Electrification of Centralized Water Heating in an Affordable Housing Community: Lessons Learned from a Pilot Demonstration

Mazen Daher, Agatha Kazdan, Siva Sankaranarayanan, EPRI
Merry Sweeney, San Diego Gas & Electric
Tim Kohut, National Community Renaissance

ABSTRACT

Domestic hot water system electrification is a high-potential decarbonization vector in multifamily buildings. Centralized systems, common in multifamily construction, are particularly interesting, as they offer the opportunity for replacing large boilers with heat pumps that can contribute to demand response potential and achieve significant efficiency gains. To further understand the implications of such retrofits, EPRI partnered with San Diego Gas and Electric (SDG&E) and National Community Renaissance (National CORE) to retrofit and monitor a 192-unit affordable housing property built in 1987 in San Marcos, California (IECC Climate Zone 3B). The community's original natural gas boiler system was replaced with CO2 heat pumps supported by swing tanks that employ electric resistance heat. Utility bills and detailed energy use have provided valuable insights on best practices in the modeling, design, and operation of retrofitted centralized heat pump systems. Other important discussion points raised by this project relate to the importance of continuous operational monitoring for cost-effective implementation of electrified systems.

Introduction

This article discusses an electrification retrofit conducted in an affordable housing community managed by National Community Renaissance (National Core) and located in San Marcos, California, consisting of 12 multifamily buildings with 16 units each, evenly divided into 2- and 3-bedroom units. The complex is located is San Diego Gas and Electric service territory and also includes three laundry buildings, an office/community center, and a maintenance building. Water heating loads are master metered, meaning that all energy costs attributable to water heating are borne by the landlord. The community is subject to SDG&E's TOU DR-1 Tariff (SDG&E, 2024).

Prior to the commencement of the project, each of the 12 multifamily buildings had its domestic hot water needs met by a centralized natural gas boiler system. The boilers were in indoor enclosures adjacent to the residential buildings/laundry rooms.

The retrofit consisted in replacing the centralized boiler system in place with a centralized heat pump system configured with a swing tank receiving return water from a recirculation loop and hot water from the heat pumps. Significant performance issues were encountered, most notably resulting in excessive electricity use (and costs). The ongoing course correction is described.

Contribution

This paper contributes to the existing literature on centralized CO_2 heat pump water heater retrofits in two primary ways, by (a) identifying issues within a field retrofit that corroborate findings from other researchers, (b) providing a high volume of field performance data for a technology that does not have high market penetration in the U.S., and (c) identifying issues in the application of typical modeling/cost-benefit analysis tools and approaches used to qualify for retrofit incentives.

Retrofit Summary

Water Heating System

The electrification retrofit package installed at this community included 42 Sanden CO2 15.4kBTU/hr heat pump water heaters. See Table 1 for heat pump specifications. Of the 42 heat pumps, 36 serve the Domestic hot water (DHW) needs of the 12 apartment buildings. The six remaining heat pumps serve the water heating needs of three laundry buildings. The retrofitted heat pump system for each residential building thus included three heat pumps, along with two (119 gallon each) primary storage tanks downstream of the heat pumps. See Figure 1 for a schematic.

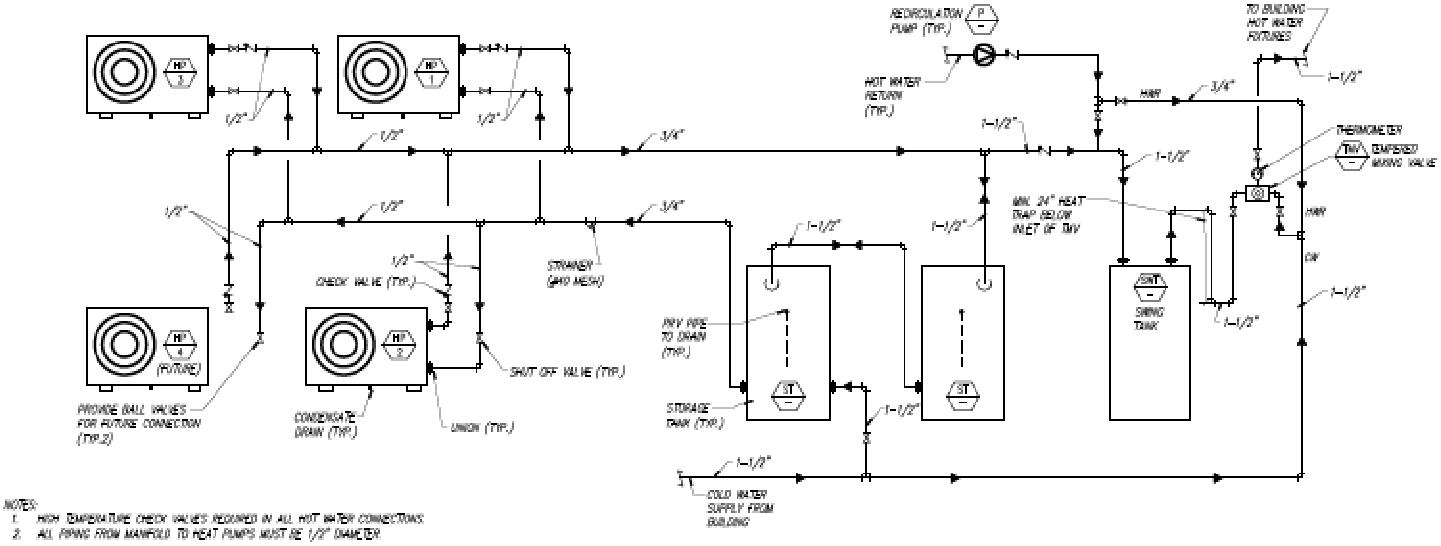

Figure 1 Retrofit schematic. As installed, there are three heat pumps in each residential building. However, official plans refer to a potential future install. The heat pumps are plumbed in parallel.

A “swing tank” is plumbed in series with the primary storage tanks, while also receiving water from the recirculation loop. This configuration should provide passive heating capability during periods of high demand, as high temperature (T>140F) water from the primary storage tanks mixes with water from the recirculation loop and goes into the swing tank..The 80-gallon swing tank is equipped with a 6kW electric resistance heater to prevent significant drops in water temperature that may result in cold water being delivered to the residents. The full system performance was modeled using a tool prescribed by the Low-Income Weatherization Program (LIWP) to qualify for retrofit incentives.

Table 1 Selected Performance Specifications, SANCO2 heat pumps.

