

Radiant Ceilings as a Residential Retrofit: Examining the Myths and Realities

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ABSTRACT

Locating ductwork in unconditioned attics has been standard practice in dry climates for over 50 years. Despite significant improvements in reducing overall duct leakage, ducts continue to be inefficient distribution systems, especially under peak load conditions. Efforts to move ducts into the conditioned space have proceeded slowly in the production home market due to architectural design challenges, subcontractor coordination barriers, and increased builder costs. Similar costs and architectural challenges prohibit moving most existing duct systems into conditioned space.

California state agencies and utilities are leading development of cost-effective and retrofittable strategies optimized for dry climates that reduce distribution losses and support the state's climate goals. One proposed strategy has been hydronic radiant ceiling panels for distribution with chilled and heated water provided by an air-to-water heat pump (AWHP). An occupied case study of radiant ceiling panels as a retrofit was conducted to examine the market barriers faced by the technology and to document actual installed cost and performance. Occupants also completed surveys to provide feedback on their level of satisfaction with the technology. The retrofit system was monitored for 12 months following a baseline monitoring period of 6 months.

This paper discusses the comfort and energy performance of the radiant system, occupant and installing contractor feedback on the technology, as well as provide a breakdown the installed costs and lessons learned. Findings suggest that while the technology provides great comfort, the labor required for installation makes it an expensive retrofit.

Introduction

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, but this can be difficult to implement in retrofit applications. Radiant ceiling panel systems offer an alternative solution to reduce distribution losses, while requiring fewer architectural or aesthetic changes, and providing equal or superior comfort compared to forced air systems (Haile, Springer and Hoeschele 2018).

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 conditioned space through convection. In general, the larger the temperature difference between the fluid and the indoor 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. Thermal radiation, is a physical phenomenon that exists at the surface of all materials. In other words, everything emits thermal radiation, always, and it is one of the fundamental modes of heat transfer. The intensity of radiative heat transfer 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 thermal 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, drop, or remain the same. The concept of radiant panels during heating cycles is to emit heat through radiative heat transfer to surrounding objects and thus increase their surface temperature. While the radiant panels emit more heat 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 1 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.

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 there have a large heat transfer surface, radiant systems deliver comfort at more moderate temperatures than hydronic fan coils, which use water temperatures around 105-120°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.

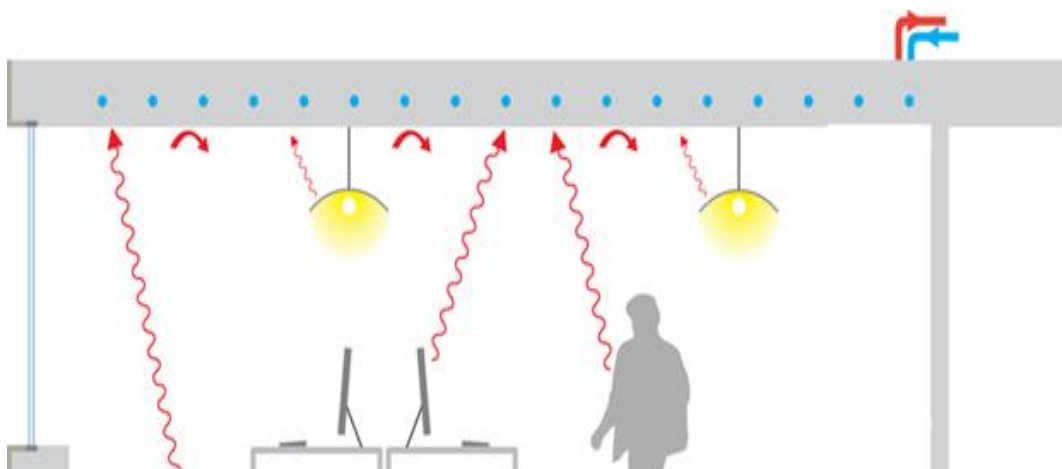


Figure 1. Conceptual exchange of energy from heating panels in a conditioned space during cooling cycles. Solid arrows represent convective heat transfer and curved arrows represent emitted radiation by surrounding objects (Image credit: Caroline Karmann, Center for the Built Environment at UC Berkeley).

