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Decarbonization of Affordable Multifamily Housing – Application of high-efficiency monoblock heat pumps

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Abstract

Affordable multifamily housing presents one of the hardest residential sectors to decarbonize. Many of these housing units have the bare minimum in terms of HVAC (e.g., swamp coolers + gas wall furnaces, etc.) and are compromised on occupant comfort. A recent innovation in the heat pump retrofit market is the development of monoblock heat pumps which do not have separate indoor-outdoor units and are relatively simple to install. These are also high-efficiency inverter-driven systems that operate on a 120V single phase. The authors were part of a project team that worked with a multifamily affordable housing complex in Fresno, CA to install 140 monoblock heat pumps in 60 living units. The project investigated various aspects of the retrofit process and collected energy use data from all the units to derive insights into the efficacy of these heat pumps for providing comfort while reducing GHG emissions. The results indicate that residents used their heat pumps similar to swamp coolers in the main living areas, and with additional heat pumps in the bedrooms, were able to achieve better cooling while staying within the building's overall current capacity. In winter, the use of heat pumps significantly reduced energy use consequently reducing the overall GHG emissions from this community. A set of recommendations on applying these heat pumps in utility customer programs to help to decarbonize affordable multifamily housing is developed.

Keywords: affordable housing; decarbonization; retrofits; monoblock heat pumps; 120V heat pumps;

1. Introduction

Historically, higher-income communities have been the early adopters of emerging energy technologies—such as rooftop solar photovoltaics (PV), high-efficiency appliances, light-emitting diode (LED) lights, heat pumps, heat pump water heaters (HPWHs), and electric vehicles. The idea behind this market-driven approach is that as deployment becomes more widespread, the technologies will eventually become more affordable to low-income communities, further expanding the market.

Today, as governments and utilities establish aggressive climate goals, the need to electrify and decarbonize residential and commercial buildings—which account for about 12% of U.S. greenhouse gas emissions—becomes more urgent. However, advanced electric building technologies such as electric heat pumps and HPWHs are generally expensive and out-of-reach for low-income households.

The cost of adoption of heat pump technologies goes beyond the equipment and labor costs for affordable multifamily housing (which houses low-to-moderate income residents) as these buildings are heavily constrained by existing electrical capacity. In a recent study conducted by the authors in a garden-style multifamily affordable housing complex in Fresno, CA, each building with up to 8 apartments each had a total capacity of 200A with each apartment having 100A panels. Full scale electrification of this community using traditional mini-split heat pumps and heat-pump water heaters would have significantly exceeded the capacity constraints in many of the buildings. The solution to this challenge required scouting, analyzing, certifying,

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and installing 120V monoblock air-source heat pumps for space conditioning. The use of 120V monoblock[1] heat pumps helped to eliminate costs for panel upgrades, additional wiring (for 240V), and potentially higher costs associated with increasing a building's current capacity all of which collectively would have doubled the per unit cost of the overall retrofit. In the following sections, we describe why the use of these monoblock heat pumps and other decarbonization measures that can form a "package" solution for decarbonizing affordable multifamily housing.

Recognized as a critical technology for efficient space conditioning and building decarbonization, electric heat pumps have become an increasingly popular option in residential buildings across the country and the globe. Using electricity instead of fossil fuel as energy source, heat pumps enable the large majority of current space heating demand to be met with lower carbon emissions. By leveraging a vapor compression refrigeration cycle to harness ambient thermal energy, heat pumps can efficiently provide heat with one-third to one-fifth of the electricity consumed by conventional electric heating equipment [1].

In the US, electric heat pumps are most adopted in single-family houses, but there is an increasing trend of electric heat pump adoption in multi-family apartment buildings as well. As of 2005, apartment buildings accounted for about 10.2% of total installed residential electric heat pump. This number has increased to 13.2% in 2015 [2]. 2021 has been a record-high year for heat pump sales. In the US, heat pump sales grew by around 15% year-on-year. Air-source heat pumps (ASHP) account for most sales, with a market share of more than 60% [1] . With continued advances in heat pump technology, heat pumps can perform well across nearly all climate zones in the country [1]. ASHPs operate most efficiently in mild and coastal climates [3]. Therefore, California climate is ideal for ASHP implementation. According to the survey of California Heat Pump Residential Market Characterization and Baseline Study, most of the construction professionals in the survey expected the heat pump market to grow in the next five years in California. Half of these professionals reported they already install heat pumps regularly and see heat pumps becoming increasingly critical to meet California's energy goals. Even in cold places like Lake Tahoe, manufacturers make heat pumps that work effectively at very cold temperatures [4].

However, there are still some barriers to widespread adoption. In addition to the negative perception carried by historical poor performance at low outdoor temperature, heat pumps require more complex and proper maintenance than furnaces to keep optimal performance. The expected average lifetime for a heat pump is 10 years or more, while 15-20 years for a gas furnace [5]. Moreover, customers and technicians are more familiar with gas furnaces and air conditioners. The lack of appropriate skills and knowledge and high upfront costs are the two other major barriers to widespread heat pump adoption, especially in the placement of the equipment of the compressor unit [4].