Brand Name	SANCO2
Model Name	GS4-45HPC + SAN-83SSAQA
Electric Usage at 125°F outlet temp (kWh/yr)	1340
Uniform Energy Factor (UEF)	3.75
First Hour Rating at 125°F outlet temp (gallons/hr)	115

Except for two buildings, the heat pumps were placed inside the same enclosures previously used for the boilers. That decision was chiefly based on cost. In other words, it was determined by the engineer of record, that placing the heat pumps indoors would not be problematic given the available ventilation, and the cost implications of placing the heat pumps outdoors.

The heat pumps were set to 145 F and the swing tank was initially set to 140 F during the system tuning period (January to April).

For more information on similar deployments, the reader is referred to a review by Valmiki et al. (Valmiki et al., 2023).

Data Sources

The data presented in this paper is collected from two main sources:

- Pre-retrofit and post-retrofit energy consumption and utility bill data is available for every individual building's common area through National Core's utility account. This data represents total electricity and natural gas use for the residential buildings' common areas (meaning it excludes laundry electricity/natural gas use, as they are separately metered).
- In addition, dedicated monitoring of every building's main electrical panel, as well as the specific circuits serving the HPWH system, was conducted post-retrofit. Therefore, electricity consumption data at the circuit breaker level was available to the team post-retrofit.

Pre-Retrofit Data

Energy Demand and Usage

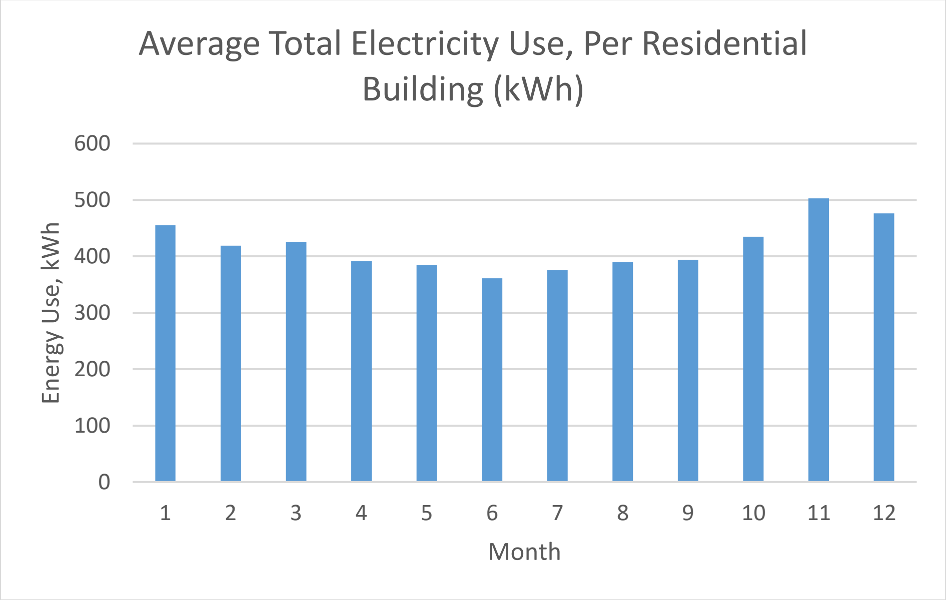

Figure 2 Average Common Area Electricity Use per Residential Building, Pre-Retrofit

Figure 2 shows the residential common area (excluding the separate laundry buildings) electricity use, per month, averaged over the five years (2017-2022) prior to the retrofit. Those numbers account for common area lighting and other miscellaneous master-metered end-uses. Natural gas use (Figure 3), in this case largely restricted to water heating, shows a typical pattern of being more pronounced in the winter months. Understanding historical natural gas use patterns proved important in assessing the response of the system to operational adjustments conducted in the summer when water heating energy use tends to decrease due to warming weather (and consequently, higher incoming water temperatures).

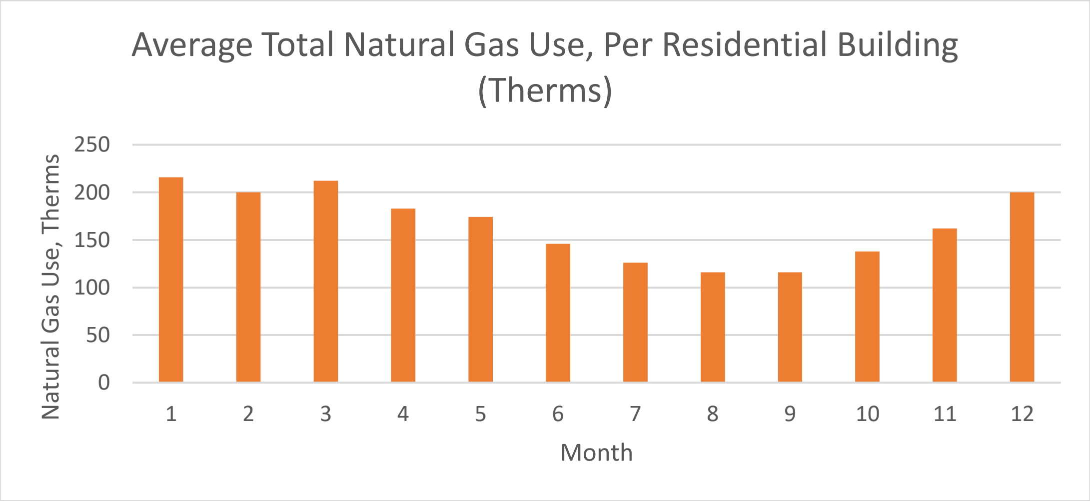

Figure 3 Natural Gas Use per Residential Building, Pre-Retrofit

Given this, understanding the magnitude of weather-driven decreases is an important aspect of adjusting operations when the data at hand is suboptimal i.e., when attempting to gauge the effectiveness of efficiency interventions undertaken during times of typically low (and decreasing) DHW demand.

