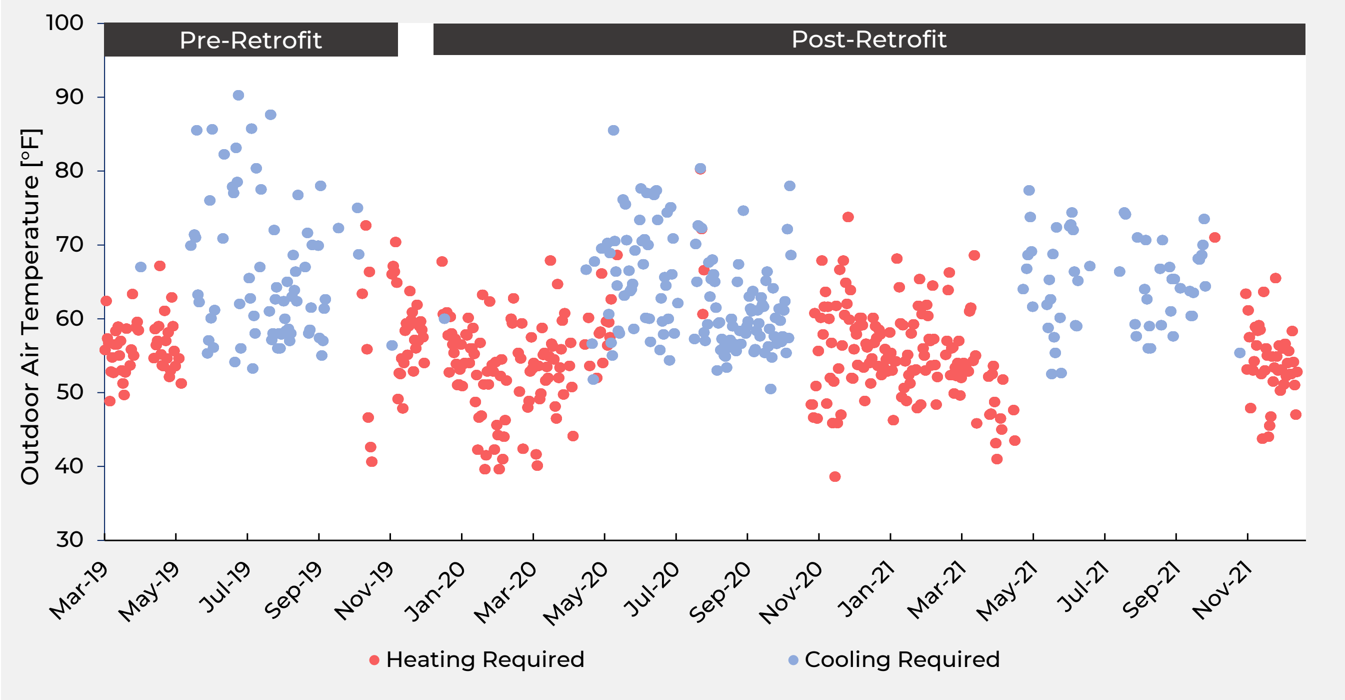


Table 11 presents actual degree hours based on temperatures presented above and the energy usage for the test site B during the period between March 23rd and November 5th of 2019 (pre-retrofit), and from November 22nd in 2019 to the end of 2020, and for the year of 2021.

Table 11 - Test site B - Heating and colling degree hours and energy usage pre- and post-retrofit for the test site A usage ratio is presented that reflect on the relation between usage and degree hours.

Time Period	**Degree Hours [H°F]**		**Usage [kWh]**		**Usage Ratio [kWh/(H°F)]**		**Savings [-]**	
	Cooling	**Heating**	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**	**Heating**
Start 3/25/2019 **End 10/6/2019**	20713	8981	550	1303 / *4445* *(kBtu)*	0.027	0.145 / *0.495* *(kBtu/h,F)*	-	-
Start 1/1/2020 **End 12/31/2020**	31059	36193	956	1741	0.031	0.048	**-16%**	**67%**
Start 1/1/2021 **End 12/31/2021**	23317	28068	297	703	0.013	0.025	**52%**	**83%**