In the Net Zero Emission by 2050 scenario, the global heat pump stock should cover at least 20% of global heating needs in buildings, while heat pumps still only meet about 10% of the need for now [1]. Policy support for heat pumps is rapidly increasing to meet decarbonization ambitions [1]. Several manufacturers are expanding heat pump production with emerging business models. Further policy support and technical innovation are still needed to reduce upfront purchase and installations costs, remove market barriers, improve energy performance, and exploit potential to enable power system integration and flexibility [1].

2. Decarbonizing Affordable Multifamily Housing

2.1. What is the motivation?

Affordable multifamily housing is one of the most challenging segments of buildings to decarbonize and this is especially true for retrofits. There are several extenuating circumstances that makes this challenging, some of these are listed below:

- **Energy Burden**: Any upgrades and technology investments made cannot result in increasing the energy burden in affordable housing communities. With decarbonization pathways that utilize electrification, there is a need to be cognizant of the potential for electrified end-uses being higher operating costs for community residents and measures to help mitigate these cost increases are necessary.
- **Split Incentives**: Given that community residents don't own the infrastructure in affordable multifamily housing communities, there is a need to make sure that the investment made by the building owner/operator has a return for the building owner/operator.

[1] Throughout the paper, the term monoblock heat pumps refer to specific class of heat pumps that have a single unit form-factor (indoor unit only) as opposed to the traditional indoor/outdoor (dual-unit) form factor.

- **Retrofit Costs**: In addition to the cost of equipment and labor, retrofits need to explicitly account for retrofit costs which could include costs for additional panel capacity, wiring for 240-V end-use devices, cost of removal of existing (old) infrastructure, asbestos abatement for older vintage buildings, etc. These costs could significantly add to the overall cost of decarbonizing affordable housing communities.
- **Infrastructure upgrade costs**: This impacts electrification based decarbonization measures which are currently being served for space and water heating via natural gas. The additional electrical load that may arise can trigger the need for upgrading distribution infrastructure such as service transformers and requires the local utility to invest in these upgrades.

Given these set of challenges, it is safe to say that if there is a way to engineer a decarbonization solution for affordable multifamily housing, there is a very high likelihood of these decarbonization solutions to find wider applicability. In that sense, this challenge has high innovation potential both in terms of technology as well as business model. The above list is not exhaustive as each community is different and may have their own set of issues that makes decarbonization challenging. However, the market availability of 120V monoblock heat pump products present a viable answer to many of these challenges.

2.2. How does 120V Monoblock heat pumps help?

To help address the challenges with decarbonizing affordable multifamily housing, the use of 120V monoblock heat pumps in conjunction with other electrification and decarbonization technologies can be considered to develop packages of energy conservation measures that can provide for decarbonization while reducing the first cost of upgrades and operating cost of energy.

- **High Efficiency**: The 120V monoblock heat pumps that are currently available in the market are high efficiency inverter driven variable speed heat pumps which have operating Coefficient of Performance (COP) of 3.0 or higher. This effectively provides for a 3x increase in efficiency compared to even the most efficient natural gas heating solutions. This increased efficiency helps to offset the cost of natural gas with higher electricity use that is more efficient for the same amount of heat.
- **120V as opposed to 240V**: The use of 120V as the operating voltage and less than 15A as the operating maximum current draw allows these heat pumps to used in capacity constrained multifamily buildings. This is especially true if these heat pumps are replacing existing low-efficiency evaporative coolers or window air-conditioning units. This also significantly reduces the risk of higher costs related to retrofit constraints. The unit’s operation at lower power draws also allows for not requiring distribution infrastructure upgrades if the unit is replacing an existing low-efficiency system at the living unit level.
- **Monoblock requires less construction**: The use of monoblock heat pump technology also requires less construction impacts as the heat pump unit does not have any ducting, wires, tubes that runs from the outdoor unit to the indoor unit. Additionally, the models used in our case study use two 6” holes for air intake and exhaust allowing for tighter air sealing.
- **Additional decarbonization**: Additional measures such as envelope improvements, community-scale solar PV, etc. with the ability to avail of federal, state, and utility level incentives such as the U.S. Department of Energy’s Weatherization Assistance Program (WAP), California’s Solar on Multifamily Housing (SOMAH) all help to address issues with split incentives, reducing energy burden, etc. and when done in conjunction with the installation of 120-V monoblock heat pumps helps to further address the challenges with decarbonizing affordable multifamily housing.

3. Case Study

3.1. Project Description

Constructed 50 years ago, Pleasant View is a 60-unit affordable housing community in Fresno, California. It is a family community comprised of 1-, 2-, 3-, and 4-bedroom units spread across ten buildings, each of which contain between four and ten apartments. The units were previously cooled by evaporative coolers and heated by natural gas wall furnaces. A closet in each apartment stored a 40-gallon natural gas water heater. The community is master metered for both electricity and natural gas, with the property owner LINC Housing paying all utility costs to PG&E, the serving utility. Each apartment is served by a 100-A electric panel, while each building is served by 200-A mains panel (regardless of number of apartments). Limits on the local distribution system precluded full-scale electrification of the property.