Field Test

The radiant panel system including the AWHP is illustrated in Figure 2. Here, the retrofit system consists of hydronic radiant ceiling panels holding cross-linked polyethylene (PEX) pipes with hot or chilled water from an AWHP. To ensure satisfying indoor air quality, bath fans are installed to provide ASHRAE 62.2 compliant ventilation. An EnergyStar certified dehumidifier is also installed to provide dehumidification if needed.

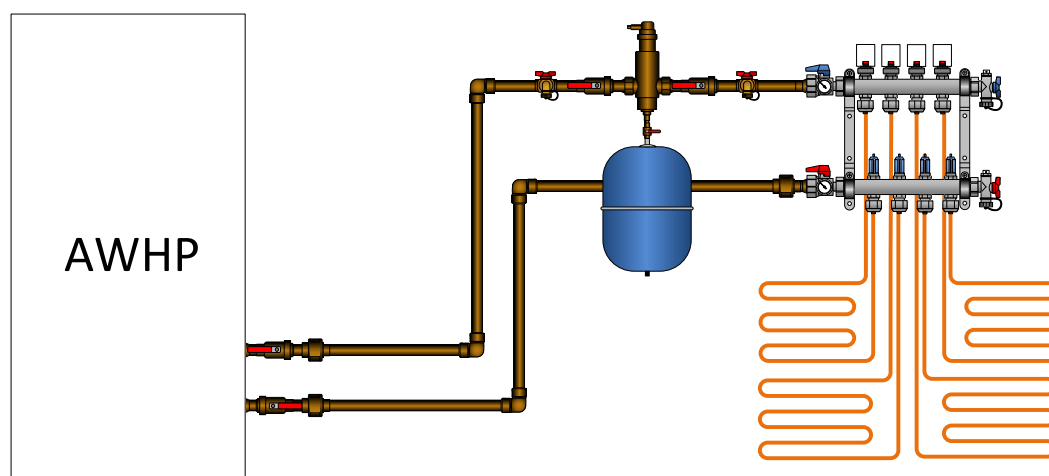


Figure 2. Diagram of evaluated hydronic system. The system includes an AWHP, fan coil, buffer tank, pump, manifold, and radiant panels.

The AWHP used in this project was manufactured by Chiltrix. Chiltrix is a United States manufacturer based out of Chesapeake, VA and has significant experience in HVAC and solar energy engineering.

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. 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).

Home energy audits and envelope improvements were performed prior to monitoring to limit differences between pre and post data collection. Six months of monitored baseline data was collected prior to the retrofits, followed by two years of monitored data collection post-retrofit. Data collected characterized on system performance, as well as occupant comfort and behavior.

The home that received radiant ceiling panels is a 1,812 square foot single story house, hosting a family of four, built in 1989 with three-bedrooms and two baths, see Figure 3 and Figure 4. Prior to the retrofit, the heating and cooling system consisted of a traditional central ducted system with gas furnace and electrical air conditioning.



Figure 3. Test site for the installed radiant panel system.

In order to make an assessment on return of investment and improved performance from installing the radiant panels, a baseline monitoring was set in place for about 6 months. Between March 25th of 2019 and October 6th of 2019, indoor temperature, and 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.

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 4 for sensor placement. In addition, the thermostat recorded relative humidity and controlled a 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. The installed data loggers and acquisition system collected information on performance of the radiant system from the end of October in 2019 to the end of December in 2021.