Utility Costs

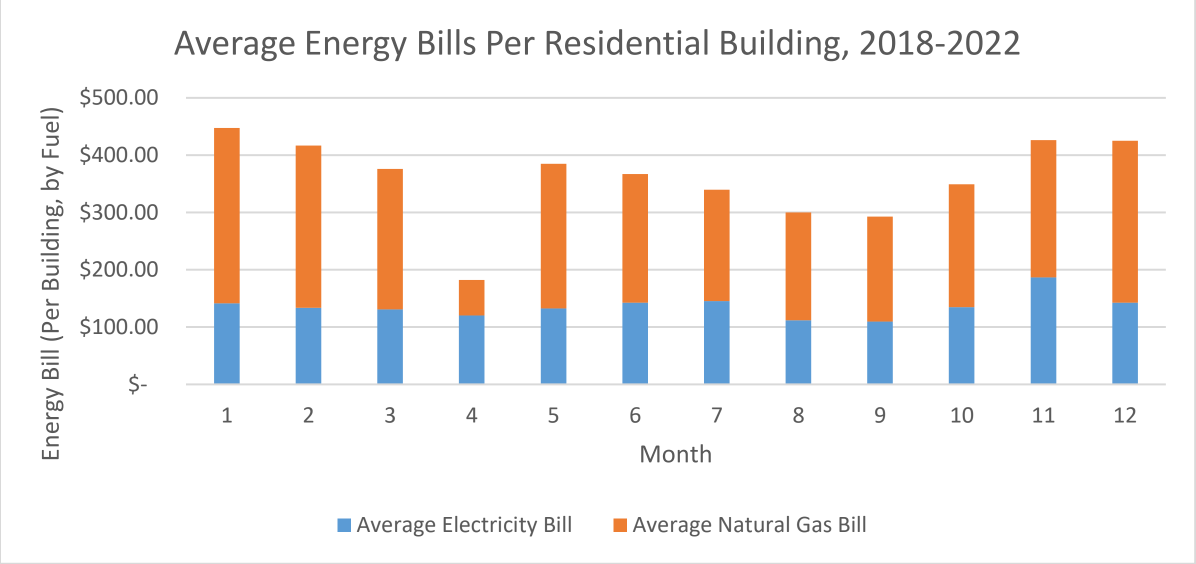

Figure 4 Average Common Area Energy Bills per Residential Building, Prior to Retrofit

Figure 4 shows the average master-metered energy bill per month per residential building within this community for the years 2018-2022. The common area meters for each residential building (i.e., excluding laundry, as those buildings are metered separately) include domestic water heating, common area lighting, and other miscellaneous common area loads. Gas billing data for April, when the California Climate Credit (CPUC, 2024) is applied, is not representative of actual energy use. Natural gas costs were substantially higher than electricity costs prior to the retrofit because centralized water heating (master-metered for all residents) is the dominant common area end-use in this community.

Post-Retrofit Data, Pre-Optimization (January - April 2023)

Figure 5 shows the average electricity use in this community, per residential building, from January to April 2023. Electricity use is significantly elevated compared to pre-retrofit patterns (see Figure 1). As the electricity use shown here is restricted to common area loads, this change is unsurprising, as common area electric loads were not substantial prior to the electrification retrofit. Nevertheless, the dramatic increases in electricity use vastly exceed the increases predicted by pre-retrofit modeling (see Table 2).

Energy Demand and Usage

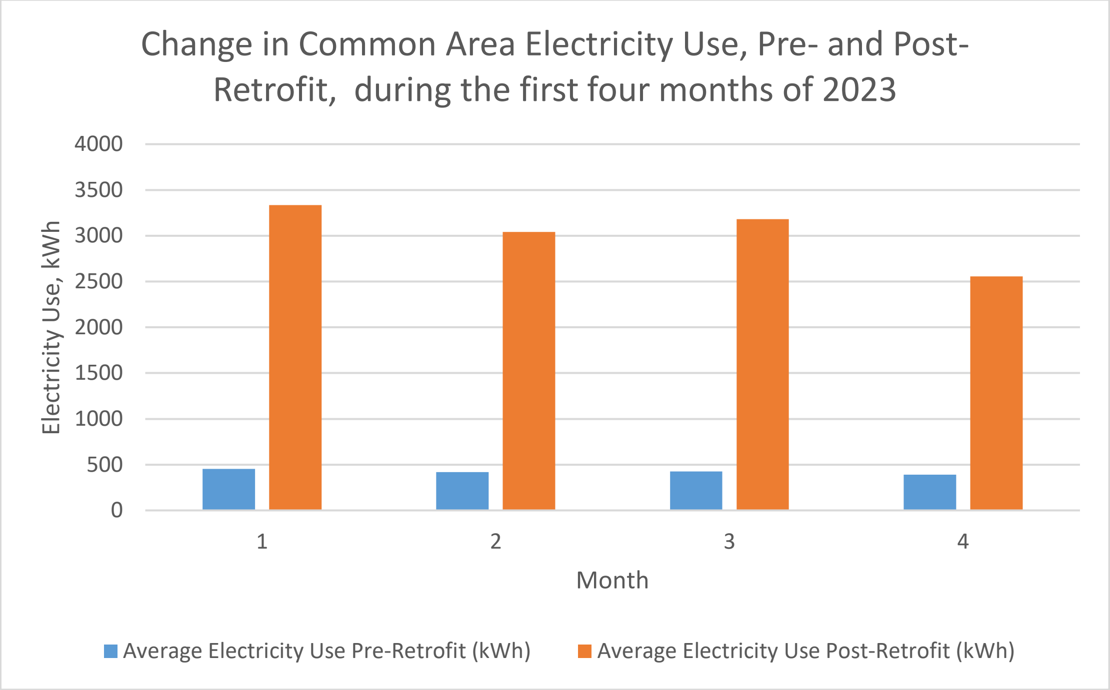

Figure 5 Average Common Area Electricity Use per Residential Building, January to April 2023

If scaled to a full year, the model underestimates actual energy consumption by a factor of approximately 2.18 (see Table 2). The modeling tool that was used is a simplified modeling tool used for calculations to qualify for certain incentive programs such as LIWP. However, it does not go into the needed detail to accurately reflect the operation of the system as described in Figure 1. In particular, the tool only requires certain nameplate performance parameters (such as Coefficient of Performance or Uniform Energy Factor) for the heat pump system, and only requires loose parameters for the plumbing system. The most significant limitations of the tool as pertains to this deployment are the following:

- It is not possible to specify where the heat pumps are placed within the building (e.g., outside vs inside), so efficiency and capacity decreases due to poor ventilation of indoor enclosures are not captured.
- Plumbing is not described in detail (e.g. three heat pumps in parallel, plus all of the associated recirculation and storage tank loops). Given plumbing imbalances shown in subsequent sections of this paper, this is an important limitation.
- It is not possible to specify hot water setpoints (e.g. heat pump, swing tank, supply setpoints). Therefore, inefficiencies due to excessively high setpoints may not be properly captured.