The project team installed the monoblock heat pump and limited (limited to 3 of the 10 buildings) centralized HPWH retrofits in the first half of 2020. Retrofits involved installing 120-V, 12-hp Innova D.C. inverter heat pump units with an energy efficiency ratio (EER) of 3.3 (min outside ambient temp of 14F in heating mode) in each apartment. Two advantages of the Innova heat pumps, also referred to as packaged terminal air conditioning (PTAC) stood out: 1) Historically most residential heat pumps installed in the U.S. are 240-V units, which would have required new electric panels and rewiring at Pleasant Hill. The 120-V Innova units minimized any need for upgrades and represented one of the first large scale retrofit installation of 120-V heat pumps in affordable multifamily housing; 2) Historically, heat pumps have been split systems, requiring heat pump components to be installed on opposite sides of the inner and outer wall. Innova's monoblock unit involves installing only a single heat pump component on the inner wall. The monoblock configuration lowers installation costs and possibly long-term maintenance costs. Innova units were installed in the living room of all living units in the building. In two-bedroom units, Innova units were installed in the living room and master bedroom. In three- and four-bedroom units, Innova units were installed in the living room, master bedroom, and secondary bedroom. No further electrical infrastructure changes were made to the living units.

The project team performed the following additional energy efficiency upgrades listed in Table 1. The utility energy savings assistance programs covered some of the common area measures, but the air conditioning upgrades were out of pocket for the property owner.

Table 1. Summary of energy efficiency measures

Energy System	Pre-Retrofit	Post-Retrofit
Wall Insulation	None	R-19
Roof Insulation	R-13	R-25 with blown insulation
Patio Doors	Single Pane	Double pane with low-e and frame sealing
Space Cooling	Direct Evaporative Cooler	120-V Innova Heat Pump
Space Heating	Natural Gas Wall furnace	120-V Innova Heat Pump
Water Heating	40-gallon gas storage water heater	Sanden CO2 shared HPWH (in 3/10 buildings)
Indoor lighting	CFL	LED
Outdoor lighting	Metal halide parking lot lights	LED integrated lamps, fixtures, and posts for parking lot lights
		LED replacement in wall scones
Appliances	Electric coil cooktop	Glass-top electric cooktop
Renewables	None	137-kW community solar PV system

3.2. Data Collection and Methodology

Data collection from the community was performed primarily at the circuit level wherein each living unit was fitted with a current-transformer based circuit level load monitors that helps to provide highly granular (1-min level frequency) disaggregated load data. The need for this level of disaggregated load monitoring was motivated by the fact that the community is master metered for both electricity and natural gas thereby not having granular energy consumption at the individual unit level. Data was collected over a 3-year period ranging from 2019 (pre-retrofit) into 2020 (mid-retrofit) and 2021 (post-retrofit). While the heat pump retrofit was done in 2020, many of the other measures such as envelope and solar PV installation happened much before (2018-2019 timeframe). Load calculations were all based on disaggregated circuit level loads with a dedicated CT monitoring the living room Innova unit and master and second bedroom Innova units monitored via 15A shared circuit CTs. The monitors provide cumulative energy data based on per-minute current and voltage measurements which was aggregated to obtain appropriate hourly energy use values. Additionally master metered electric and gas data was used to calculate community level energy use and associated GHG using CAISO provided emissions factors.

3.3. Results

3.3.1. Summary

Total energy increased a small amount in the summer (shown as the small negative orange bars in Figure 1) but decreased significantly in the winter (shown as the orange bars at right). In other words, gas consumption decreased, while electricity consumption increased. Gross energy use decreased by 22%, mostly from winter gas savings.