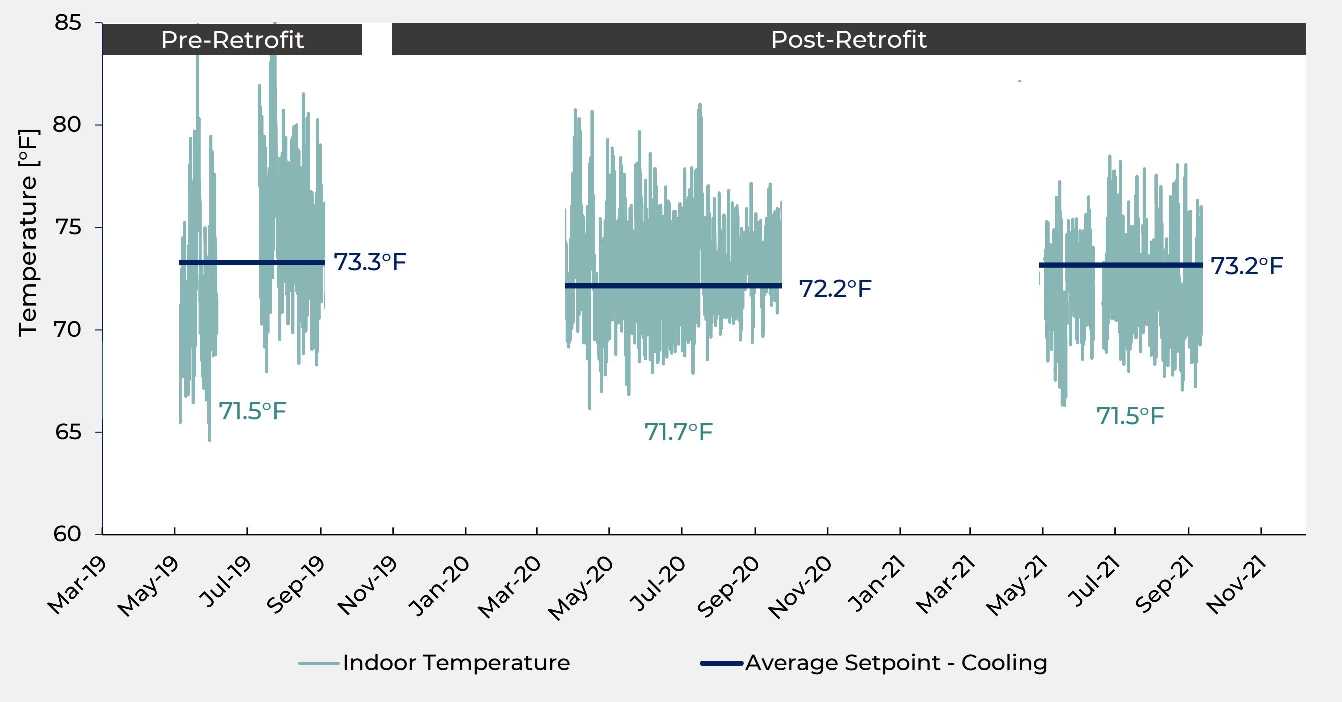
In Table 11, the energy usage ratio for heating and cooling demand serves as a normalized indicator of energy utilization per degree hour. For cooling, the usage ratio is 0.027 kWh per degree hour prior to the retrofit. Post-retrofit, the ratio increases for the first year, only to drop to 0.013 in 2021. The reason to why the energy demand for cooling increases in 2020 is not fully understood. The summer of 2020 was warmer than the summer of 2021, but the way the actual degree hours are defined should reflect on such variations.

For heating, the savings are more consistent between the two years after the installation of the AWHP system. Pre-retrofit, the usage ratio is 0.145 kWh per heating degree hour. Post-retrofit, the usage drops to 0.048 for 2020 and 0.025 for 2021. The drop in usage corresponds to a decrease in heating energy demand of 67 to 83%. Again, remark that this comparison is made by converting kBtu of natural gas usage pre-retrofit to kWh.

Major variables on energy demand include human comfort levels and preferences. For the test site, there were no restrictions given on temperature range and limits for the thermostat. Thus, the homeowners were free to adjust the setpoint temperatures as they pleased.

Figure 36 presents thermostat setpoints for cooling (blue) and the variation in indoor temperature during the cooling season (green). It also provides the average indoor temperature during the time of cooling. The high peaks in indoor temperature seem to be lower post-retrofit, which may indicate that the AWHP system is more successful in maintaining a preferred indoor temperature. The thermostat setpoint temperatures are about the same through the total test period.

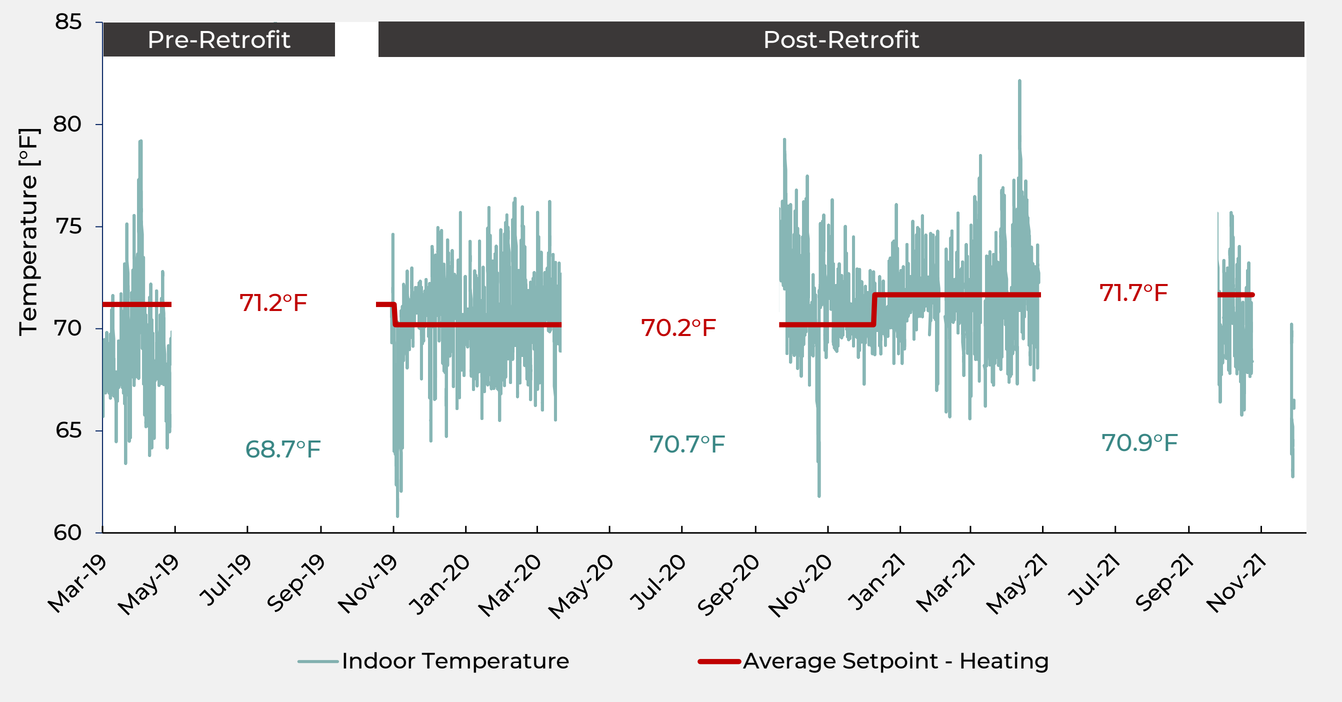
Figure 36 - Test site B - Average thermostat setpoint during cooling (blue horizontal line), and variation in indoor temperature during the time of cooling (green). The average indoor temperature during the cooling season is also presented.



