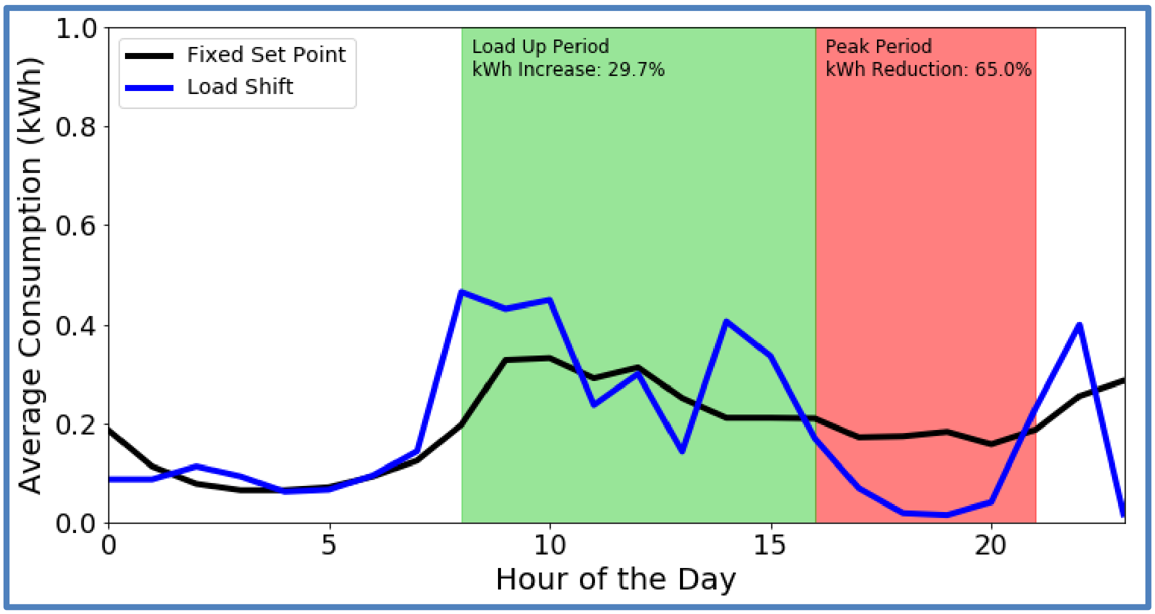
Evaluation of Unitary Heat Pump Water Heaters With Load-Shifting Controls in a Shared Multi-Family Configuration

ET Project Number: ET18PGE1901



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ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ANSI	American National Standards Institute
API	Application Programming Interface
Btu	British Thermal Unit
BPA	Bonneville Power Administration
CAISO	California Independent Systems Operator
CO_2	Carbon dioxide
CBECC	California Building Energy Code Compliance
cfm	Cubic feet per minute
CSV	Comma separated value
COP	Coefficient of Performance
DOE	United States Department of Energy
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
Energy Commission	California Energy Commission
gpd	Gallons per day
GHG	Greenhouse gas
HPWH	Heat pump water heater
kW	Kilowatt
kWh	Kilowatt-hour
MADIS	Meteorological Assimilation Data Ingest System

NEEA	Northwest Energy Efficiency Alliance
NOAA	National Oceanic and Atmospheric Administration
NRDC	National Resources Defense Council
PG&E	Pacific Gas and Electric Company
PV	Photovoltaic
RH	Resistance Heating
RMSE	Root Mean Squared Error
RTD	Resistance Temperature Detector
SCE	Southern California Edison
SMUD	Sacramento Municipal Utility District
T	Temperature, °F
TDV	Time Dependent Valuation
TOU	Time of use
U	Heat transfer coefficient, $^{Btu}/_{h \cdot ft^2 \cdot °F}$
UA	Product of "U" (heat transfer coefficient) and surface area "A"
UEF	Uniform Energy Factor
ZNE	Zero Net Energy

FIGURES

TABLES

CONTENTS

EXECUTIVE SUMMARY

PROJECT GOAL

The primary goal of this project was to demonstrate through detailed monitoring and modeling, the operating performance, and grid and carbon impacts of unitary heat pump water heaters (HPWHs) with load-shifting controls in a multi-family application where the HPWH is shared among multiple apartments. The shared configuration offers reduced construction costs but presents potential challenges in serving multiple apartments under coincident hot water load events. This study evaluates: 1) the ability of the units to meet hot water demand, 2) utility cost and carbon impacts, and 3) the effectiveness of load-shifting strategies in terms of building load mid-day and shedding load during peak periods.