Those issues are further discussed and substantiated with data in a subsequent section of this paper and a survey of the existing literature suggests they have been encountered by other researchers (Banks et al., 2022; Nawaz et al., 2018; Valmiki et al., 2023).

Table 2 Difference in Observed Incremental Electricity Use and Modeled Projected Incremental Electricity Use (January-April 2023)

Difference between January-April 2022 and January-April 2023 (kWh)	Modeled Incremental Electricity Use (January-April)	Percent Difference
160,057	73,413	118%

Given these limitations in the modeling used for incentive program compliance, it may make sense to conduct more detailed, physics-based modeling of heat pump water heating systems prior to a retrofit.

Community-Wide Summary

Table 3 shows total DHW electricity use (based on submetering data) in April 2023 for 10 out of the 12 buildings (two buildings had incomplete data for April and were excluded). Historical gas use data is shown for 2021, to identify buildings with high historical water heating needs. Gas use is a good proxy for historical DHW loads in the case of this community because prior to November 2022 water heating was the only natural gas end-use.

Table 3 DHW Electricity Use Summary, with Historical Comparison, April 2023

Building	**Total Measured DHW Energy Use for April 2023 (kWh)**	**Historical Gas Use in MWh (Full Year 2021)**	**Heat Pumps Indoors or Outdoors?**
1	2159.451	58.2	Indoors
2	2064.436	50.5	Indoors
3	3981.29	50.5	Indoors
4	2498.736	50.7	Indoors
5	1112.946	63.1	Indoors
6	2214.989	53	Indoors
7	4304.592	73.3	Indoors
8	3171.977	Unavailable	Indoors
9	2566.914	74.8	Outdoors
10	669.0547	74.8	Outdoors

Load Shapes

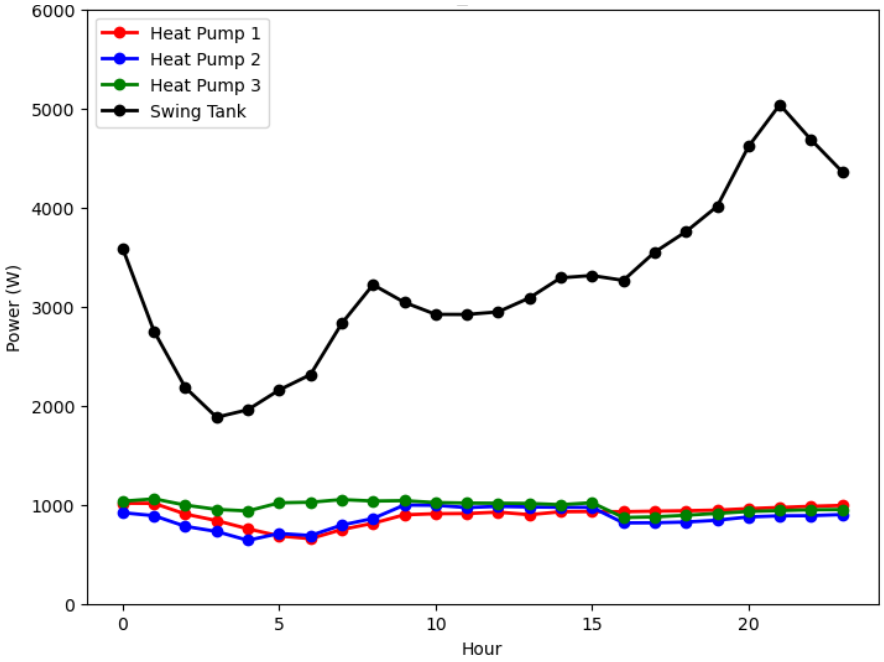

Figure 6 Average Load Shapes for Building 7, April 2023

Figure 6 shows the DHW load shapes for Building 7 in April 2023, prior to operational upgrades. The most notable pattern seen here is the apparent overreliance of this building on the swing tank for hot water. Given that the swing tank uses electric resistance heat, which can be three to four times less efficient at providing hot water than the HPWH, this is an undesirable outcome that increases energy use and costs. This building had the highest estimated increase in electricity bills from water heating in April ($2,414). Further exacerbating the issue of high utility bills is the fact that the swing tank appears to ramp-up backup heat provision between 4 p.m. and 9 p.m. Under SDG&E's TOU-DR1-Residential Rate to which this community is subject, the period between 4 p.m. and 9 p.m. is an on-peak period subject to elevated rates.

Building 3, another building exhibiting a high bill increase ($2,228 in April 2023), exhibits a similar pattern to building 7. Figure 7 clearly shows overreliance on the swing tank in comparison to the heat pumps.

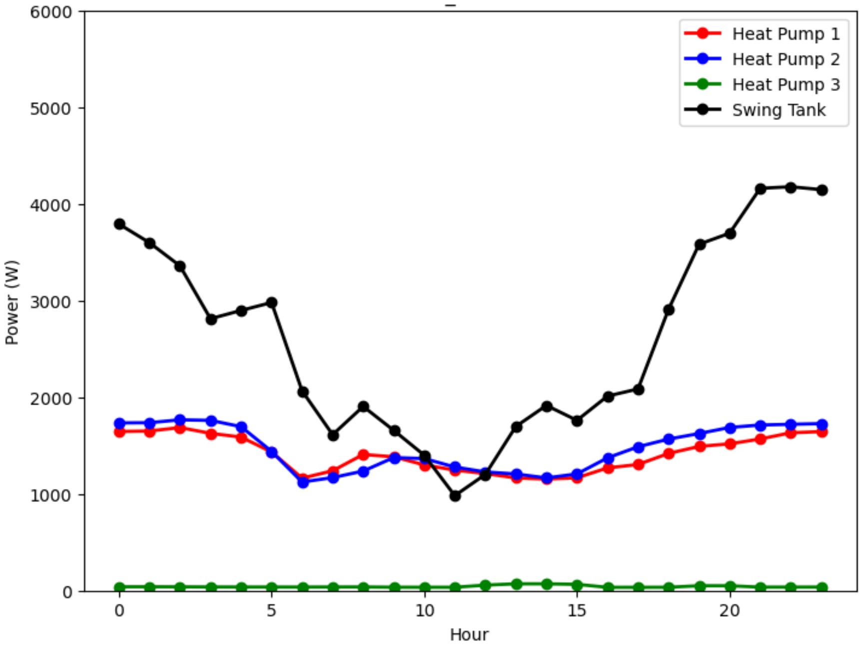

Figure 7 Average Load Shapes for Building 3, April 2023

A pattern that can clearly be seen here and is shared with other buildings is the insignificant operation of one of the three heat pumps and the simultaneous, near-identical operation of the other two. Further communication between the research team and the manufacturer suggests that the plumbing of three heat pumps in parallel may cause the internal water pumps in each outdoor unit to “compete” for flow, resulting in apparent imbalances seen in figure 6 and other figures within this paper. In the most extreme cases, a heat pump may go into error mode, resulting in non-operation. Six of the buildings monitored during that period showed imbalances in heat pumps operation (where one heat pump was either non-operational, or operating at a lower intensity than others).