For heating, Figure 37 reveals that indoor temperature seems to be somewhat higher post-retrofit, despite similar setpoint temperatures. This may indicate that the AWHP system is able to maintain a preferred indoor temperature more sufficiently than the old system. It may also be in combination with improving the building envelope performance by adding more insulation in the attic and making the house more airtight.

Figure 37 - Test site B - Average thermostat setpoint during heating (red horizontal line), and variation in indoor temperature during the time of heating (green). The

average indoor temperature during the heating season is also presented.



The estimated energy savings for test site B is presented in Table 12. Here, the difference in usage ratio pre- and post-retrofit by Table 11 is applied to calculate a savings ratio. The savings ratios are multiplied with the cooling and heating degree hours to estimated energy savings. According to Table 12, the electricity savings for heating and cooling add up to about 4,250 kWh annually on average between 2020 and 2021. In addition to installing the AWHP system, the total savings are assumed to also be a result of improvements made to the building envelope and overall building airtightness.

Table 12 - Test site B - Estimated energy savings using annual average savings usage ratio (post-retrofit usage subtracted from pre-retrofit), and estimate energy savings for Santa Rosa, CA from applying same saving ratios. The heating and cooling degree hours represents a Typical Metrological Year (TMY).

Time Period	Degree Hours [H°F]/[D°F]		Savings Usage Ratio [kWh/(H°F)]/[kWh/(D°F)]		Estimated Savings [kWh]	
	Cooling	Heating	Cooling	Heating	Cooling	Heating
Test site, average of 2020 and 2021	27188	32131	0.014	0.120	**376**	**3856**
Santa Rosa, CA TMY, 2008	18228	30566	0.014	0.120	**252**	**3668**

Table 12 also presents estimated energy savings if applying the savings in usage ratios to a typical metrological year (TMY) for Santa Rosa, California. Here, the saving usage ratios from test site B are applied and multiplied with cooling and heating degree hours for the selected TMY. Heating and cooling degree hours are calculated based on standard baseline temperatures of 65°F for cooling and 55°F for heating. The estimated reduction in energy use is estimated at roughly 250 kWh for cooling and 3,750 kWh for heating annually. Pre-retrofit, the test site uses natural gas for heating. Since the savings in Table 12 is dominantly for heating and due to the cost of natural gas compared to electricity, the savings in energy use may result in an increase in cost.

Electricity Savings

Table 13 and Table 14 reveal an assessment of cost of energy for the two test sites. The assessment includes collected data, as well as predicted data if no retrofit measures were conducted, and future cost of energy based on statewide escalation rates (Energy and Environmental Economics, 2019). During 2020 and 2021, there are negative savings for test site A and test site B during 2020 compared to if no retrofit measures were conducted. There is a slight positive cost saving for test site B during 2021. The cost of natural gas and electricity are pulled from average rates during heating and cooling season for each year (PG&E, pge.com, 2022).

Table 13 - Test Site A. Actual and estimated cost of energy post-retrofit, and under the scenario that no retrofit measure was conducted. The cost analysis also includes what the savings may look in 10 years from 2021, based on predicted California statewide escalation rates. The cooling and heating demand for 2031 is based on averages of 2020 and 2021.

Time Period	No Retrofit (estimated)							
	Degree Hours [H°F] (Pre-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kBtu)	Cost[c] ($/kBtu)	Total Cost	
Start 1/1/2020 End 12/31/2020	14960	36734	238	$0.26	14014	$0.0121	**$231**	
Start 1/1/2021 End 12/31/2021	10335	44359	164	$0.28	16923	$0.0143	**$288**	
Start 1/1/2031 End 12/31/2031	12647	40546	201	$0.33	15468	$0.0219	**$405**	
Time Period	**Post-Retrofit**							
	Degree Hours [H°F] (Post-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kWh)	Cost[b] ($/kWh)	Total Cost	Annual Savings
Start 1/1/2020 End 12/31/2020	12665	50271	100	$0.26	1190	$0.26	**$336**	**-$104**
Start 1/1/2021 End 12/31/2021	8561	60161	94	$0.28	1705	$0.28	**$504**	**-$216**
Start 1/1/2031 End 12/31/2031	10613	55216	97	$0.33	1448	$0.33	**$511**	**-$106**

[a] *Cost of electricity during cooling season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of electricity for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).*

[b] *Cost of natural gas during heating season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of natural gas for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).*

[c] *Cost of electricity during heating season of 2020 and 2021 (PG&E, Tariffs, 2022)*

The degree hours in Table 13 and Table 14 depends on pre- and post-retrofit user behavior and settings. For the “no retrofit” assessment, the settings for 2020 and 2021 are based on baseline data. Even future predicted costs generate negative savings are presented.

Table 14 - Test Site B. Actual and estimated cost of energy post-retrofit, and under the scenario that no retrofit measure was conducted. The cost analysis also includes what the savings may look in 10 years from 2021, based on predicted California statewide escalation rates. The cooling and heating demand for 2031 is based on averages of 2020 and 2021.