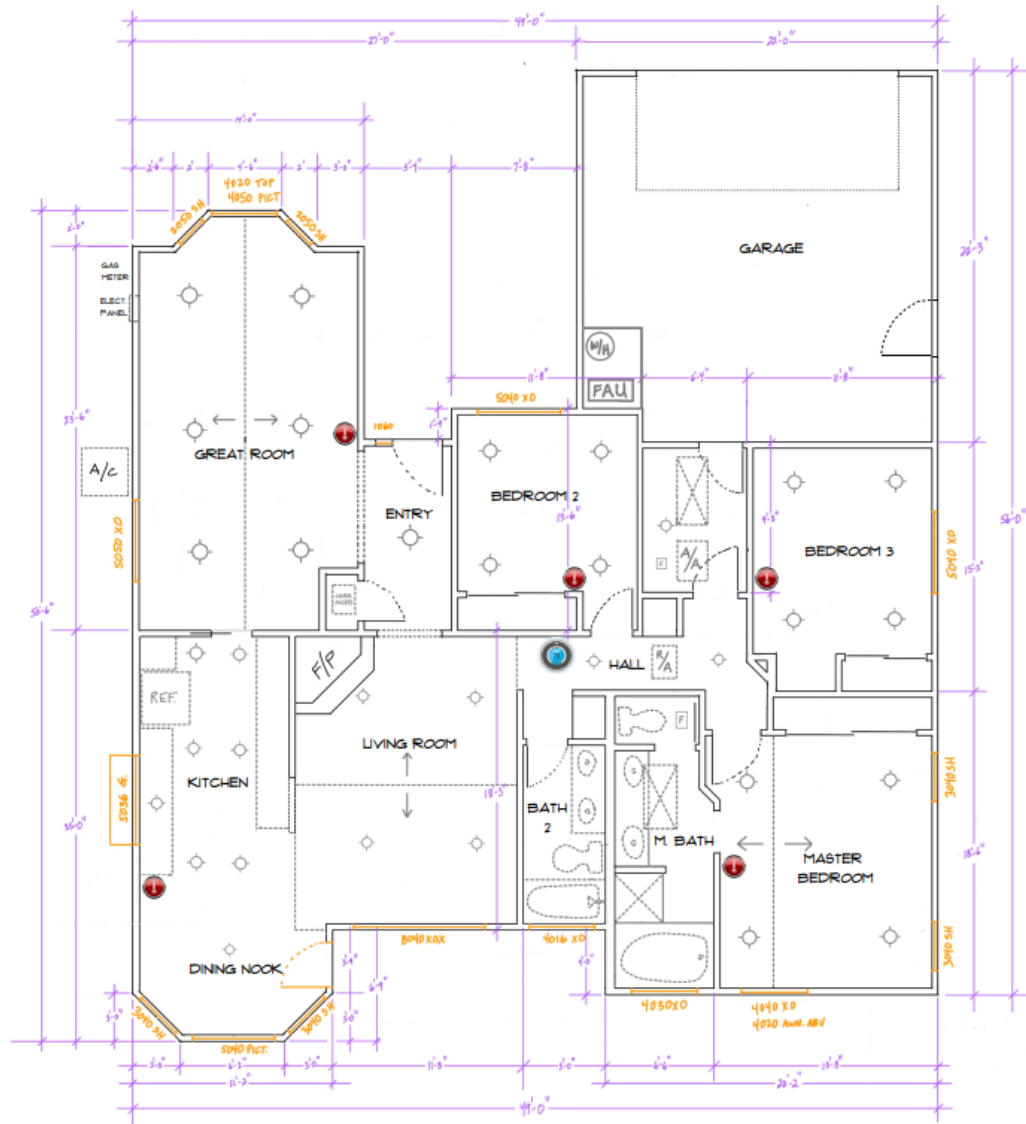


Figure 4. Floor plan of the test home. The red symbols indicate locations of the temperature sensors and the blue symbol where the thermostat is mounted.

For the test site, radiant panels from Warmboard® were installed. Though intended for use in floor systems, the Warmboard-R panel is light and thin enough to install on ceilings (approximately 3.2 lbs/sq.ft. installed). Warmboard-R was selected because it had a good balance of manufacturer attested performance and cost per square foot (\$8 per sq.ft. for panels) compared to other brands. Because of the intrusiveness of the installation (see Figure 5 and Figure 6), 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 the manifold and controls.
- Caulk and spray foam ceiling plane to seal gaps around penetrations and joist/drywall interfaces.
- New blown-in attic insulation with R-60 cellulose insulation.
- Installing ducted dehumidifier to mitigate any condensation concerns (AprilAire 18XX series).
- Installing the air-to-water heat pump (Chiltrix CX34).
- Commissioning and testing the new system.