Figure 8 shows the average load shapes for building 10, which saw the lowest (albeit still substantial at $1,059 in April 2023) increase in its electricity bills from electrification. In contrast to the prior two buildings, 459 shows minimal swing tank use. Interestingly, building 10 is one of two buildings where the heat pumps were located outdoors. Given that CO2 heat pump performance is highly dependent upon ambient air conditions (Nawaz et al., 2018), it seems as though the other buildings may not be properly ventilated. However, Building 9, the other building with outdoor heat pump placement, does not show markedly reduced electricity use, underlining that there are other issues impeding system performance in that building (and overall, that indoor heat pump placement is not the sole cause of system underperformance).

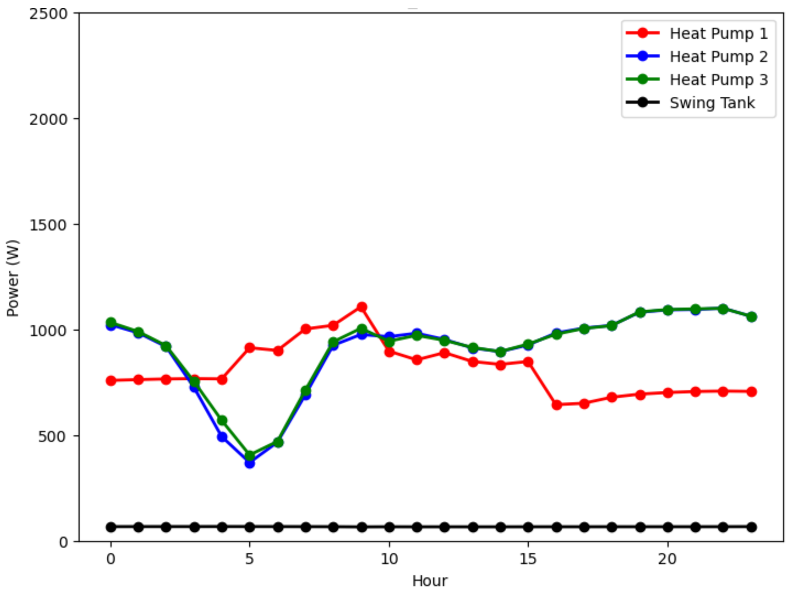

Figure 8 Average Load Shapes for Building 10, April 2023

Similarly, Building 1 (Load shapes shown in Figure 9), shows less pronounced reliance on the swing tank, with the heat pumps contributing more significantly to meet its water heating needs. Swing tank use spikes during the on-peak period as defined in the applicable tariff, which suggests that there is an opportunity for peak shifting as a cost mitigation strategy for this building.

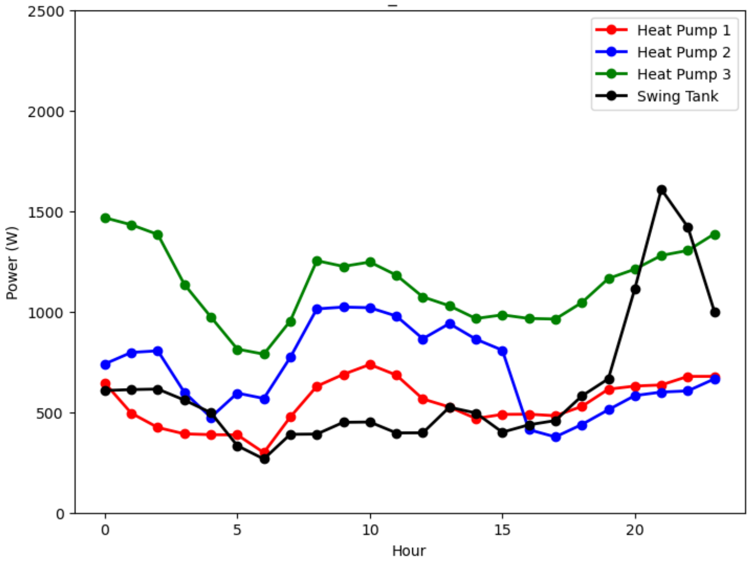

Figure 9 Average Load Shapes for Building 1, April 2023

Energy Costs

As seen in Figure 10, total energy bills (i.e., total energy billed to the common area meters in all 12 residential buildings, irrespective of end-uses) more than doubled during this period, compared to prior years. Electricity costs appear to be even more exacerbated than electricity use in the first four months of 2023, with increases in billing that are close to tenfold. This amplification is unsurprising, given the load profiles that are observed, and the fact that the community is subject to a time of use rate with evening peaks. Accordingly, and although out of the scope of the present study, load-shifting approaches may be useful in reducing the peak rate-driven amplification of energy costs.