Time Period	No Retrofit (estimated)						
	Degree Hours [H°F] (Pre-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kBtu)	Cost[c] ($/kBtu)	Total Cost
Start 1/1/2020 End 12/31/2020	24482	41861	650	$0.26	20720	$0.0121	**$420**
Start 1/1/2021 End 12/31/2021	17458	23956	464	$0.28	11858	$0.0143	**$299**
Start 1/1/2031 End 12/31/2031	20970	32909	557	$0.33	16289	$0.0219	**$540**

Time Period	Post-Retrofit							
	Degree Hours [H°F] (Post-Retrofit Settings)		Cooling (kWh)	Cost[a] ($/kWh)	Heating (kWh)	Cost[b] ($/kWh)	Total Cost	Annual Savings
Start 1/1/2020 End 12/31/2020	31059	36193	956	$0.26	1741	$0.26	**$701**	**-$282**
Start 1/1/2021 End 12/31/2021	23317	28068	297	$0.28	703	$0.28	**$280**	**$19**
Start 1/1/2031 End 12/31/2031	27188	32131	627	$0.33	1222	$0.33	**$611**	**-$71**

[a] *Cost of electricity during cooling season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of electricity for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).*

[b] *Cost of natural gas during heating season of 2020 and 2021 (PG&E, Tariffs, 2022), and cost of natural gas for 2031 based on California statewide escalation rates (Energy and Environmental Economics, 2019).*

[c] *Cost of electricity during heating season of 2020 and 2021 (PG&E, Tariffs, 2022)*

Economic Benefits

The energy performance analysis has demonstrated that an AWHP system with hydronic fan coils and indirect water heating does not result in significant energy savings. Still, it’s of great importance to also evaluate the initial costs from the installation to assess overall cost-effectiveness. The breakdown of labor hours and cost were similar between the test sites. The breakdown from one of the test sites are presented in

Table 15 and add up to about $55,450. As for the radiant panels test site, it is worth noting that many different trades were involved in the installation. Again, this calls for organized work schedules and time management, which if not carefully planned for, can result in unnecessary costs. Further considerations and reflections are discussed upon in Success Criteria and Conclusion at the end of Chapter 2.

Table 15 - Cost of labor to install the three function AWHP fan coil system at one of the test sites.

LABOR BREAKDOWN			
DESCRIPTION	**TOTAL HRS**	**Cost Rate**	**Subtotal**
Attic air sealing	24	125	$3,000.00
Attic insulation	16	125	$2,000.00
Clean up	16	125	$2,000.00
Commissioning	16	150	$2,400.00
Crawlspace vapor barrier	36	125	$4,500.00
Drywall	21	150	$3,150.00
Ducts	34	125	$4,250.00
Electrical	10	150	$1,500.00
Framing, furring, backing	2	150	$300.00
Interior protection	8	150	$1,200.00
Mechanical (ventilation, dehumidifier)	22	150	$3,300.00
Miscellaneous	4	150	$600.00
Painting	8	150	$1,200.00
Planning	2	150	$300.00
Plumbing (master)	60	172.4	$10,341.20
Plumbing (apprentice)	60	137.5	$8,250.00
Vacuum attic insulation	16.5	125	$2,062.50
Off-site labor & mgmt.	34	150	$5,100
PROJECT TOTAL			**$55,453.70**

The cost of materials and equipment for one of the test sites are presented in Table 16. The total cost adds up to about $14,900. According to the breakdown, there are no major items sticking out as highly contributing to the total cost rather than the AWHP Chiltrix CX34.

Table 16 - Cost of materials and equipment of installing the AWHP system at one of the test sites.

EQUIPMENT AND MATERIALS BREAKDOWN				
QTY	**DESCRIPTION**	**UNIT**	**EXTENSION**	**EXT WITH TAX**
1	Chiltrix CX34	$4,385	$4,385	$4,747
1	Chilled Hydronic Fan Coil Unit	$1,000	$1,000	$1,083
1	Electrical wiring, breakers, disconn.	$150	$150	$162
1	Plumbing parts, vent parts (existing)	$175	$175	$189
1	Ducts, elbows, transitions, mastic, etc.	$350	$350	$379
1	Sheet metal plenums and pans	$500	$500	$541
0.25	FSK Roll R-8	$200	$50	$54
2	Panasonic Fans	$160	$320	$346
1	Ecobee thermostat	$300	$300	$325
1	Interface module	$200	$200	$217
24	Cans foam	$15	$360	$390
135	Cellulose Insulation R-50	$8	$1,080	$1,169
1500	Reinforced CS Vapor Barrier 12 mil	$0.35	$525	$568
1500	Pins and tape for VB	$0.25	$375	$406
6	Tubes caulk, sealants	$7	$ 42	$45
1	Rolls tapes, adhesives, plastic, mask	$150	$150	$162
1	Color matched paint	$75	$75	$81
1	Personal protective equipment	$200	$200	$217
1	Drywall, framing, mud, tape, etc.	$250	$250	$271
4	Electrical cans, fixtures in ceiling	$30	$120	$130
1	HERS verification	$450	$450	$487
1	Project permit	$250	$250	$271
6	Shoemaker cans, return air grille	$50	$300	$325
12	Roof and sidewall vents	$20	$240	$260
1	Insulation removal equipment rental	$350	$350	$379
1	Insulation disposal costs	$450	$450	$487
1	Attic blow equipment	$500	$500	$541
1	Garbage disposal dumpster rental	$650	$650	$704
	PROJECT TOTAL			**$14,935.25**

The total cost from Table 15 and Table 16 is about $70,400.

