Field Evaluations in the Time of COVID-19: Overcoming Unexpected Challenges when Testing Occupied Buildings

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ABSTRACT

This paper discusses challenges that were overcome during the evaluation of eleven emerging energy efficiency and electrification technologies in 61 occupied homes and businesses as part of a community-based utility program in Northern California. All technologies were commercially available but underutilized due to insufficient market awareness or lack of demonstrated energy savings in retrofit applications. These technologies included ducted mini-split heat pumps, air-to-water heat pumps with radiant ceiling panel or fan-coil distribution, grid-interactive heat pump water heaters, aerosol envelope sealing, phase change materials (in both commercial and residential applications), tubular daylighting devices, induction cooktops, heat recovery dishmachines, and night ventilation cooling.

Each of these projects included a field test component to quantify energy savings, cost-effectiveness, and measure durability. Many challenges were encountered and addressed along the way. Most significant was the outbreak of the COVID-19 pandemic during the program, severely complicating the analysis of energy savings because of the impact on usage patterns for both residential and commercial buildings. In some cases, accurate energy savings estimates were not possible. This paper documents the range of solutions developed by the project team to overcome these challenges and maximize the knowledge gained from the program. Lessons learned from the program may help future researchers avoid pitfalls and ensure backup options are available when evaluating emerging technologies in occupied buildings.

1. INTRODUCTION

The home retrofit program discussed in this paper focused on research, development, and demonstration projects in existing buildings, exploring a range of innovative technologies, program features, and market approaches to engage and motivate homeowners and business owners. The authors and their colleagues conducted both applied research projects and technology demonstrations to assess the market readiness of emerging energy efficiency technologies. The applied research projects combined laboratory testing and field demonstrations with detailed tracking of the technologies' performance, durability, costs, installation challenges, and occupant satisfaction. Technology demonstrations aimed to show how certain underutilized energy efficiency technologies perform when installed in retrofit applications in the mild northern California climate, and to identify potential technological and market barriers to the adoption of these technologies.

Field testing of 11 technologies was conducted in 48 residential and 13 commercial buildings between January 2019 and March 2023 in Sonoma County, California. A brief summary of the technologies is provided in Table 1. Most sites included a 3-12 month pre-retrofit monitoring period, followed by 9-16 months of monitoring after the installation of the energy efficiency measures. The COVID-19 pandemic caused a shutdown of most businesses in March 2020. The pandemic affected each project differently, sometimes occurring prior to installation, sometimes after. The effects gradually diminished over time, but in many cases there were permanent changes to building operations because of increased telecommuting. Studies by DNV (Ham-Su & Lopes, 2021) and CEC (California Energy Commission, 2020) demonstrated that energy use increased in residential buildings and decreased in commercial buildings during 2020 and 2021. A more detailed analysis of electricity use in residential buildings before and after the COVID-19 pandemic performed by Kawka and Cetin (2021) characterized the changes in energy use for various building subsystems in Austin, Texas. Further details about the field tests described in this paper, and the methods used to address COVID-19 impacts can be found in Simonson et al (2024), Pallin and Haile (2022), Hendron et al (2022a), and Hendron et al (2022b).

Table 1: Overview of technologies evaluated by Lead Locally

Technology	Description	Test Sites	Installation Dates
Attic phase change materials	Material encapsulated in flexible mats that absorbs and releases heat via melting and freezing, placed above or below the attic insulation.	5 residential buildings	December 2019
Drop ceiling phase change materials	Salt compound encapsulated in rigid panels that absorbs and releases heat via melting and freezing, placed above drop ceilings.	6 commercial buildings	March 2021 – December 2021
Ducted mini-split heat pumps (MSHPs)	Space heating and cooling utilizing a smaller, variable speed version of a ducted air source heat pump system; all ducts in conditioned space.	7 residential buildings	September – November 2019
Radiant ceiling panels	Hydronic heating and cooling system using plastic pipes mounted to ceiling panels served by an air-to-water heat pump (AWHP).	1 residential building	October 2019
AWHPs with fan coils	Integrated hydronic space heating, cooling, and hot water system with central fan coil for distribution.	2 residential buildings	November 2019 – January 2020
Grid-interactive heat pump water heaters (HPWHs)	Tank water heaters utilizing heat pump technology with electric resistance backup; potential to communicate with electric grid for load shifting.	9 residential buildings	December 2020 – March 2021
Induction cooking	Rangetops that utilize electromagnetism to heat cookware instead of less efficient gas flame or electric resistance heating.	5 residential and 1 commercial building	June 2020 – August 2021
Heat recovery dishmachines	Commercial dishmachines that recover heat from the steam exhaust and use it to pre-heat water incoming from the tank.	2 commercial buildings	July – October 2021
Aerosol envelope sealing	Solution sprayed into a space that can plug small gaps in walls and ceilings when applied under pressure.	10 residential buildings	July 2020 – March 2021
Tubular daylighting devices	Reflective tubes that direct free natural light from the roof to interior spaces; electric lighting controls to maintain lighting levels withing a target range.	3 commercial buildings	November 2020 – May 2023
Nighttime ventilation cooling	Addition to ducted heating system that precools the house overnight using outdoor air to avoid the need for an air conditioner.	10 residential buildings	July 2020 – March 2021