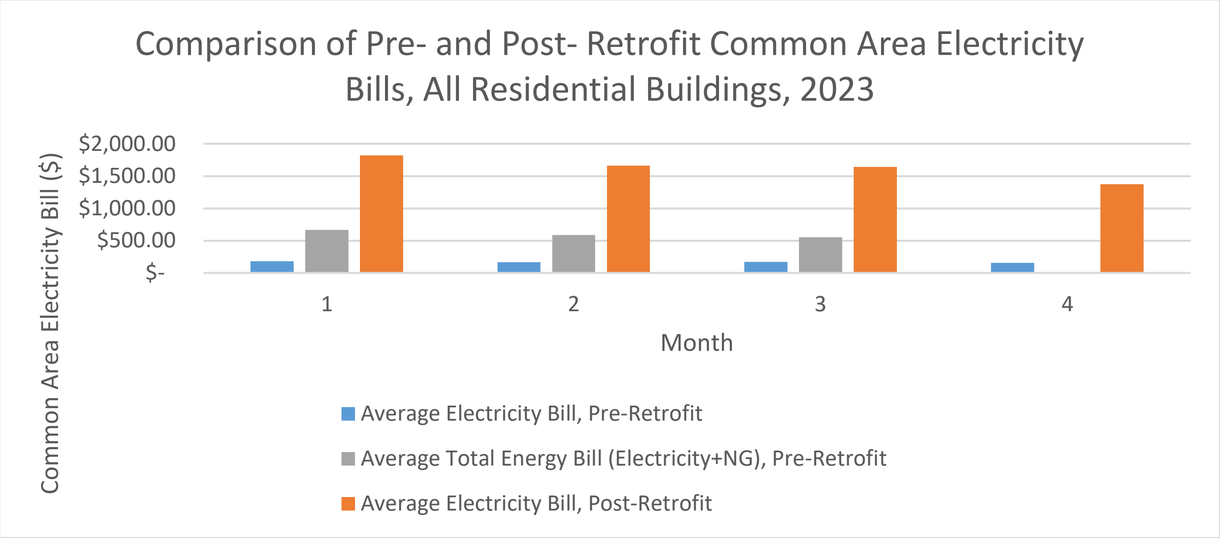

Figure 10 Comparison of Pre- and Post- Retrofit Common Area Energy Bills

One hypothesis that the team tested as to why costs were so exacerbated compared to the model was that the swing tanks were being used excessively. Figure 11, plotting the increase in DHW electricity cost against the contribution of the swing tank to that increase, shows a significant

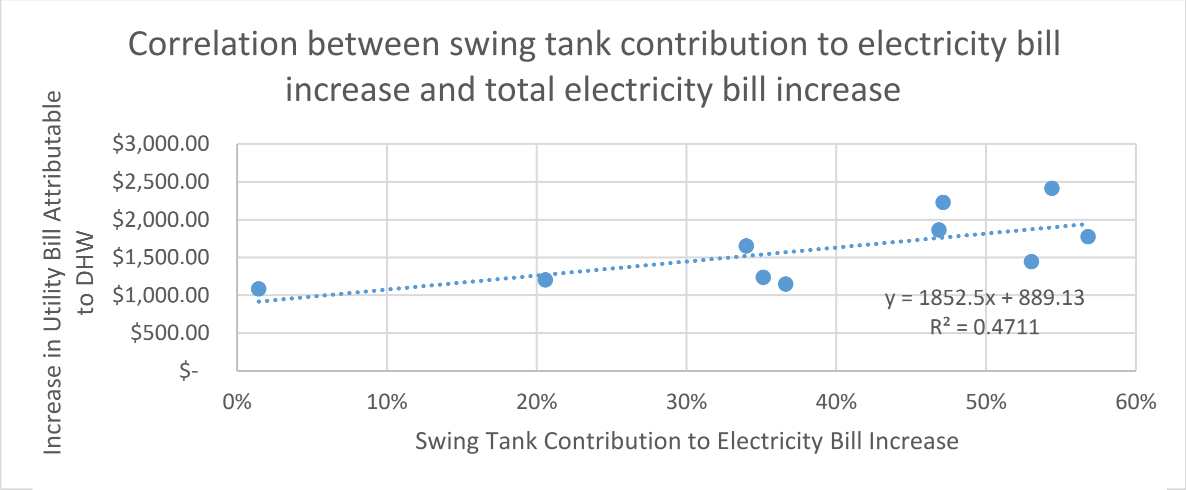

Figure 11 Correlation between swing tank contribution to electricity bill increase and total electricity bill increase.

correlation (R=0.69) between the percentage of the electricity bill due to the swing tank and the increase in the electricity bill.

Summary of observed operational irregularities.

By the end of April, it was apparent to the team that the following issues were impeding ideal operation of the system (and causing large deviations from modeled data):

- The ventilation of the enclosures was not meeting expectations, resulting in low temperatures. Although continuous monitoring of ambient air temperatures within the boiler rooms was not within the scope of the present study, a site visit revealed temperatures in the high-50s outside and in the low-30s inside the boiler rooms in one case. The indoor placement of the heat pumps in most buildings was potentially resulting in reduced performance.
- Excessive swing tank operation was conducive to increased electricity bills and needed to be controlled through a readjustment of the setpoint. Valmiki et al. emphasized the importance of properly controlling swing tanks in their review (2023).
- The parallel configuration of the heat pumps was causing imbalances in their operation, with a common pattern seen in multiple buildings where one of the heat pumps was either non-operational or showing irregularities. A similar issue had previously been identified by Banks et al. (2022), who recommended that redundancy be incorporated into CO2 HPWH designs.

Post-Retrofit, Post-Optimization Data (May-December 2023)

Interventions

The following operational improvements were finalized by the installing contractor by the end of April 2023:

- Where water heating loads allowed, a heat pump in each building was set to turn off from 4 to 9 pm.
- The swing tank temperature was reduced to 110F (from the original 140F), with the balancing valve on the return line set to 110F.

Energy Use

Figure 12 shows the recorded total energy use attributable to water heating systems (measured and scaled through submetering) in orange for every month starting April 2023. The gray bars represent modeled electricity use for every month starting in April 2023. Following the operational measures implemented in May, we see a significant decrease in measured DHW electricity use, and much better agreement with the cost-benefit model. Overall, deviation from the model drops from 119% in the first quarter to 20% during the remainder of the year. This substantial decrease reinforces the team's reasoning that swing tank control is critical in systems such as the one studied here. While excellent agreement is seen in the summer, significant deviations persist during the winter months (reaching approximately 50% deviation in December). Higher water heating loads may exacerbate issues that have been identified in this paper, such as excessively cold air inlet temperatures from indoor placement of the heat pumps, and plumbing imbalances.

Regarding modeling, it appears that simplified cost-benefit analysis tools, such as those used to qualify for incentive programs, may still fall short in properly reflecting system operation, and may need further calibration through a combination of (a) more detailed physics-based modeling, and (b) calibration based on field data.