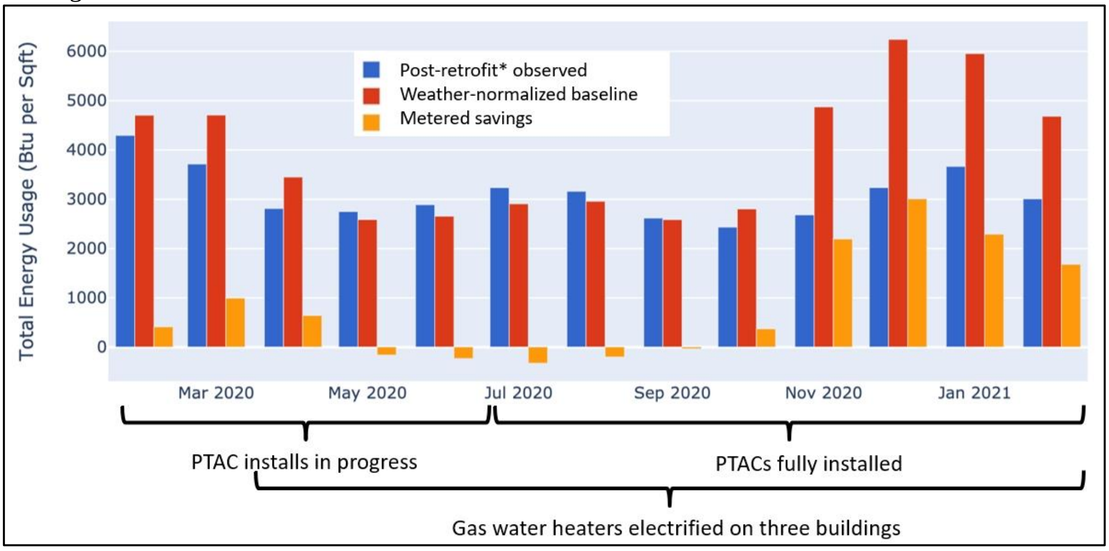

Figure 1 Total Energy (Gas and Electric) Usage[2]

Replacing evaporative cooling with compressor-based cooling, combined with the stay-at-home Covid-19 effect, increased summer GHG emissions. Electrification of water heating all year round overcame these increases, leading to a net GHG emission reduction. Figure 2 indicates the energy use converted to lb CO2e using California Independent System Operator (CAISO) published hourly emissions intensity. Overall emissions (site emissions + source emissions from grid electricity) decreased by 13%, largely due to winter gas savings.

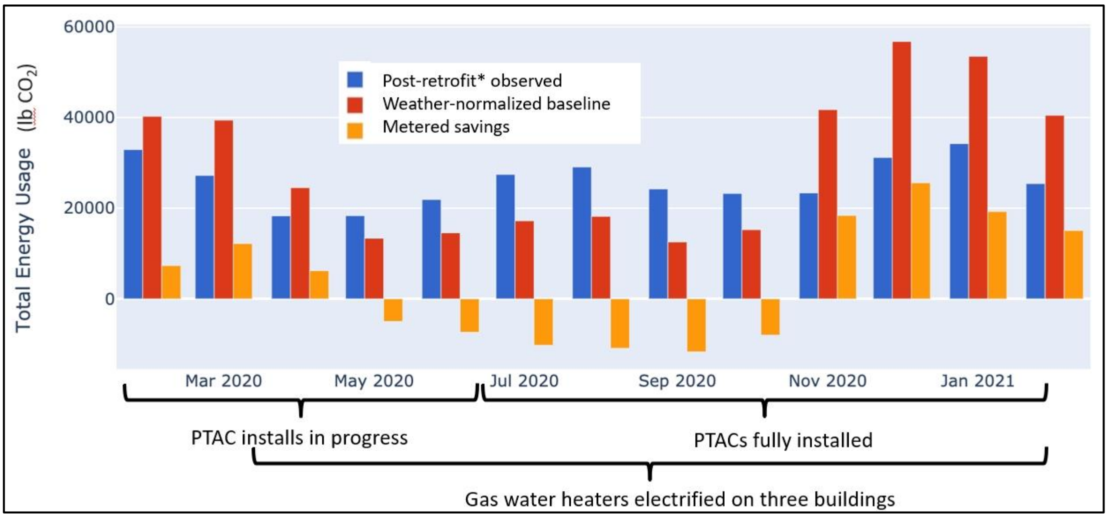

Figure 2 Monthly GHG emissions

While these results indicate the overall effect of PTAC and heat pump water heaters for the time periods under consideration (as indicated in Figure 1 and Figure 2), a detailed analysis of the 120V monoblock heat pumps was conducted to characterize the field performance of this new & emerging heat pump technology.

[2] This is total community level energy use based on master metered gas and electric meter data could not be further disaggregated for the periods shown without combining data from utility meters and circuit level monitors which don't have the same levels of accuracy.

3.3.2. Field performance of monoblock heat pumps

The field performance of monoblock heat pumps (PTAC units) were analyzed from the point of view of four research questions:

- How are residents of the community using these PTAC units? Is there a significant behavioral difference between living units?
- How does the load shape of the PTAC unit relate to the load shape of status-quo cooling solution? Can the load shape differences be attributed to efficiency or more to customer behavior?
- What happens when multiple PTAC units are used concurrently in buildings? Does simultaneous use of multiple PTAC units cause significant current draws that can potentially trip circuit breakers?
- What is the result of the use of PTAC units compared to status quo in terms of overall energy use (and potentially energy bills) in summer and winter?

3.3.2.1. Average user behavior

The July performance of the Innova heat pumps in the 1-bedroom units are shown in Figure 4. Most one-bedroom units show continuous, low-power draw, without significant periods of non-use. There is high-efficiency due to variable-speed performance. The load increases moderately with higher outdoor air temperatures. The data shows afternoon peaking performance and significant differences between living units with some living units running the PTAC units continuously in summer. With the status quo being inefficient evaporative coolers, which were under-utilized because of non-performance, many residents were happy to use a functioning high efficiency air conditioning unit. A qualitative survey of customer satisfaction was corroborated by data collected from the living units.