The COVID-19 pandemic had a significant impact on field testing of energy efficiency retrofits in several ways:

1. Changes to operating conditions: The pandemic caused many businesses to temporarily close their doors, reduce staffing levels, or shorten hours of operation. Residential buildings were often occupied by more people for longer periods of time, resulting in changes to thermostat settings, internal gains, cooking activities, and plug load usage.
2. Reduced access to buildings: With many buildings, particularly commercial, operating at reduced capacity or being temporarily closed during lockdowns and other COVID-19 restrictions, researchers had limited access to conduct in-person field testing and assessments of energy efficiency retrofit measures.
3. Disruptions to supply chains: The pandemic caused disruptions in the supply chains for materials, equipment, and components needed for energy efficiency retrofit projects. This made it more challenging to obtain the necessary items to install and test retrofit measures in the field.
4. Workforce availability issues: COVID-19 related illnesses, quarantines, and safety concerns reduced the available workforce for conducting field testing and retrofit installations. This led to delays and scheduling challenges.
5. Reprioritization of projects: In some cases, energy efficiency retrofit projects were delayed or reprioritized as homeowners and businesses focused resources on pandemic response, building safety, and other immediate operational needs.

Overall, the COVID-19 pandemic created significant logistical and practical challenges for conducting robust field testing and evaluation of energy efficiency retrofit measures. Researchers and practitioners had to adapt their approaches to continue making progress where possible. The remainder of this paper describes how these challenges were addressed for each technology and draws some general conclusions that can be applied to future field studies.

2. PROJECT IMPACTS

2.1 Attic Phase Change Materials (PCMs)

The testing of PCMs in residential attics was impacted a few months after installation in December 2019 (see Figure 1). Many of the occupants began working at home, increasing internal gains and influencing thermostat comfort settings and schedules.