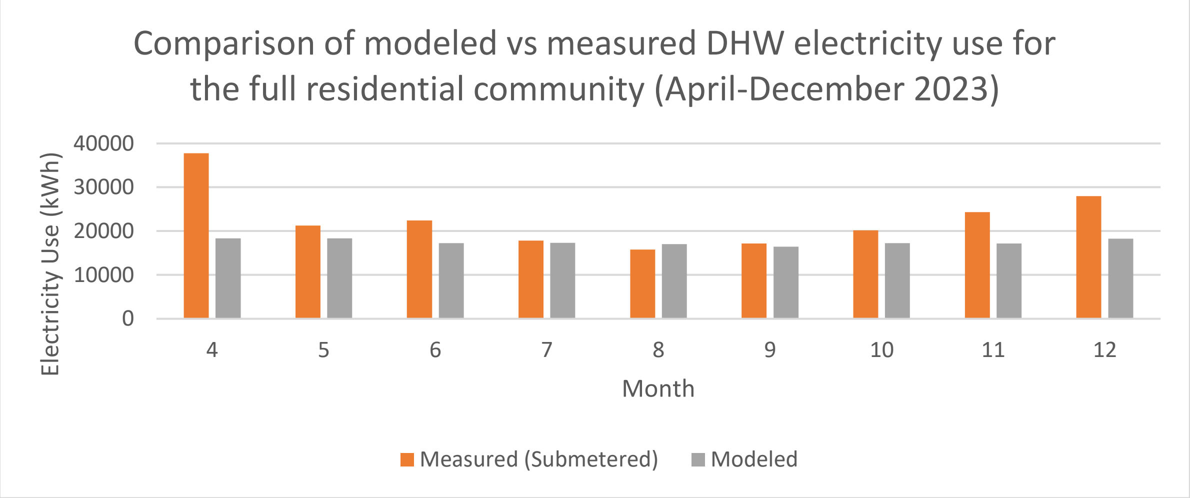

Figure 12 Comparison of measured and modeled DHW electricity use, Q2-Q4 2023

Load Profiles

Figure 13 shows the December load profile for building 7, previously discussed for April. Compared to April, energy use in December saw a 41% decrease. Given the typically increased hot water demand in December, this decrease is very significant. From Figure 14, it can be

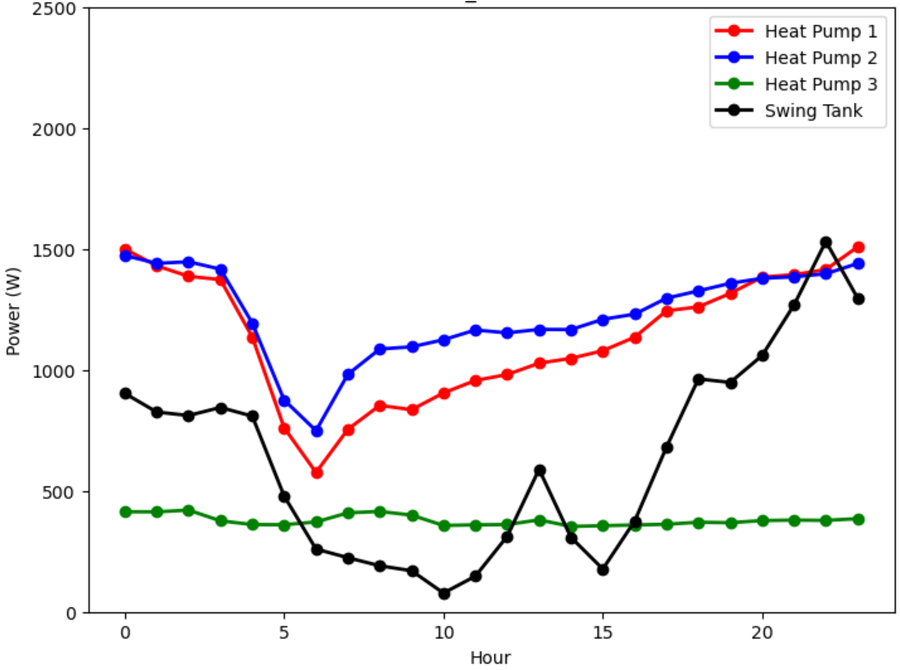

Figure 13 Average Load Shapes for Building 7, December 2023

inferred that this decrease is chiefly attributable to the improved usage patterns of the swing tank. The swing tank exhibits a much less extreme load profile than in April. Observing the proportion of DHW electricity use attributable to the swing tank tends to confirm this trend, with a significant decrease from April (54%) to December (19%). Figure 13 shows the December load profiles for building 3, which exhibits a similar, albeit less pronounced change as that seen in building 7. Namely, swing tank use decreases significantly, with the proportion of DHW electricity use attributable to the swing tank dropping from 47% to 33%. Heat pump usage patterns, conversely, are reasonably comparable between April and December. While building 451 saw a 45% decrease in its DHW-attributable electricity bills, building 439 only saw a 23% decrease. This comparison further reinforces the notion that for this community, controlling swing tank use is a critical action item for limiting elevated electricity bills.

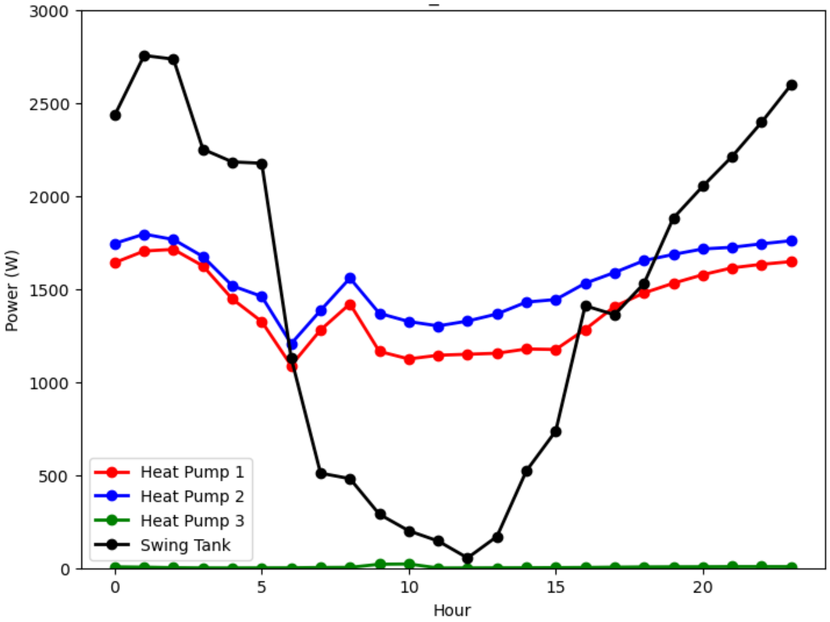

Figure 14 Average Load Shapes for Building 3, December 2023

For this building, it seems that defects in the operation of Heat Pump 3 may be triggering excessive swing tank operation. Banks et al. (2022) similarly found that for heat pump water heating designs that incorporate backup electric resistance heating, significant departures from normal (i.e., as designed) heat pump operation can lead to excessive, and undesirable, electric resistance energy use. As previously mentioned, the authors of that study suggested that oversizing the heat pump system by adding an additional heat pump may be a beneficial strategy, where increases in capital costs can be offset by a reduction in operating costs from “contribution of the added heat pump: reduced operation hours under normal conditions, less contribution from backup systems, and recovery during periods of failure of one or two heat pumps” (Banks et al., 2022).