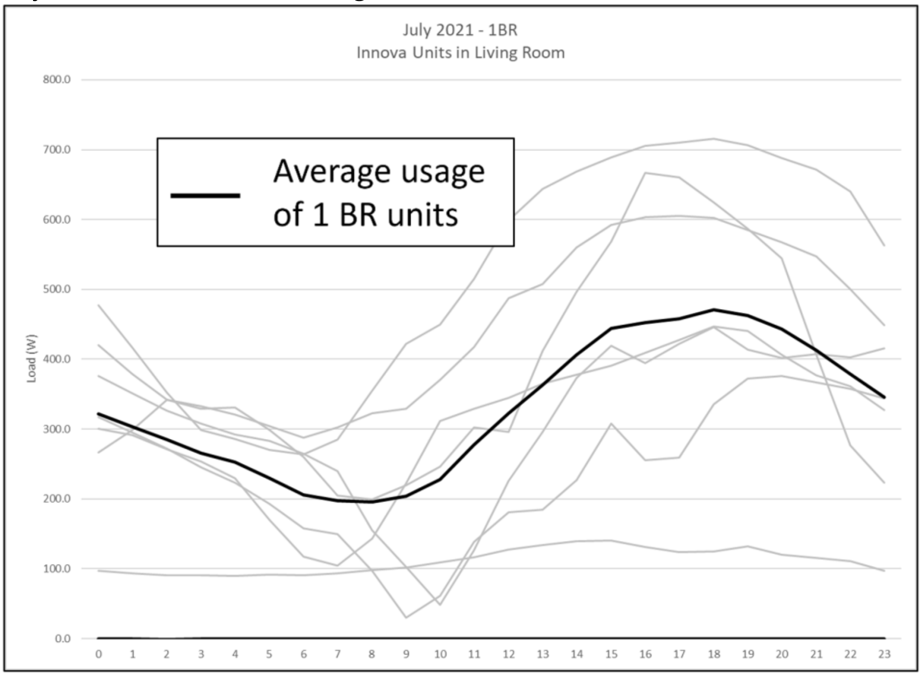

Figure 3 Innova Heat Pump Use Characterization (July 2021 – 1BR)

The January performance of the Innova heat pumps in the 1-bedroom units are shown in Figure 4. The data shows very low energy draw during the winter for heating. Significant variation between units is observed. When actively being used, the data shows dual peaking behavior corresponding to early morning and late evening hours, which is to be expected.

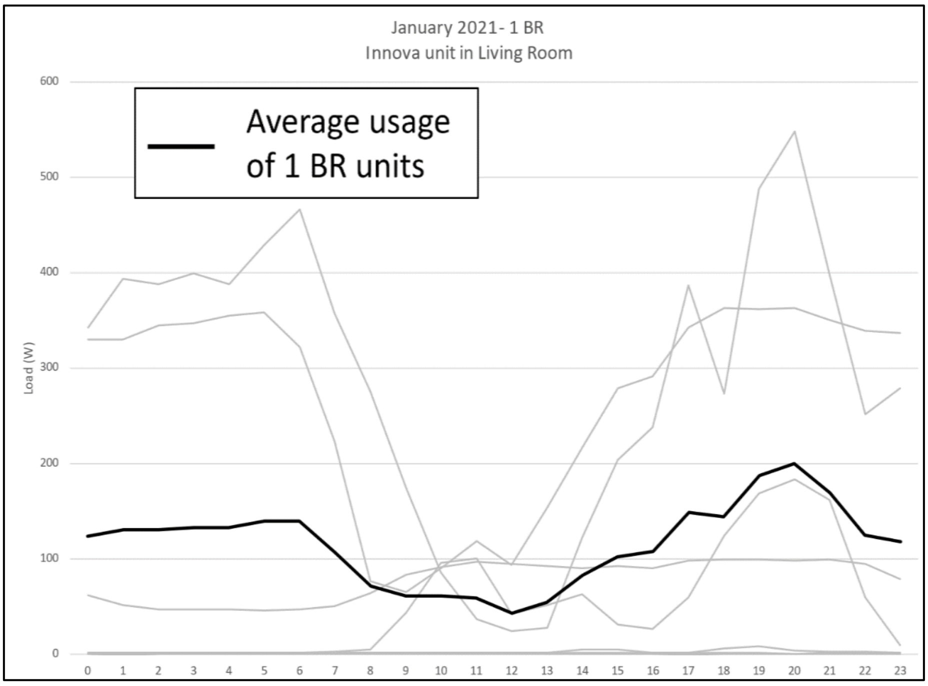

Figure 4 Innova Heat Pump Use Characterization (January 2021 – 1BR)

3.3.2.2. Comparison of monoblock heat pump load shape to status quo

The average summer load shapes for 1-bedroom units, displayed in Figure 5, show that 1-bedroom units use the heat pump to gain more comfort and that the living room Innova performance is similar to the swamp cooler. The higher efficiency mode allows less power despite continuous use. Note that winter load shapes couldn't be compared because the status quo is a natural gas wall furnace.