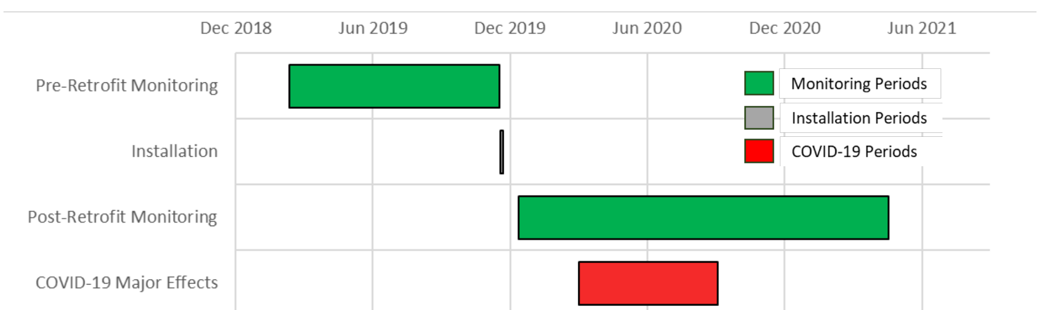

Figure 1: Timeline for residential PCM field test

It was unlikely that significant behavioral changes would have been caused by the PCM alone, although comfort may have been marginally improved. Therefore, all changes to thermostat settings were attributed to temporary COVID-19 impacts. To adjust for these effects, measured thermostat settings were averaged for daytime and nighttime periods, before and after the retrofit, for each of the five test homes (see Figures 2 and 3). In addition, internal gains from occupants were assumed to increase by about 50% during the day based on survey data indicating much higher levels of occupancy during COVID-19. Changes in lighting and plug loads were neglected because no pre-retrofit measurements were available for comparison, but these loads may have also increased along with occupancy. Energy modeling was used to quantify the percent change in heating and cooling loads resulting from the changes in thermostat settings and occupancy levels, and measured heating and cooling energy use was adjusted accordingly. These adjustments ranged from -13% to +19% for heating, and +2% to +149% for cooling across the five test homes. As shown in Figures 4 and 5, these COVID-19 adjustments for heating and cooling proved to be as large and erratic as the measured energy savings, resulting in a great deal of uncertainty about the true energy savings for PCM in this application.

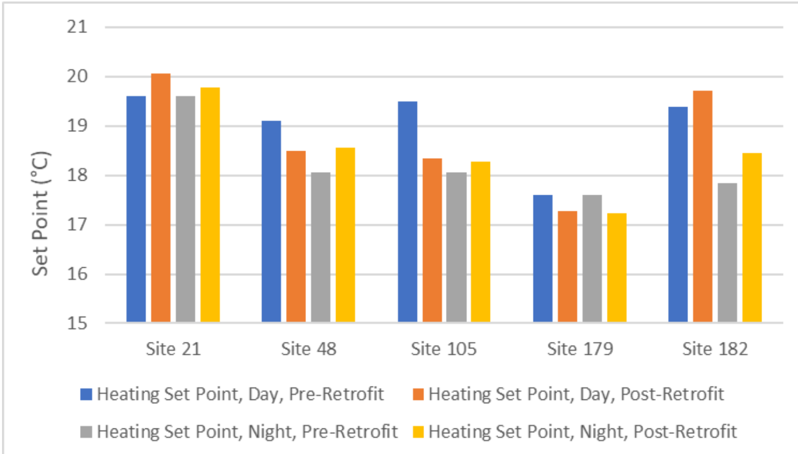

Figure 2: Heating set points before and after residential PCM retrofit

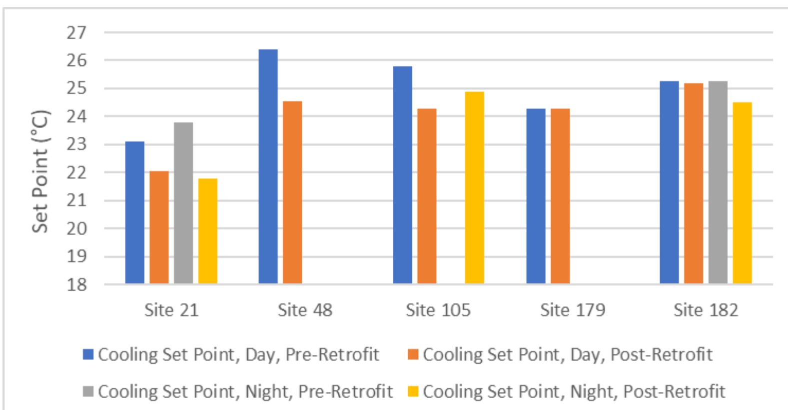

Figure 3: Cooling set points before and after residential PCM retrofit, where sufficient data was available

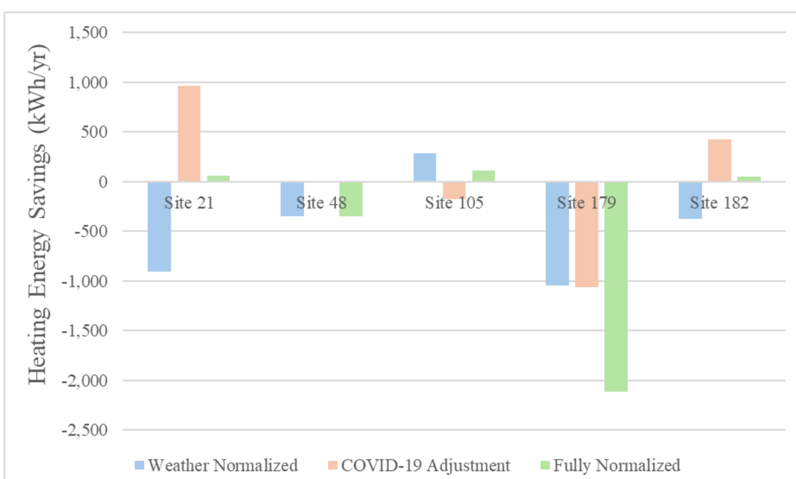

Figure 4: Heating energy savings for five test sites based on HVAC measurements normalized for weather and changes to occupant behavior due to COVID-19