Since the estimated annual utility cost savings for the AWHP and hydronic fan coil system show little to negative savings, any analysis of payback period or assessment of present value becomes irrelevant.

3.6 Success Criteria and Conclusion

The main purpose of installing the AWHP system with indirect water heating was to evaluate the technology in terms of its benefits and applicability for wider adoption across the entire SCP territory, as well as broader feasibility across the State of California through IOU EE programs. From the assessment of the cost-effectiveness above, it's made clear that the total cost of labor, equipment, and material far exceeds estimated savings.

A few thoughts on the retrofit measures.

- Installing a vapor retarder in crawl space can potentially improve the indoor air quality, reduce the risk of pest problems and/or moisture damage. However, this measure is not critical for the AWHP system and overall energy performance.
- In a case where the ducts are in acceptable condition, there is likely no need for replacement.
- Removal of existing attic insulation is in most cases unnecessary, since it will still contribute to overall thermal resistance if new insulation is added. Caulking and applying spray foam to improve airtightness can still be done by moving existing insulation around.

Despite some of the potential means of reducing costs as described below, a reduction of more than $20,000 cannot reasonably be expected; making the AWHP system as installed not yet cost-effective. Part of the problem is that the AWHP technology is still in its infancy in this country and therefore product costs are high and contractor familiarity is low.

General takeaways from the test sites related to (a) communication and outreach, (b) scoring and evaluation/suitability, and (c) technology and structure of project can be found in "Success Criteria and Conclusions" under the radiant panel chapter.

CHAPTER 4: Conclusions and Recommendations

4.1 Technology Readiness

Radiant panels

Modern radiant systems using plastic tubing have been popular in custom homes for decades. Still, it has mainly been installed in new construction. For retrofits, the cost-effectiveness depends on many variables and how effectively radiant panels condition homes is yet not fully analyzed. After evaluating radiant panels as part of the Lead Locally grant, there are potential market barriers in terms of labor and knowledge when installing the radiant panel system. Despite having two experienced hydronic system and radiant installers on the team, the cost of labor was roughly three times higher for the test site than the cost of material and equipment. This was largely due to the number of trades involved: carpentry, HVAC, plumbing, and drywalling. Until radiant panels are designed to require less trades and total labor, the cost-effectiveness will remain a market barrier when installed in existing homes.

Originally, this study intended to evaluate the radiant panel system at five test sites. Unfortunately, the cost-effectiveness was found negative early on and not more than one test site was installed with the system. If proceeding with more than one test site, the idea was to evaluate a different radiant panel system with pre-installed tubing. These systems are more costly, but possibly of interest to evaluate to decrease cost of labor, and possibly become more cost-effective.

In terms of technologies available, all the material and equipment installed at the radiant panel test home are readily available and fully market ready.

Hydronic Fan Coils

Hydronic fan coils have been readily available for a long time. The system efficiency mainly depends on the performance of the AWHP, which is a technology that keeps evolving with improved efficiencies. Mainly, because of evolving high-efficiency refrigerants and more energy efficient compressors.

Just as radiant panels, it’s made clear that cost-effectiveness becomes a market barrier. Again, systems that requires less labor are likely to become more cost-effective. The AWHP system with hydronic fan coils and indirect water heating, as installed at the two test sites, reveals a cost of labor almost four times that of material equipment.

4.2 Recommendations for Deployment and Lessons Learned

In this study, none of the test homes generate obvious cost savings from the installed technologies. According to the collected data, there may be cost savings from at one of the two sites with the hydronic fan coil systems.

The reason for minimal or negative savings for both the radiant panels and the hydronic fan coils originates from switching from utilizing natural gas for heating to electricity. To better understand this statement, let’s look at a fundamental conversion between kBtu and kWh.

$$\begin{aligned} 1\ \text{kBtu} &= 0.2931\ \text{kWh} \\ 3.412\ \text{kBtu} &= 1\ \text{kWh} \end{aligned} \tag{2}$$

The cost of natural gas and electricity used in this report originates from rates pulled from PG&E for 2020 and 2021. For example, the cost of natural gas in 2021 was on average \$0.0143/kBtu and \$0.28/kWh for electricity (PG&E, pge.com, 2022). Using the conversion given by Eq.(2), the cost of natural gas expressed in kWh reads \$0.0488 kWh_{gas}. Comparing the rates reveals that cost of electricity as an energy source is almost six times higher than that of natural gas.

$$\frac{\$0.28}{\$0.0488} = 5.74 \tag{3}$$

With that in mind, any electrical equipment must be 6 times more efficient than the equivalent natural gas driven equipment to become cost-effective. According to the manufacturer of the AWHP used at the three test sites, the energy efficiency rating (EER) for cooling is 23 and coefficient of performance (COP) for heating of 3.92 (Chiltrix, 2022). Now, it’s possible that the EER value for cooling efficiency will result in savings that may compensate for negative savings during heating. However, it’s clear that 3.92 COP is less than 6. Meaning, using electricity for heating with this equipment, and at current rates for natural gas and electricity, make the switch from traditional furnace heating to AWHP not financially cost-effective.

4.3 Areas for Further Research

Both hydronic systems evaluated in this study are labor intensive to install. The cost of labor was roughly three to four times higher than the cost of material and equipment for the two AWHP systems.

In addition, heat pumps with higher efficiency during heating mode can result in significant energy savings. Possibly, a dual refrigerant system which works efficiently under both warmer and colder outdoor temperature conditions.