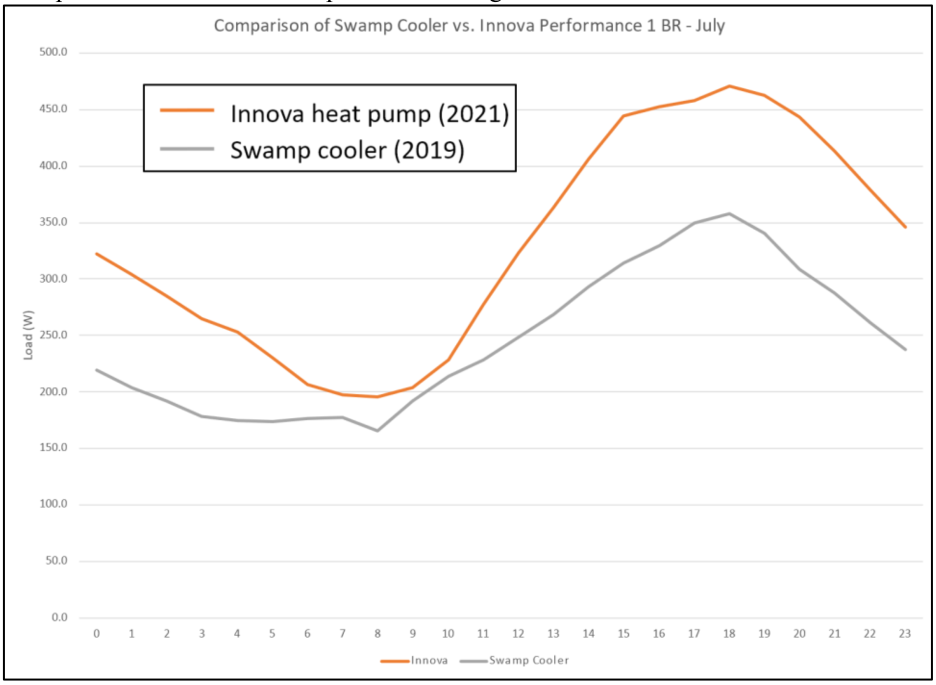

Figure 5 Comparison of swamp cooler vs. Innova heat pump performance (July – 1BR)

3.3.2.3. Impact of simultaneous multiple PTAC use on building's current draw

Figure 6 shows the hourly building level current draw in July 2021. The maximum current draw with multiple Innova heat pumps is an average of about 15-A per living unit. At a maximum of about 7.5-Aper Innova, use of a second Innova is not likely to cause the circuit breaker to trip unless other current loads are on the same circuit.

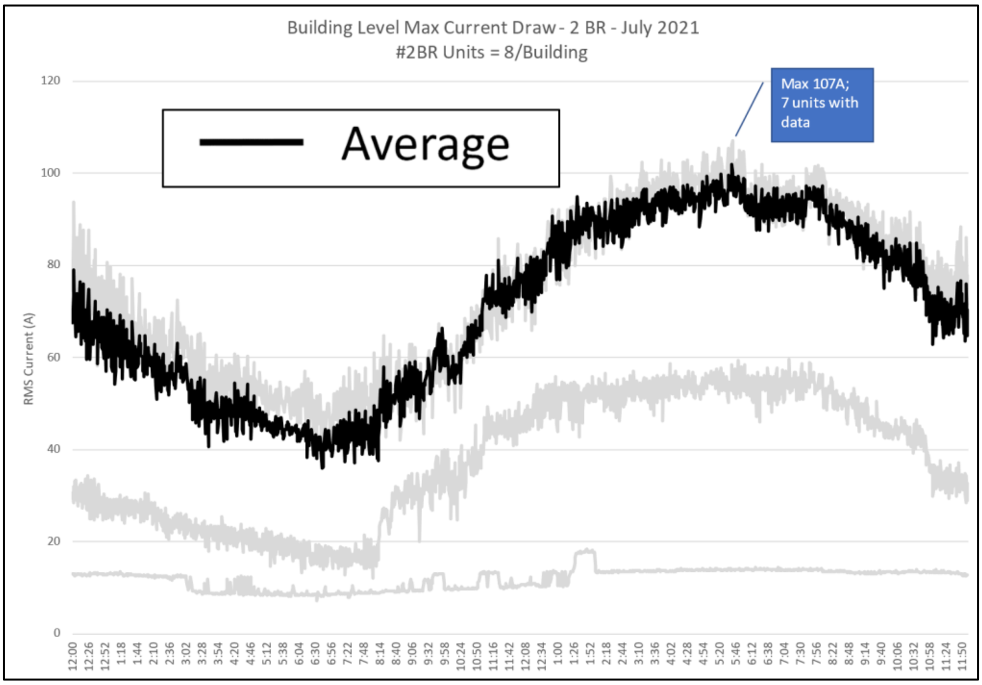

Figure 6 Innova Heat Pump Current Draw at Building Level in July 2021 (2 BR)