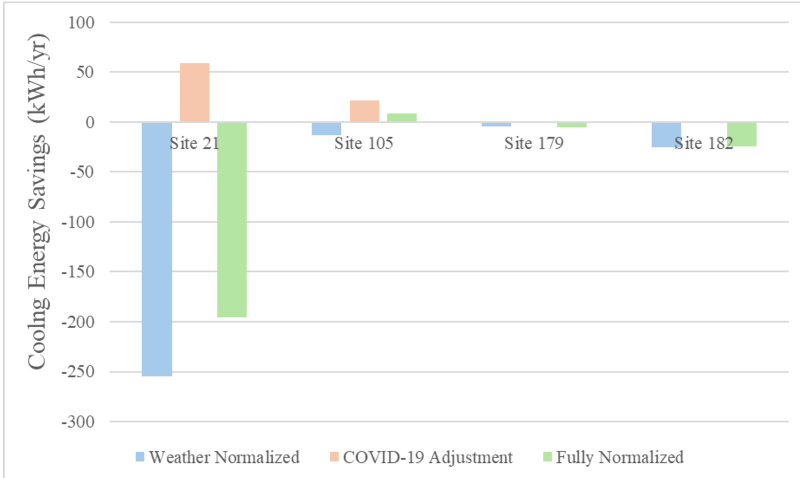

Figure 5: Cooling energy savings for four test sites based on HVAC measurements normalized for weather and changes to occupant behavior due to COVID-19

2.2 Drop Ceiling PCMs

The six commercial buildings with PCM installed above drop ceilings were affected by COVID-19 prior to the retrofit. The timeframe of events is shown in Figure 6.

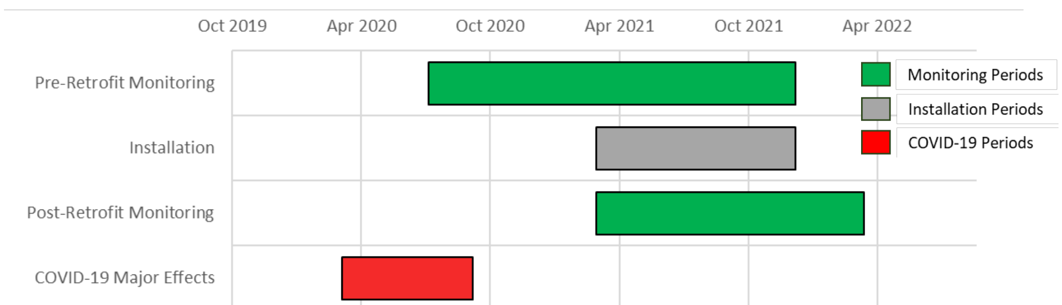

Figure 6: Timeline for drop ceiling PCM field test

For this project, utility bills were the primary method of estimating energy savings, and monitoring was performed primarily to verify that the PCM panels were freezing and melting at appropriate times. Two of the sites included major repurposing of the building, and energy savings comparisons based on utility bills would not have been meaningful. Calibrated energy modeling of savings would have been the optimal approach for these sites, but it was not within the scope of the project budget. The four sites with meaningful utility billing data were affected by the COVID-19 outbreak during the year preceding the retrofit, either because business was slow or operations were discontinued for an extended period of time. To address this issue, the utility bills for the year prior to COVID-19 were used for the pre-retrofit case. This introduced the potential for other changes to building operations that may have occurred prior to program participation (business growth, changes in operating hours). In addition, some businesses never fully recovered from COVID-19 even by the summer of 2021, and post-retrofit utility bills may be partly affected by the pandemic. However, comparing utility bills from 2019 to those of 2021 was deemed the most accurate approach available.