For both buildings discussed in this section, imbalances in heat pump electricity use (hypothesized to be due to imbalances in plumbing according to the manufacturer) are a persistent issue that the research and maintenance teams are still investigating at the time of writing.

Energy Costs

Figure 15 shows the changes in energy costs incurred by the electric water heating system over the course of the April-December 2023 timeframe. As with energy use, there is overall a remarkable decrease in energy bills, even as DHW energy use ramps up towards the end of the year.

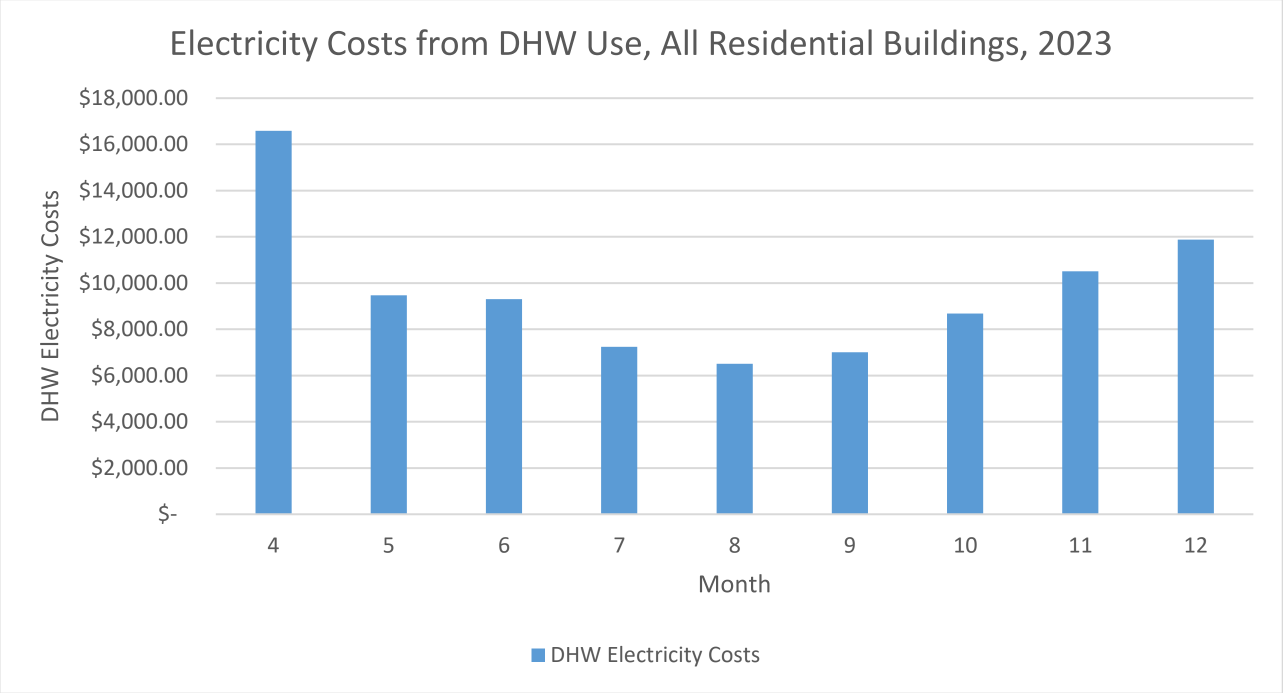

Figure 15 Energy Costs Attributable to Domestic Hot Water, All Residential Buildings, April to December 2023

Conclusion

Ultimately, this project is a useful demonstration of the different issues that may be encountered when retrofitting centralized water heating systems in multifamily buildings. The main conclusions from this study are the following:

- **Proper Modeling is Critical:** The modeling used for compliance with incentive programs may not be of the granularity required for effectively designing retrofits, particularly for centralized water heating systems, where operation and plumbing can be highly heterogeneous. Further calibration is required to make those low-cost tools more reliable.
- **Electrification retrofits are not "plug and play" processes:** The present study required a significant course correction in system commissioning, accompanied by comprehensive analysis, to bring electricity bills down from their unexpectedly high numbers in the first quarter of 2023. Given the sensitivity to time of use rates in this service territory, controls (notably temperature setpoints) were a major focus of the study. Furthermore, significant operational issues that may not have been captured by most typical energy modeling packages (such as plumbing imbalances) have required significant, ongoing

troubleshooting. All those findings reinforce the point that those increasingly complex systems will require more involved monitoring (Banks et al., 2022).

Acknowledgments

The authors thank the Association for Energy Affordability (AEA), Bottom Line Utility Solutions, and Eco2 Systems LLC for their collaboration and assistance.

References

Banks, Adria, Colin Grist, Jonathan Heller, and Hyunwoo Lim. "Field Measurement of Central CO2 Heat Pump Water Heater for Multifamily Retrofit." Sustainability 14, no. 13 (2022): 8048.

CSD (Community Services and Development). 2019. Low-Income Weatherization Program Guidelines. Sacramento, CA: California Department of Community Services & Development. www.csd.ca.gov/Shared%20Documents/LIWP-MF-Program-GuidelinesAmended-2019.pdf.

“California Climate Credit.” California Public Utilities Commission. Accessed June 6, 2024. https://www.cpuc.ca.gov/climatecredit

Eco2 Systems LLC. 2021. “SANCO2 Heat Pump Water Heater.” https://www.eco2waterheater.com/_files/ugd/e88920_293f399a2a3a432396b1805a76f21c80.pdf.

Nawaz, Kashif, Bo Shen, Ahmed Elatar, Van Baxter, and Omar Abdelaziz. "Performance optimization of CO2 heat pump water heater." *International Journal of Refrigeration* 85 (2018): 213-228.

“Time of Use, TOU, Pricing Plans, TOU Pricing Plans | San Diego Gas & Electric,” n.d. https://www.sdge.com/residential/pricing-plans/about-our-pricing-plans/whenmatters.

Valmiki, M. M., P. E. A. S. K. Energy, Treasa Sweek, P. E. Ecotope, Madison Johnson Ecotope, and Scott Spielman. "Commercial and Multifamily CO2 Heat Pump Water Heater Market Study and Field Demonstration." (2023)