Figure 7 show the maximum current draw with multiple Innova heat pumps is an average of about 6-A per heat pump (or 42-Atotal for the 7 units). At a maximum of about 6-Aper Innova, use of a second Innova is not likely to cause the circuit breaker to trip unless other current loads are on the same circuit

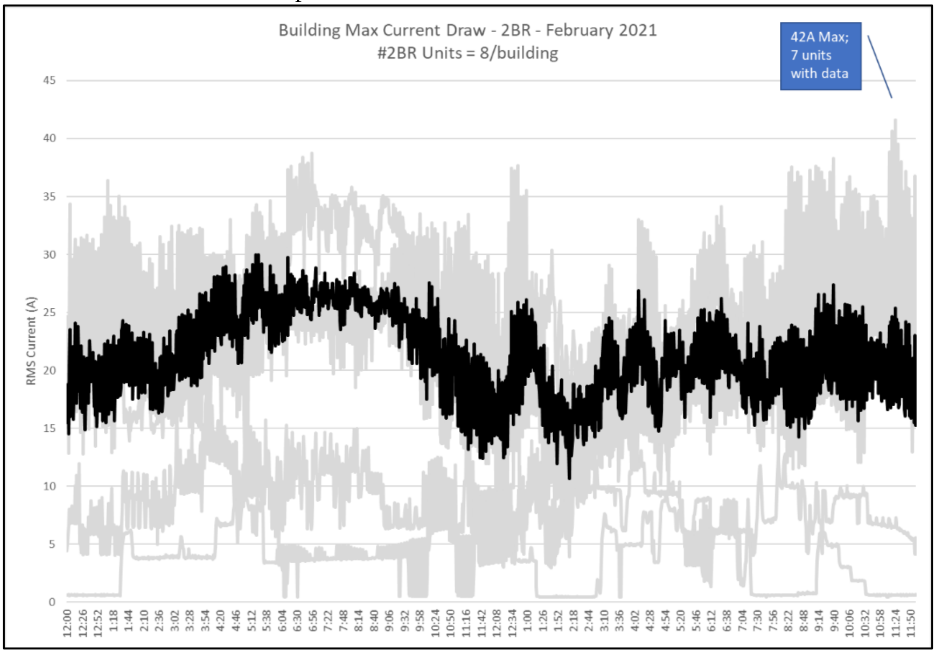

Figure 7 Innova heat pump current draw at building level in February 2021 (2 BR)

3.3.2.4. Summer and Winter energy performance of PTAC and status quo

Figure 8 shows that the monthly energy consumption is slightly higher for the Innova heat pumps than for the swamp coolers due to Innova continuous use. Higher energy use of Innova is also due to increased cooling needs in 2021 compared to 2019. However, Figure 9 show that energy consumption is significantly lower for the Innova heat pumps than for the gas wall furnace in the winter (electricity consumption in kWh was converted to US Therms for comparison). Significant performance improvement may also be attributed to envelope improvements that were added.

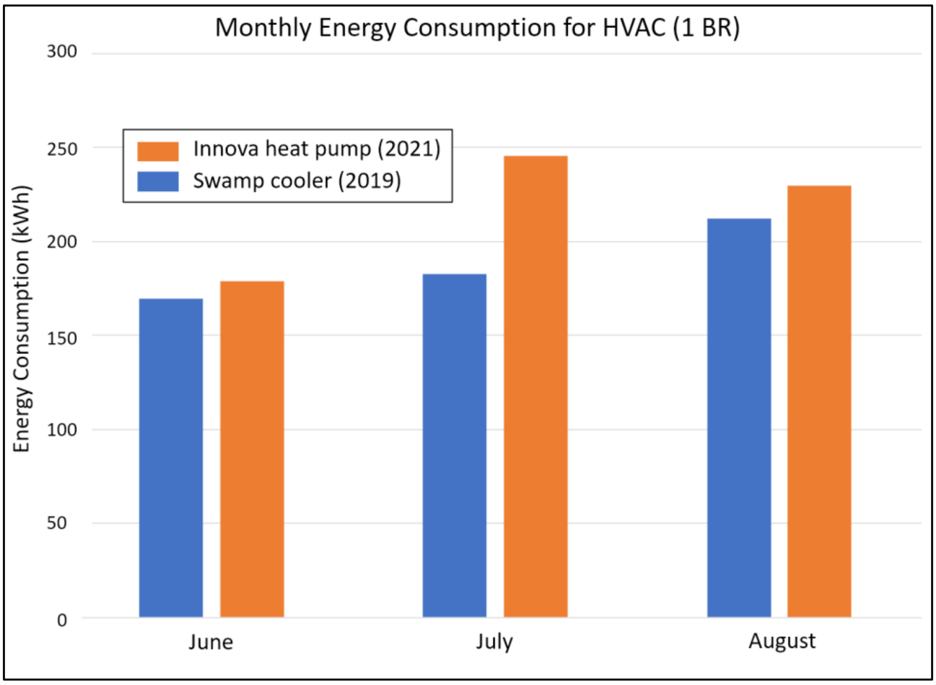

Figure 8 Energy Performance: Innova heat pump comparison to swamp cooler (1 BR)