2.3 Ducted MSHPs, Radiant Ceiling Panels, and AWHPs with Fan Coils

COVID-19 impacted the three HVAC projects 2-5 months after the new systems were installed, early in the post-retrofit monitoring period (see Figures 7-9). The start of the COVID-19 pandemic in early 2020 complicated the cost-effectiveness analysis considerably. The occupants spent more time at home (increasing HVAC run time and internal gains), and thermostat settings changed for many homeowners.

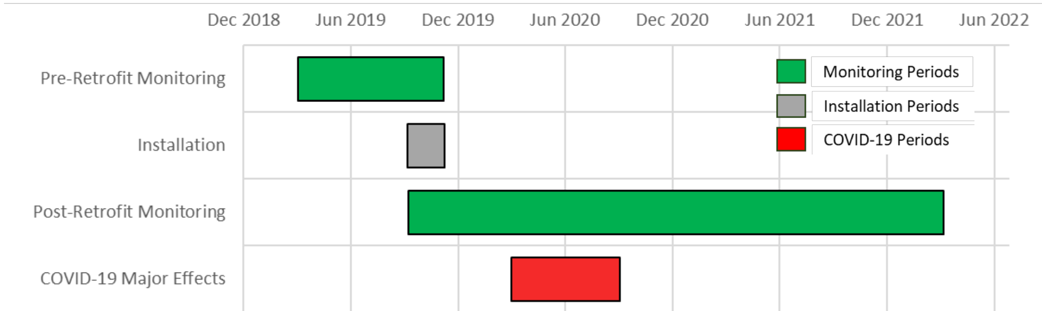

Figure 7: Timeline for MSHP field test

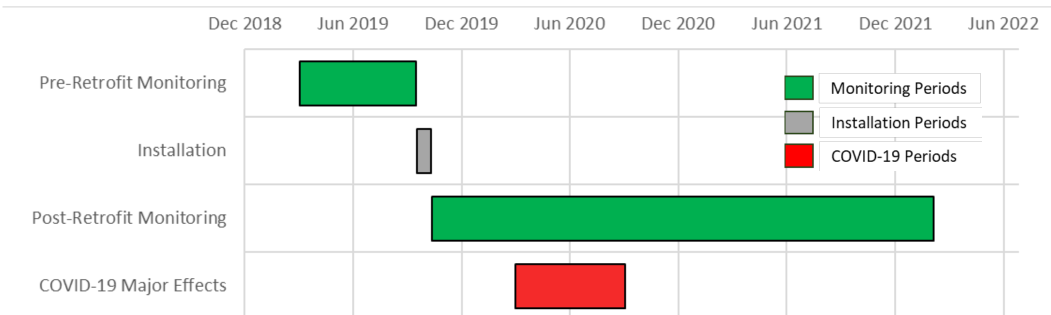

Figure 8: Timeline for radiant ceiling panel field test

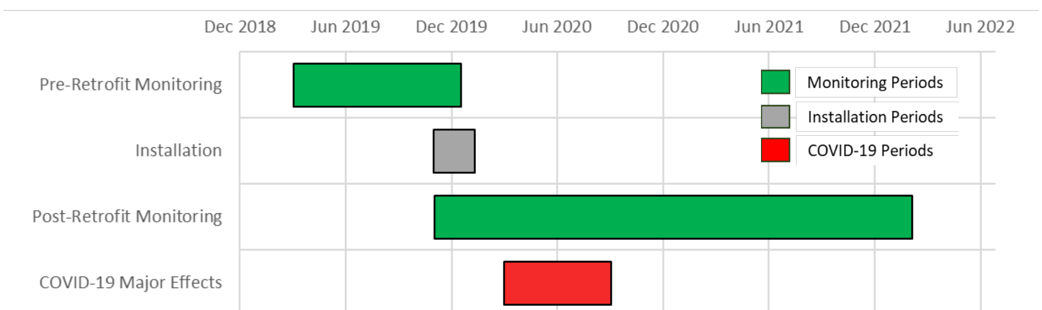

Figure 9: Timeline for AWHP with fan coils field test

For these three projects, operating conditions may have changed in part because the heat pump systems had very different delivery systems compared to the pre-retrofit HVAC and they operated at variable speeds, influencing comfort levels as a function of thermostat setting. There may also have been take-back effects following efficiency improvements when occupants trade off enhanced comfort against some of the energy savings. Although occupant surveys were conducted before and after the retrofits, they indicated both a change in comfort and a change in occupancy level. Because these behavioral effects on thermostat settings could not be separated from COVID-19 effects, it was not possible to quantify savings independent of the pandemic. However, post-retrofit monitoring lasted for nearly two years after most businesses and schools were shut down in March 2020, and it was possible to disregard the first year of monitored results following the retrofit when the effects were at their peak.