Figure 5. 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).

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, a 31% reduction. With a total house air volume of 14,500 ft³, 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 6. The great room from upper left to lower right: pre-retrofit, panel installed, finished retrofit, post-retrofit thermal image.

Pre- and post-retrofit performance

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. First, the 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 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 7. Here, cooling and heating energy demand is depicted together with the variation in outdoor ambient air temperature. Figure 7 presents the use of natural gas in means of kWh.

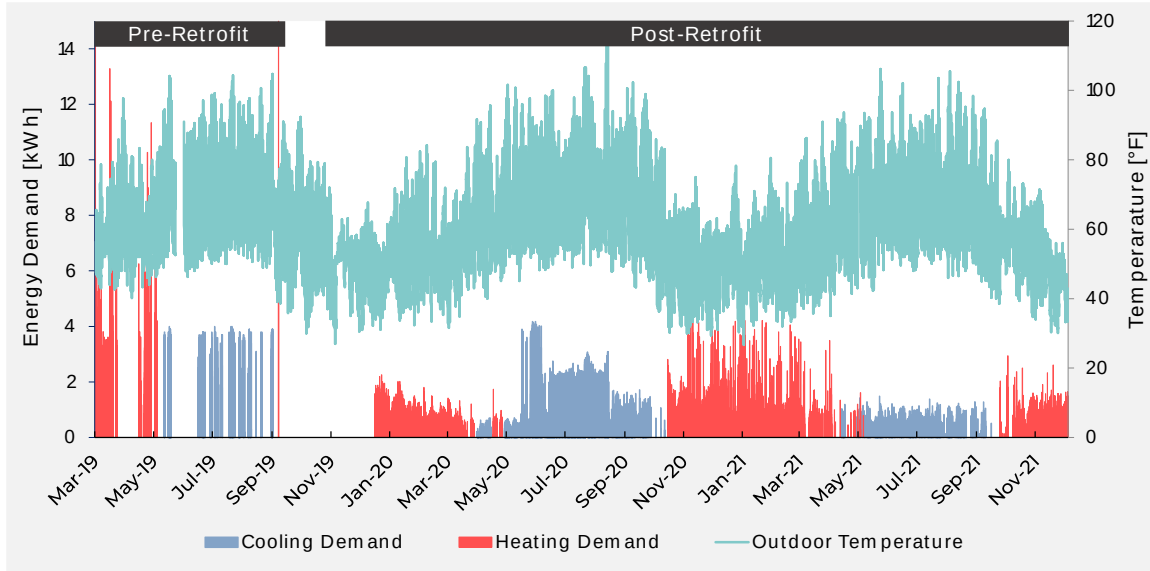


Figure 7. Cooling (blue) and heating (red) energy demand pre- and post-retrofit. The outdoor temperature (green) during the time of data collection is also depicted. Here, heating pre-retrofit is expressed in kWh.

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, Fundamentals Handbook - Chapter 19 2021). This approach make 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 happen at temperatures higher than 65°F. In reality, whether heating or cooling is required mainly depends on four variables. (1) The thermostat setpoints, (2) building envelope and HVAC system characteristics, (3) user prefer (such as opening windows), and (4) internal heat loads from appliances, lighting, etc. 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 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 lowest outdoor air temperature to calculate degree hours

for cooling drops to 63.9°F and the highest temperature for when heating is need drops to 53.1°F after the retrofit is completed. The datapoints used to calculate lowest outdoor air temperatures for when cooling is needed and highest outdoor temperature for when heating is needed are presented in Figure 8. The reason for the drop in outdoor air temperature for cooling post-retrofit, is a result of new comfort preferences because of a more self-controlling system.