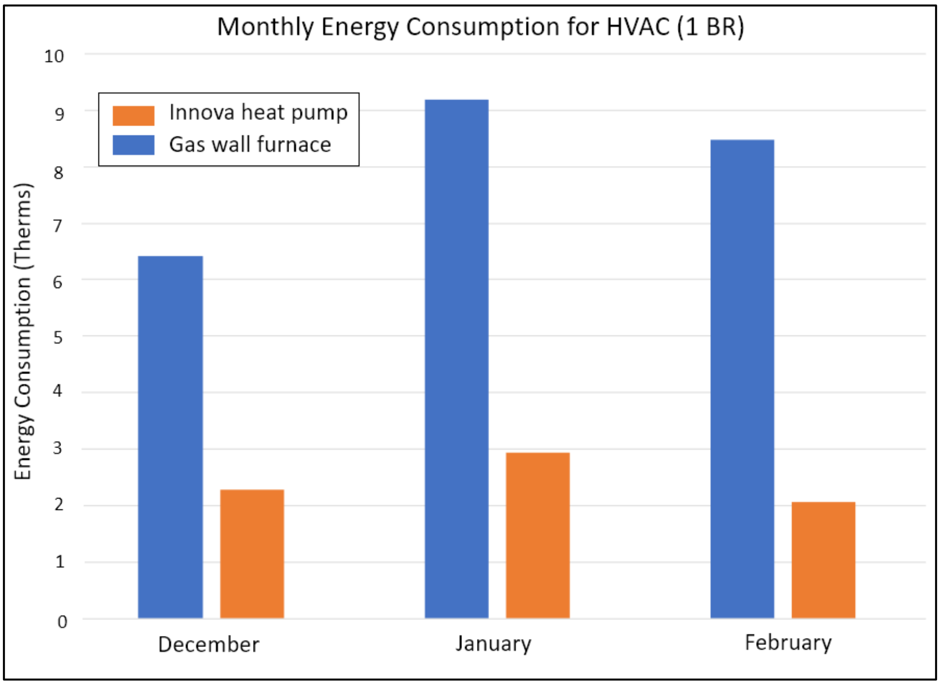

Figure 9 Energy Performance: Innova Heat Pump Comparison to gas wall furnace (1 BR)

4. Conclusions & Recommendations

The Pleasant View project was a showcase illustration of the unique application of emerging technologies to surmount barriers to electrification.

The results indicate that the Innova units are ideal for smaller living units, given the increased usage (and possibility for increased energy bills) in summer compared to reduction in gas use in winter. In a few cases, high overall usage (indicated by continuous use and low thermostat set points) caused maintenance issues. The product supports a "hoteling" mode that can help prevent extreme set points from causing maintenance issues, especially in master-metered facilities. Further, with a peak around 700-W and an average load of about 400-

W, each of these monoblock heat pumps represent about 300-W in flexibility potential, assuming adoption of a suitable controls platform that can implement demand-side flexibility.

While the technology itself shows promise in terms of performance, projects need to address split-incentives, and consider that total energy costs may increase with electrification depending on the energy use patterns and local utility rates. Improved energy efficiency and on-site PV are important steps to reduce tenant and owner energy costs.

The project team recommends the following actions to develop better pathways for the scaling of electrification retrofits of affordable multifamily and other residential markets to maximize decarbonization impacts.

- **Improve planning and implementation models**: The process for understanding and integrating the many support programs for the affordable multifamily market is daunting. For example, coordinating solar PV, roof upgrades, and energy conservation measures is essential for optimizing the electrical upgrades needed for the entire decarbonization retrofit.
- **Improve economic models for split incentives:** Scaled community decarbonization retrofits are emerging as evidenced by this project. To accelerate market adoption, improved models for overcoming split incentives and distribute savings from the community solar and other decarbonization retrofits are needed.
- **Upgrade policy or codes for electrification/decarbonization:** The shift to carbon-based metrics and incentives is underway in many utility service territories and are important to the successful scaling of decarbonization retrofits for affordable multifamily communities. Using carbon savings metrics can increase the incentives and cover a significant portion of the first cost of decarbonization retrofits as shown by California's Low-Income Weatherization Program incentives. Solutions for mitigating the electric infrastructure costs are essential for stimulating the electrification/decarbonization retrofits. New federal, state, and utility programs need to be developed and tested to cover these costs.
- **Work with manufacturers and stakeholders:** A significant barrier to the electrification retrofits of affordable multifamily communities is the lack of heat pump products for the retrofit market. New heat pump products designed for the retrofit market are needed. Recent advances such as the Innova monoblock heat pumps and Gradient window cold-climate heat pumps are good examples. A sustained program working with domestic and international manufacturers, utilities, designers, installers, and government organizations is recommended.
- **Demonstrate evaluation of integrated solutions:** Demonstration programs and test beds for utilities and stakeholders is needed for rapid evaluation of new integrated decarbonization retrofit solutions to accelerate market adoption of these new solutions.

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