2.4 Grid-Interactive Heat Pump Water Heaters

COVID-19 impacted the HPWH project during the pre-retrofit monitoring period prior to installation of the systems in late 2020 (see Figure 10). Unlike the HVAC retrofits, there was no indication that hot water usage changed due to the pandemic at the homes participating in the study. As a result, no adjustments to energy savings were necessary.

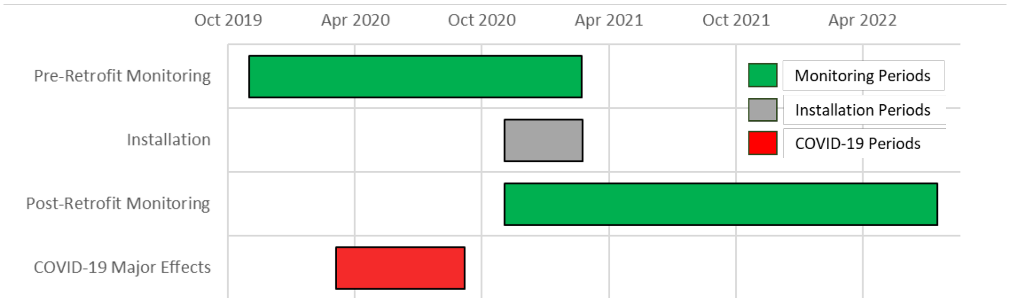

Figure 10: Timeline for grid-interactive HPWH field test

2.5 Induction Cooking

The induction cooking projects in five residential buildings were hampered by the COVID-19 outbreak, which occurred while monitoring equipment was being installed and continued through most of the retrofit process (see Figure 11).

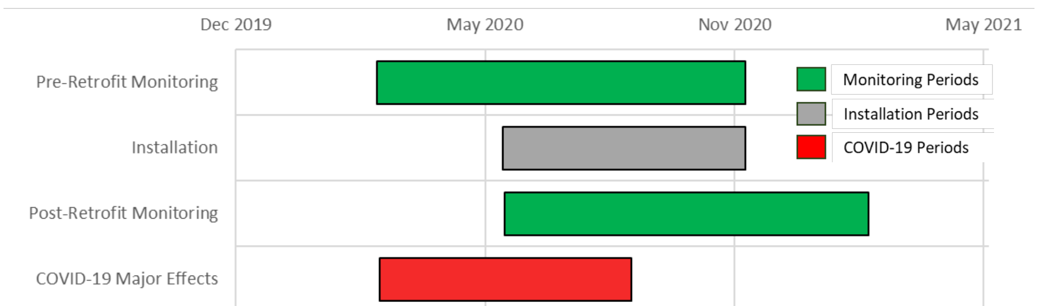

Figure 11: Timeline for induction cooking field test

There was generally more cooking activity during the post-retrofit period when most occupants were quarantined. To adjust for these effects, the energy savings calculations were performed relative to the number of cooking events. It is possible that the cooking activities were simpler and shorter during the pandemic, including more breakfast and lunch events. But there was no practical way to determine the complexity of the meals, and it was assumed that the number of meals cooked and the efficiency of the stove were the primary drivers of energy use.

The induction stove at the commercial site was installed in August 2021. This was long enough after the COVID-19 outbreak that even with a 3-month pre-retrofit monitoring period, there was likely no difference in usage of the stove before and after the retrofit. Regardless, the energy use calculations were normalized based on number of cooking events, as they were for the residential applications.

2.6 Heat Recovery Dishmachines

The field testing of the two heat recovery dishmachines installed in commercial kitchens occurred several months after the worst of the COVID-19 impacts, as shown in Figure 12. However, these sites had not yet fully recovered from the loss of business, and the number of dishwashing loads per day was significantly different during the post-retrofit period.