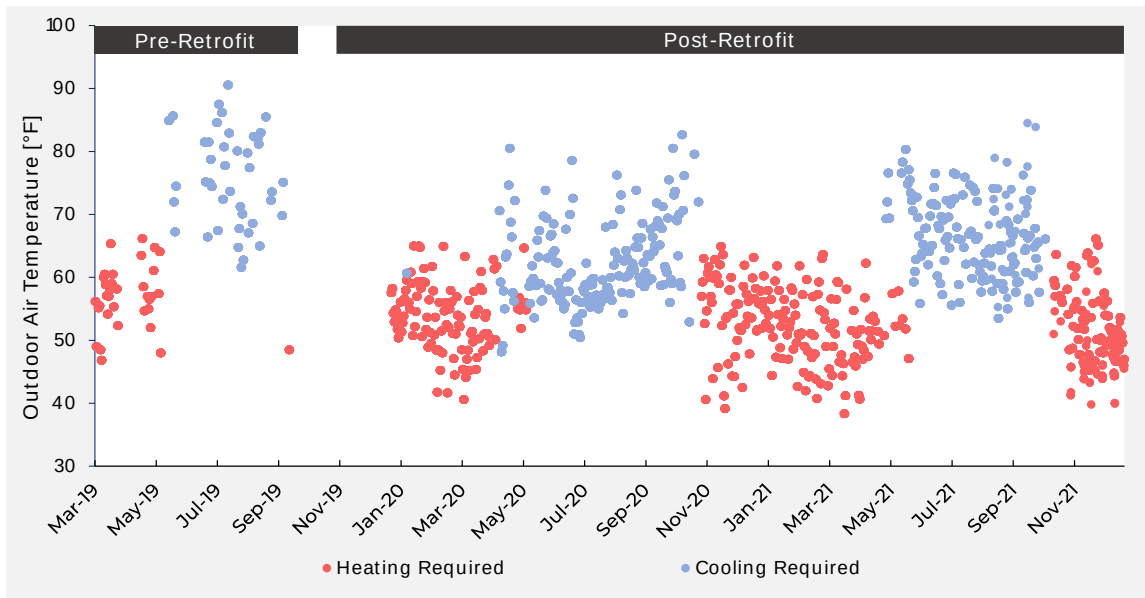


Figure 8. Lowest daily temperatures for when cooling and heating is needed. The data points help to determine base line temperatures used to calculate heating and cooling degree hours.

Table 1 presents actual degree hours based on temperatures presented above and energy usage for the test site during a time period between March 25th and October 10th in 2019 (pre-retrofit), and for the full year of 2020 and 2021 (post-retrofit).

Table 1. 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				974 /		0.134 /		
End	10/6/2019	9,310	7,285	792	3,323	0.085	0.456	-	-
					(kBtu)		(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 1 provides energy usage pre- and post-retrofit. Hence, the radiant panel system consists of a 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 1 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 to 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 1. 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 thermostat was reading indoor relative humidity at 10%RH higher than the actual 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 usage, 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 9 and Figure 10 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 9, 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 10 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 9) 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 1 are assumingly on the conservative end and can be expected higher.