For radiant panels, future research could potentially include to:

- Evaluate radiant panels requiring less trades. Today, the radiant ceiling panels are required to be finished with gypsum board, mudded and sanded, and finally finished up with paint. If panels can be designed to be esthetically appealing without the finishing process, there is room for cost savings. Potentially, panels can come pre-piped where quick-connects between the panels would allow for significantly less installation time.
- Evaluate higher level of insulation above the radiant panels to reduce upwards thermal bridges. To avoid higher levels of attic insulation, the panels can potentially be equipped with high-R insulation above the running PEX tubes.

The performance of hydronic fan coil relies mainly on the AWHP, for which potentials in improved performance are discussed upon above.

4.4 Conclusions

Several key conclusions were drawn from this applied research project:

- Field testing and lab testing indicate that the energy savings potential is small in the mild Sonoma County climate and may even be negative in some applications.
- Lab testing indicates that the delivery effectiveness (efficiency) of the radiant panels is mainly influenced by the amount of attic insulation and temperature gradient between the panels and indoor space. Increasing R-value and difference between indoor air temperature and radiant panel supply water temperature, increases efficiency.
- The cost of labor to install the two AWHP heating and cooling systems are too high to become cost-effective.
- Because of converting from natural gas to full electric, and the cost of natural gas compared to electricity, the two AWHP systems reveal better saving potential for cooling than heating. This implies that both AWHP heating cooling systems are assumed to generate better cost savings if installed in homes already using electricity for heating.
- To the homeowners, both systems are perceived as providing higher comfort post-retrofit and cost savings.
- Changes in user behavior and time spent inside the test homes were affected by the spread of SARS-COV-2 and the pandemic. The biggest changes happen almost immediately after the retrofit measures were conducted, which complicated the pre- versus post-retrofit energy and cost savings assessment.

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APPENDIX A:
Post-installation Survey

The following questions and request for feedback were handed to the homeowners of the three sites presented throughout this report. For clarification and to assist the reader, the responses from the homeowners are marked in different colors. The radiant panel test site is red, test site A of the two homes with hydronic fan coils is blue, and test site B is green. The surveys were handed out a year after the retrofit measures were conducted.

Section 1 – Satisfaction with the Current Primary HVAC System

For each of the following categories, please rate your satisfaction with your current (post-retrofit) primary heating and cooling system.

If satisfaction varies by room, please indicate how on one of the attached floorplans.

Additional detail is always appreciated and can be provided under “Additional Comments” at the end of the section.

Comfort Provided by the Heating/AC System

(Very Dissatisfied) 1 – 2 – 3 (Neutral) – 4 – 5 (Very Satisfied)

1. Temperature control

   5 - 4 - 3

2. Humidity control

   3 - 4 - 5

3. Feeling of drafts

   5 - 4 - 5

4. Distribution of temperatures

   5 - 4 - 5

5. Perception of air quality

   5 - 5 - 5

   Note: After our own purifier was added.

6. Noise

   5 - 5 - 5

7. Overall comfort

   5 - 5 - 4

Heating / AC System Controls

8. Ease of use

4 - 5 - 4

9. Availability of options (ex. temperature, schedule, fan speed, etc.)

3 - 2 - 4

10. Responsiveness of controls

3 - 4 - 4

11. Overall Satisfaction

4 - 4 - 5

Quality of the Heating / AC System Equipment

12. Visual appearance of the indoor components of the system (i.e. supply grilles)

4 - 4 - 5

13. Appearance of the outdoor components of the system (i.e. outdoor unit)

5 - 5 - 5

14. Appearance of the controls

5 - 5 - 5

15. Ease of maintenance

4 - 5 - 5

16. Cost of maintenance

3 - 5 - 5

Note: Unknown

17. Cost of operation (excluding maintenance; i.e. energy costs)

3 - 5 - 5

Additional Comments

Please indicate to which question number the comment applies.

Section 2 - General Questionnaire

Please answer the following questions about your heating/AC system to the best of your ability.

Changes in Heating/AC System Activity and Use

In the table below, mark in the “Yes” or “No” column to indicate your response to each numbered question, then proceed to the next columns unless they are greyed out.

Please use attached floorplan for responses to these questions.

No.	**“In the last year I have…”**	**Yes**	**No**	**Follow up Questions**	**Would you say you did this activity more frequently than usual, less frequently than usual, or about the same as usual in the last year?**
18	Used my system for cooling?	X X X			*- Less* *- More* *- More*
19	Used my system for heating?	X X X			*- Less* *- More* *- More*
20	Changed my thermostat setpoint?	X X X		**If yes**, please describe: *- t's different than a traditional HVAC. Took some time to get used to.* *- Cool 78, Heat 68* *- Set 71*	
21	Opened windows or doors for ventilation?		X X X	**If yes,** indicate the locations on the attached floorplan by marking them with ④.	*- No, same* *- In the heating season I open all windows when the outside temperature is above 68°.* *- Just to get some fresh air in when temp ~ 71°.*
22	Opened or closed supply registers?		X X X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑤.	*- N/A* *- The registers have no open/close feature.*

No.	"In the last year I have…"	Yes	No	Follow up Questions	Would you say you did this activity more frequently than usual, less frequently than usual, or about the same as usual in the last year?
23	Kept interior doors closed for 1 day or more?		X X X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑥.	*- N/A*
24	Hung laundry to dry indoors?		X X X X	**If yes,** for how long? *- Only in the garage.* **If yes,** how frequently? **If yes,** in the laundry room or elsewhere?	
25	Replaced your air filter?		X X X	**If yes or no,** by your best estimate, when was the filter last replaced? *- Dec 2020* *- 1/29/2021* *- Every 3 mo.* **If yes,** describe the condition of the filter:	

No.	**"In the last year I have…"**	**Yes**	**No**	**Follow up Questions**	**Would you say you did this activity more frequently than usual, less frequently than usual, or about the same as usual in the last year?**
				- New System *- Slightly gray, no visible dust.* *- Dirty*	
26	Used ceiling fans?	X X	X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑨.	
27	Used other circulation fans?	X	X X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑩.	*- Bathroom fan no longer work?* *- Air purifiers.*
28	Used your fireplace?	X X	X	**If yes,** was the fireplace operated for the purposes of heat or ambiance?	*- Both, but mostly ambience.* *- Ambience x2.*
29	Used space heaters?		X X X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑫.	
30	Used portable/window air conditioners?		X X X	**If yes,** indicate the locations on the attached floorplan by marking them with ⑬.	