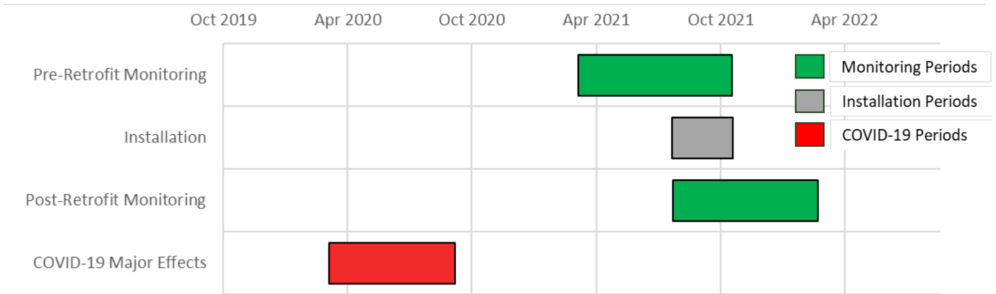

Figure 12: Timeline for heat recovery dishmachine field test

The large differences in throughput at the two sites skewed the total energy usage such that the energy savings needed to be calculated on a per-rack-washed basis to compare the pre- and post-retrofit periods. This approach was probably adequate to adjust for COVID-19 impacts, but it highlights the difficulties related to the gradual and sometimes volatile nature of returning to normal business following the worst of the pandemic.

2.7 Aerosol Envelope Sealing

Field testing of the aerosol envelope sealing process was performed during and just after the COVID-19 outbreak, as shown in Figure 13.

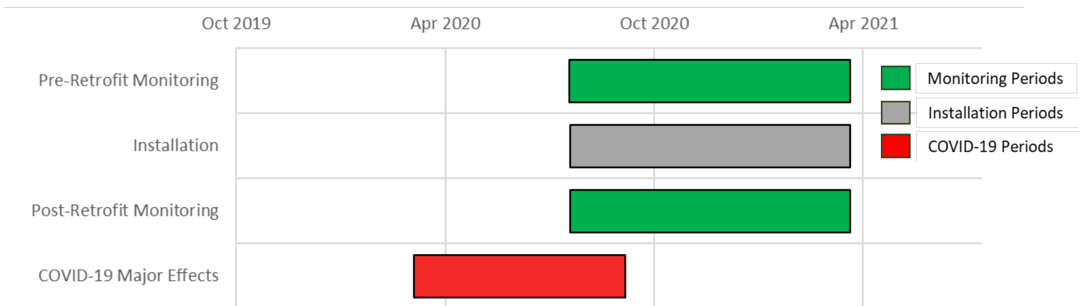

Figure 13: Timeline for aerosol envelope sealing field test

Long-term monitoring was not performed on the ten homes where aerosol sealing was applied. The process included measurements of air leakage before and after sealant application. Because all homes underwent a change in occupancy or a major renovation at the same time aerosol sealing was performed, utility bill analysis was not an option. For these sites, energy modeling was performed using standard operating conditions and the effective leakage area before and after the sealing process to estimate energy savings. Therefore, COVID-19 had no impact on the project except to make site recruitment more difficult.

2.8 Tubular Daylighting Devices (TDDs)

The field testing of TDDs in three commercial buildings was performed across several years, because of site recruitment difficulties that were exacerbated by the COVID-19 pandemic. There was no pre-retrofit monitoring at these sites, and the installations occurred after the worst of the pandemic, as shown in Figure 14.