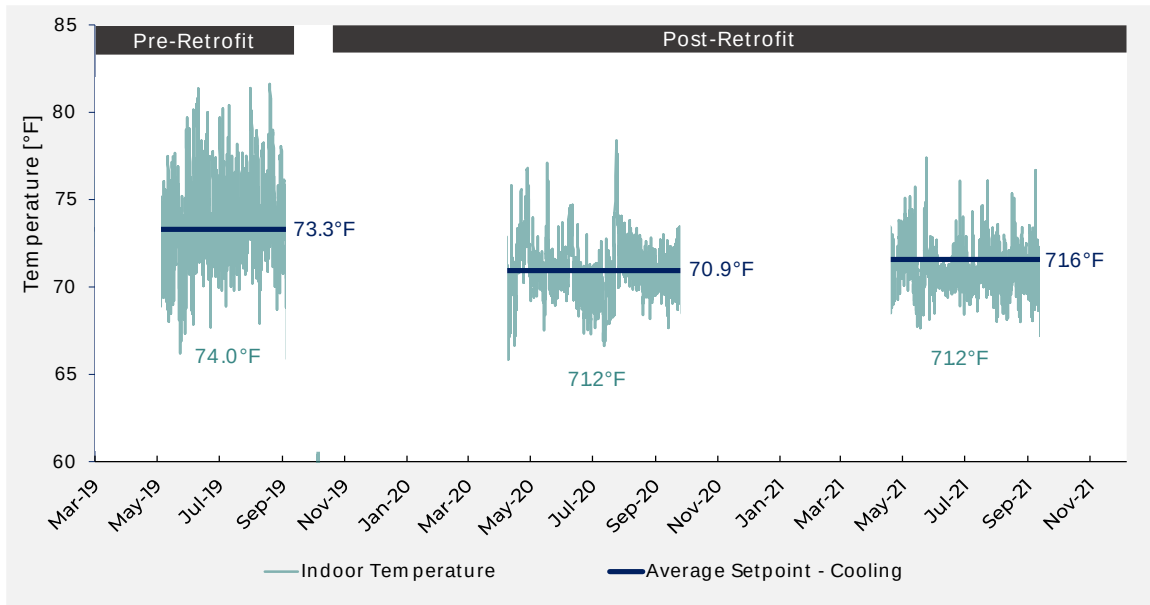


Figure 9. Average thermostat setpoint during cooling (blue horizontal line), and variation in indoor temperature during the time of cooling (green). The average indoor temperature during the cooling season is also presented.

Though, the same trend in more fluctuating temperature pre-retrofit is seen for heating (Figure 10) as well, the time for which data was collected is not substantial enough to draw conclusion similar to that of cooling.

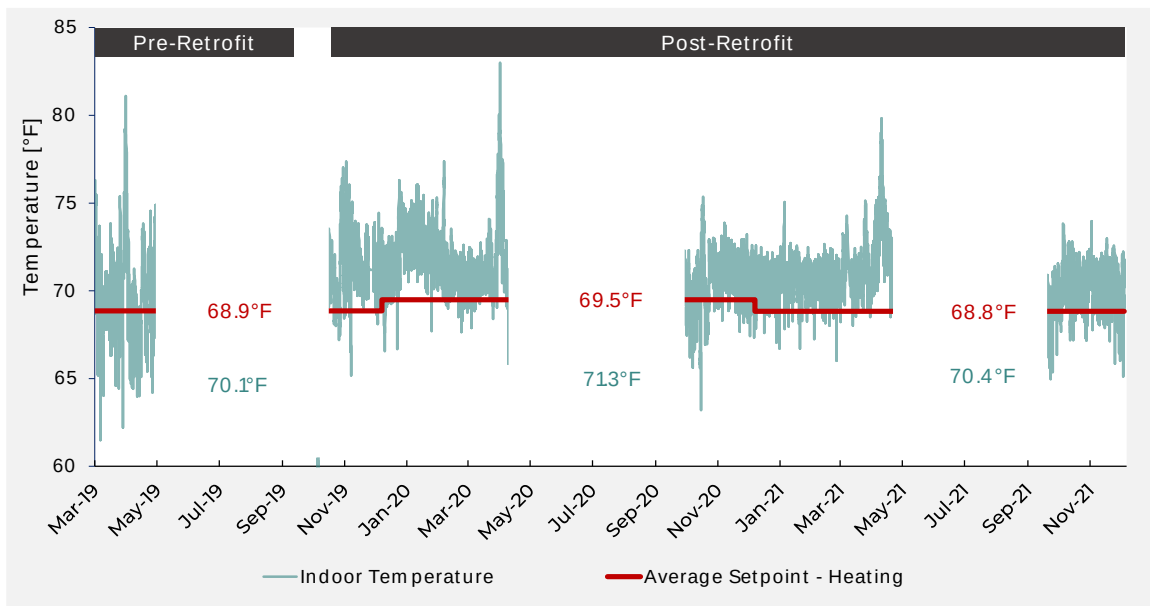


Figure 10. Average thermostat setpoint during heating (red), and variation in indoor temperature during the time of heating (green). The average indoor temperature during the heating season is also presented.

The estimated energy savings for the test site is presented in Table 1. 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-60 and the airtightness of the building was significantly improved.

Electricity Savings

Though 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 home used natural gas for heating pre-retrofit, the actual savings in cost is unclear until rates and cost of energy are accounted for.