Additional Comments

Please indicate to which question number the comment applies.

Opinion Statements

In the table below, mark in the "True" or "False" column to indicate whether you agree with each statement as it pertains to your heating/AC system and resulting indoor environment.

No.	"My opinion is that..."	True	False	Follow up Questions If True
31	Temperatures are not consistent throughout the day.	X	X X	Please describe how: *- The AC switches off in the heat of night to heat water that we don't need at the time.*
32	The indoor environment is slow to react to thermostat/controls changes.	X X	X	How long does it take for the system to react? *- Hours* *- Less than 5 minutes usually.* *- ? Keep is set* How often do you change control settings? *- Less often* *- Usually only when returning from being away for extended periods.* *- Rarely* Describe in general how you control your system (e.g. set it and forget it, set it lower if slow, etc.): *- Have learned to leave controls alone. Expect slow changes. Was nothing more than a learning curve.* *- Set and forget.*
33	It feels cooler or warmer than indicated on the thermostat.		X X X	By about how many degrees Fahrenheit? Is this for all rooms?

No.	"My opinion is that…"	True	False	Follow up Questions If True
34	I don't understand what the heating/AC system is doing.	X	X X	Is it operating differently from how you would expect it to? How so? Would you like to have a conversation with an engineer to go over how the system operates? *- Need to be able to override DHW during hot days.*
35	I don't like my heating/AC system.		X X X	Please try to describe why: Is there anything that could be changed to improve your opinion of it? *- Just the above issue.*
36	I like my heating/AC system.	X X X		Please try to describe why: *- I have not blowing air through vent systems.* *- I love not having a system constantly starting and stopping.* *- It is much more efficient in general.* *- Would be soooo much more "model" if we ran solar…, the system would shine financially.* *- It's quiet and efficient, but slow to heat, especially when outside temperature s near or below freezing.* *- Quiet, electricity rather than gas, comfortable, efficient.*

Additional Comments

Please indicate to which question number the comment applies.

- (9) Would like the ability to override the system to control priority of heating vs. hot water.

- (9) Would like ability to adjust fan speed.

- (6) External unit is loud and runs a lor during the winter.

- (2) Used a humidifier during periods of very dry air.

- (12) Would have liked to have the option to choose finishes of the registers.

Section 3 – Household Questionnaire

Please answer the following questions regarding your home **over the last year**. Please **circle one answer only**. All questions are required.

Occupancy

1. **In the past year, has anyone moved in?**

   No - *No* - *No*

   If you answered Yes:

   a. How many people moved in?

      1 – 2 – 3 – 4+

   b. What date did they move in?

      Date: ______________________________

2. **In the past year, has anyone moved out?**

   No - *No* - *No*

   If you answered Yes:

   a. How many people moved out?

      1 – 2 – 3 – 4+

   b. When did they move out?

      Date: ______________________________

3. **In the past year, have any occupants left the home for a period of 2 weeks or more?**

   No - *No* - *No*

   If you answered Yes:

   a. How many people left the home?

      1 – 2 – 3 – 4+

b. How long were the occupants away from the home?

2 weeks to 1 month

1 to 3 months

3 to 6 months

More than 6 months

4. In the past year, have any visitors stayed at the home for a period of 2 weeks or more?

No - *No* - *No*

If you answered Yes:

a. How many people stayed at the home?

1 – 2 – 3 – 4+

b. How long did the visitors stay?

2 weeks to 1 month

1 to 3 months

3 to 6 months

More than 6 months

Additional Comments

Please indicate to which question number the comment applies.

Unusual Circumstances

5. In the last year, have you or other members of your household spend significantly more time at home due to COVID or wildfires?

Yes - *Yes* - *Yes*

If you answered Yes:

a. Approximately when did this begin?

Date: *3/2020* – *3/2020* – *3/12/2020*

b. During the time that you or members of your household spent significantly more time at home, did you make any adjustments to your thermostat schedule? Circle all that apply.

Yes, increased heating set point (made space warmer).

- Yes. Changed schedule to home instead of away on weekdays Monday through Thursday.

Yes, decreased cooling set point (made space cooler).

- Yes. Changed schedule to home instead of away on weekdays Monday through Thursday.

No, no changes.

- No

- No

c. Are you or members of your household still spending significantly more time at home?

Yes - *Yes* - *Yes*

d. If you answered No to 5c: Approximately when did this end?

Date: ______________________________

6. In the past year, have there been any unusual circumstances, other than COVID and wildfires, that have impacted your energy usage (such as construction, non-functioning HVAC equipment, etc.)?

No - *No* - *No*

If you answered Yes:

a. Please describe the unusual circumstances:

b. Approximately when did this begin and end?

Begin date: ______________________________

End date, if applicable: ______________________________

7. Were you evacuated due to wildfires?

Yes – No

If you answered Yes: When did your evacuation begin and end?