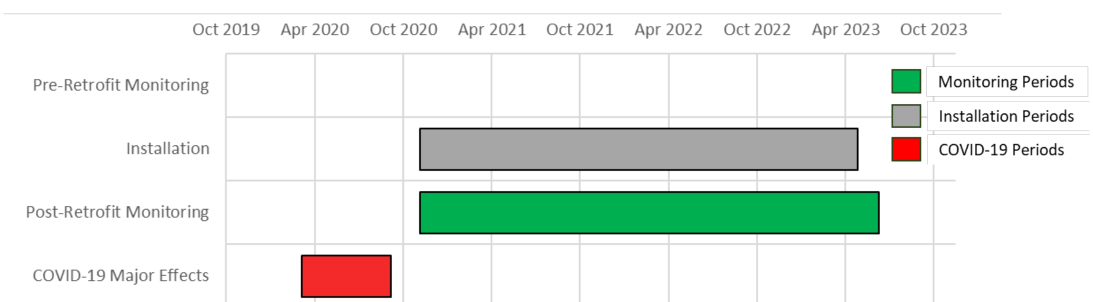

Figure 14: Timeline for TDD field test

The energy saving for the TDDs was calculated analytically based on the use of the TDDs and electric lighting following the retrofits, along with occupant surveys. As a result, COVID-19 did not influence the energy savings calculations, although building operations may have been different from previous years, and lighting energy use and energy savings may have been lower than they would have been if the retrofits had been performed two years earlier.

2.9 Nighttime Ventilation Cooling

The night ventilation cooling systems were installed in ten homes without air conditioners beginning in the midst of the COVID-19 outbreak, as shown in Figure 15. Pre-retrofit monitoring of the test homes was significantly impacted by the pandemic.

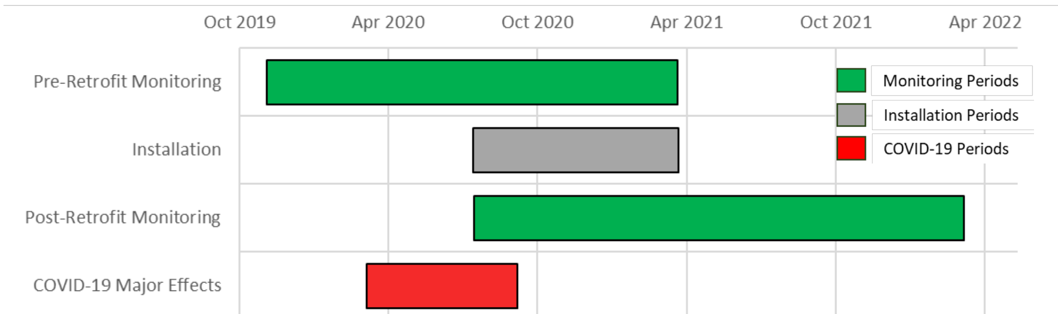

Figure 15: Timeline for nighttime ventilation cooling field test

Two methods were used to calculate energy savings for this project. The first was monitoring of energy use for heating before the retrofit, and heating plus ventilation fan energy after the retrofit. These calculations used weather normalization with a variable balance point temperature that partially adjusted for changes to thermostat operations. This analysis was focused on heating energy, which was minimally affected by the retrofit. Cooling energy was not relevant because no air conditioner was present, and the ventilation system was only present after the retrofit. The second method was energy simulation compared to the same house with an air conditioner installed, and using standard operating conditions and weather. The use of standardized thermostat settings eliminated issues related to the COVID-19 pandemic.

3. CONCLUSIONS

3.1 Key Findings

This paper described the challenges associated with performing a major field test program during the extremely disruptive period following the outbreak of COVID-19 in the U.S. Each project was affected differently, and multiple techniques were developed for addressing the unexpected changes to building occupancy, operations, and thermostat settings:

- Energy modeling with standard operating conditions.
- Adjustments to measured savings based on modeled effects of changes to operating conditions.
- Normalized energy use based on meals cooked or dishmachine loads.
- Weather normalization that included a variable temperature balance point.
- Neglecting the effects when justified by the measured data or surveys.

In some cases, energy savings could not be calculated with high confidence. But in most cases, an effective method was found that provided reasonable accuracy despite the confusion and uncertainties of the pandemic.

3.2 Lessons for Future Studies

Based on the experience gained from this project, there are several recommendations for similar studies of occupied buildings in the future, where any unexpected external variable could undermine the accuracy of measured results. In the case of the study described here, the COVID-19 pandemic was the greatest challenge, but in other studies it may be wildfires, earthquakes, extreme weather events, economic downturns, or grid outages. Recommendations from our experience include the following:

- Perform detailed surveys of households prior to the retrofit, so later changes to occupancy or behavior can be more easily quantified.
- Monitor important relevant operating conditions such as thermostat settings, hot water use, plug loads at the circuit level, window operation, and even room-by-room occupancy with the homeowner's permission.
- Set aside a budget for energy modeling to supplement field monitoring when possible.

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