Table 2 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 2. 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 (Pre-Retrofit Settings) [H°F]		Cooling (kWh)	Cost ^a (\$/kWh)	Heating (kBtu)	Cost ^c (\$/kBtu)	Total Cost	
Start 1/1/2020 End 12/31/2020	12,761	37,741	1,085	\$0.26	17,216	\$0.0121	\$490	
Start 1/1/2021 End 12/31/2021	8,860	38,799	753	\$0.28	17,698	\$0.0143	\$464	
Start 1/1/2031 End 12/31/2031	10,811	38,270	919	\$0.33	17,457	\$0.0219	\$686	
Time Period	Post-Retrofit							
	Degree Hours (Post-Retrofit Settings) [H°F]		Cooling (kWh)	Cost ^a (\$/kWh)	Heating (kWh)	Cost ^b (\$/kWh)	Total Cost	Annual Savings
Start 1/1/2020 End 12/31/2020	36,579	23,938	2,007	\$0.26	1,462	\$0.26	\$902	-\$411
Start 1/1/2021 End 12/31/2021	28,540	23,729	543	\$0.28	1,315	\$0.28	\$520	-\$56
Start 1/1/2031 End 12/31/2031	32,560	23,834	1,275	\$0.33	1,388	\$0.33	\$881	-\$195

^a Cost of electricity during cooling season of 2020 and 2021 (PG&E 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 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 2022)

Prior to the retrofit, natural gas was used for heating, while the retrofit system was all-electric. 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 2 also presents the difference in cost of energy between actual and estimated (if no retrofit was conducted). Unfortunately, the radiant panel system result in an energy cost penalty for 2020 and 2021 despite using less energy. For a future estimate, Table 2 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 why cost savings are not as notable as the drop in energy demand, is because the cost of natural gas is significantly less than electricity. However, because the radiant ceiling panel retrofit did result in less energy use, a home already using electricity for heating would derive greater benefit from the technology and may generate positive cost savings. A home with rooftop solar similarly may generate positive savings, as gas use would be replaced with site generated electricity.

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 3. 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. Remark, Table 3 include site and project specific costs, such as crawlspace vapor barrier, and to some extent off-site management.

Table 3. Labor breakdown to install the radiant panels at the test site.

Description	Total hours	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 4. Here, the major costs are associated with the boards holding the PEX tubing, the plumbing parts, and the AWHP.

Table 4: Equipment and materials breakdown of installing the radiant panels at the test site.

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
-	Reinforced cs vapor barrier 12 mil	-	\$634	\$686.52
-	Pins and tape for vapor barrier	-	\$453	\$490.37
6	Tubes caulk, sealants	\$7	\$42	\$45.47
1	Rolls tapes, adhesives, plastic, mask	\$150	\$150	\$162.38
-	Color matched paint	-	\$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 3 and Table 4 is about \$114,500. Though some items can be claimed as site and project specific, it is reasonable to conclude that the total cost for a similar retrofit would land over \$100,000.

Since the cost savings from installing the radiant panels are negative and the installation cost is high, no assessment of present value, return of investment or simple payback time was conducted.

Conclusion

This paper presents a field study to evaluate radiant panel systems for retrofit applications. Throughout the installation, it was made clear that the total cost of labor far exceeded planned costs, and expected savings in cost of energy failed to occur. Specifically, the barriers to cost-effectiveness and/or market adoption of radiant ceiling retrofits include, but are not limited to, the items noted below.

- **Occupant Relocation** - Occupants are forced to find an alternative living while the panels are being installed.
- **Labor Availability and Costs** – Radiant ceiling panels, as installed at the test site of this study, require experienced installers, and will involve various trades. The more trades involved, the greater the labor cost for the project. The cost of labor was roughly three times higher than the cost of material and equipment, despite contractors being experienced with radiant systems. 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 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. This required significant coordination and logistics. 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.
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, or on-site electricity generation using rooftop solar, 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.

- **Ceiling Features** – Radiant panels installed in existing buildings may require special attention and design around penetrations through the ceiling plane (lighting, ceiling fans, etc.) and depending on architectural features (odd ceiling geometries). 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.
- **Performance** – To minimize upward energy losses from the 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.

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