Begin date: ______________________________

End date, if applicable: ______________________________

8. Did you experience any public safety power shutdown (PSPS) event(s)?

No - *Yes* - *No*

If you answered Yes: When did the PSPS event(s) begin and end?

Begin date: *- Don't remember. Multiple events.*

End date, if applicable: ______________________________

Additional Comments

Please indicate to which question number the comment applies.

Section 4 - Program Questionnaire

Please rate your level of satisfaction with the following, using the same 1 – 5 scale as Section 1. If any are rated below 3, please provide a description of the problem and/or suggested improvements under “Additional Comments” on the next page.

(Very Dissatisfied) 1 – 2 – 3 (Neutral) – 4 – 5 (Very Satisfied)

37. The program administrative/support staff you interacted with

    4 - 5 - 5

38. The program staff that performed the site visit at your home

    5 - 5 - 5

39. The contractor you worked with (if applicable)

    5 - 5 - 5

40. The process from application to participation selection

    5 - 5 - 5

41. The process from participation selection to date

    5 - 5 - 5

Please rate your awareness of the following, on a scale of 1 – 5.

(Not Aware) 1 – 2 – 3 (Neutral) – 4 – 5 (Well Understood)

42. The program’s goals

    5 - 5 - 5

43. How the technology installed in your home saves energy

    5 - 5 - 5

44. The coming Advanced Energy Center

    3 - 4 - 1

45. The resources that will be offered at the coming Advanced Energy Center

    3 - 4 - 1

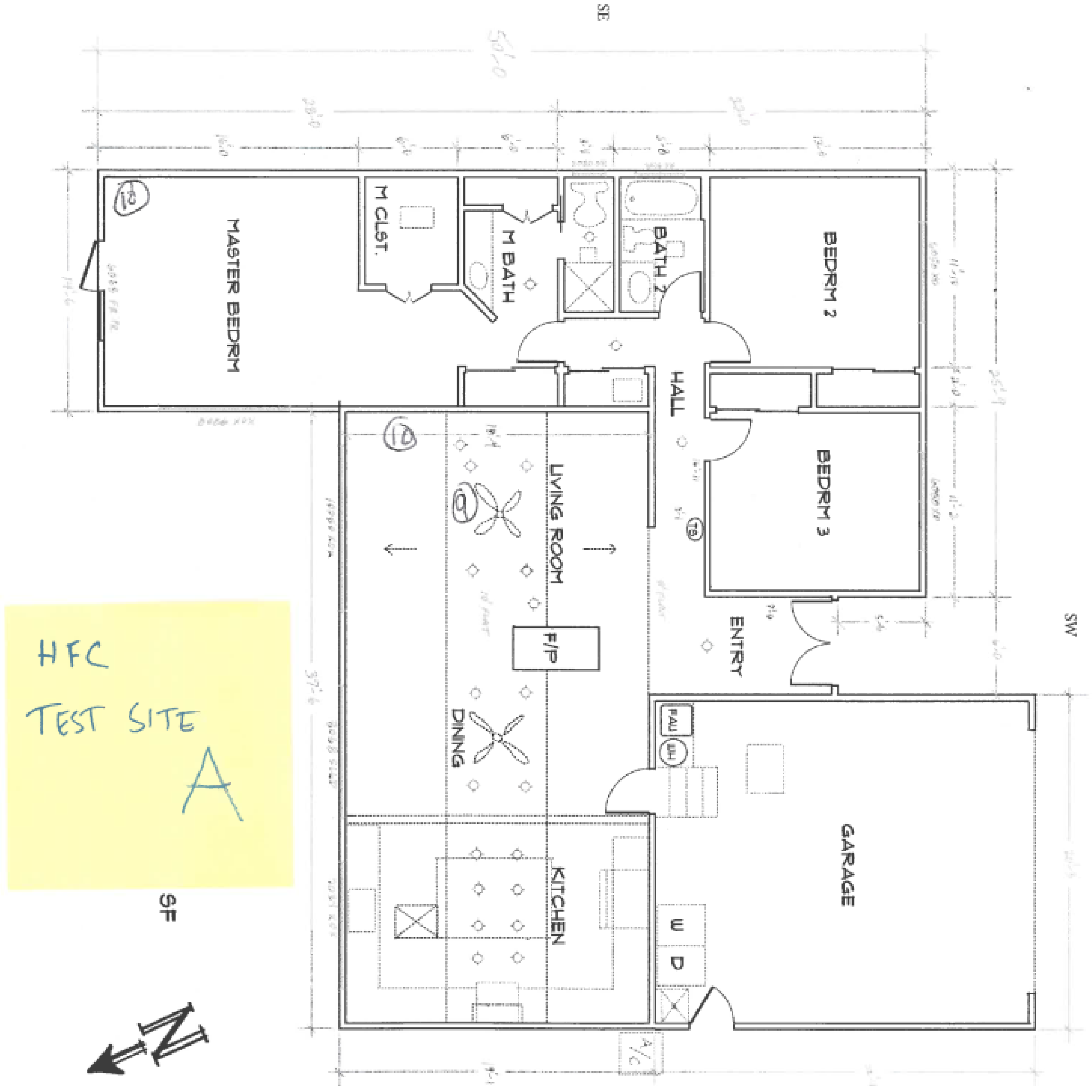
Additional Comments

Please indicate to which question number the comment applies.

- *The survey itself is formatted badly. Difficult to read, needs page numbers, questions split onto multiple pages. Took a long time to fill out and spend a lot of time figuring out the page order after flipping pages back and forth.*

Attachments

Test site A (Hydronic fan coils)



Test site B (Hydronic fan coils)