PROJECT DESCRIPTION

Frontier Energy was funded by PG&E in 2017 to provide Zero Net Energy design consulting support of the 90-unit Creekside affordable multi-family project in Davis, CA. The resident population targeted for the project includes 25% extremely low-income occupants. 40% of the units are for individuals who are disabled, currently homeless, or have other special needs. Over 90% of the apartments are single bedroom units with the remainder being two bedroom units. As part of the evaluation, R-410A heat pump water heaters (HPWHs) using load-shifting controls while serving four apartments in close proximity to the water heater were used as an efficiency measure. Potential benefits of the "shared load-shifting strategy" include reduced installation, replacement, and maintenance costs; operation biased to reduce mid-day grid renewables curtailment; reduced peak electrical demand; reduction in CO_2 emissions; and reduced utility costs under time of use rate structures.

PG&E's interest in the shared HPWH design concept led to this project which focuses on the detailed monitoring of ten of the 23 installed 80 gallon unitary HPWH's (3.70 Uniform Energy Factor) over an 18 month period, field testing of both conventional and load-shifting HPWH operation, and use of a validated simulation model to allow for annual projections of energy consumption, CO_2 emissions, and utility cost impacts for the various configurations under standardized hot water loads and evaporator inlet air conditions.

PROJECT FINDINGS/RESULTS

The most important project findings include:

- A shared HPWH configuration (four single occupant apartments per 80 gallon unitary HPWH) are projected to outperform individual 50 gallon HPWHs (one per apartment) in terms of first cost (~$1,850 per apartment cost savings), energy usage (13-32% reduction), annual CO_2 emissions (16-36% reduction), and operating costs (10-32% reduction). Lower hot water loads translate to higher savings impact.
- An optimal load-shifting control with the shared HPWH configuration is projected to generally outperform individual 50 gallon HPWHs without load-shifting in terms of

energy usage (3 to 24% reduction), CO_2 emissions (11 to 35% reduction), and on-peak energy usage (27 to 82% reduction).

- The above benefits are generally highest at low and medium hot water load levels and diminish under very high hot water loads as more 2nd stage (resistance heating, possibly with the heat pump compressor active simultaneously) resistance heat operation is needed to maintain set point and successfully complete load-shifting.
- A larger 1 ton compressor for the shared 80 gallon HPWH configuration is projected to outperform the standard sized compressor by 11-14% in both energy usage and CO_2 emissions due to reduced 2nd stage operation and improved load-shifting performance. This translates to improved utility bill savings, ranging from 6-26% under medium and high load cases.

More detailed findings follow:

Monitoring

Ten of the 23 HPWH's, each serving four apartments, were monitored over an 18 month period (June 2020 to November 2021) to assess performance under various conventional (fixed set point) and load-shifting (varying set point) control strategies. Covid-19 slowed occupancy rates resulting in the formal 12 month monitoring period being October 2020-September 2021. Detailed monitoring including hot water flow data, energy consumption, cold and hot water temperatures, and HPWH ambient air conditions were logged continuously. The HPWH manufacturer's Application Program Interface (API) was used to remotely control scheduling of the various control strategies. Due to the high degree of variability in hot water loads/patterns and operating conditions, results are presented as aggregated findings for fixed set point and load-shifting operation. Key findings include:

- Hot water usage of the ten HPWHs averaged 92.0 gal/day over the nominal annual reporting period, with average daily usage ranging from 52.6 to 168.9 gal/day.
- Averaged over all modes of operation, the annual COP for the ten HPWH's was 1.96, ranging from 1.58 to 2.17. The 1.58 COP HPWH was subjected to the highest average hot water use over the 12 months (169 gpd), causing 67% of the unit's annual energy consumption to be 2nd stage heating. This unit was also subjected to the greatest amount of high volume draws (25% of all hot water flow was part of draws greater than 30 gallons). These large draws resulted in 9.3% of all hot water flowing from the mixing valve below 112°F, triggering increased 2nd stage operation.
- In comparison, only 8.9% of the hot water flow from the other 9 HPWHs came from events over 30 gallons, with 4.7% of flow leaving the mixing valve below 112°F.
- HPWH energy use seasonality is best expressed in terms of kWh per 100 gallons of hot water delivered. Averaged over all operating modes, HPWH usage ranged from 8.4 kWh/100 gallons delivered at an average evaporator air inlet temperature of 53°F (mid-winter), to a low of about 3.0 kWh/100 gallons at an average evaporator air inlet temperature of 82°F (mid-summer). This finding reinforces HPWH performance variability with climate and load and highlights the need for more than a single numeric metric to assess water heater efficiency.
- On average over the course of the 12 month monitoring period, load-shifting operation decreased on-peak (4-9 PM) energy use by 68% relative to the fixed set point case and increased use by 39% during the 10 AM to 4 PM load-building period.

Simulation Model Development

To further evaluate system performance the project team developed the Flexible HPWH Performance Predictor (Flexi-HPWH). This Python-based tool is designed to easily accept either monitored or modeled input data and draw from a library of load-shifting control strategies and HPWH control logic functions. Flexi-HPWH uses a multi-node storage tank model to track water temperature at different heights in the tank and emulates the observed performance and control decisions of the heat pump and resistance elements.

Flexi-HPWH validation consisted of: 1) comparing simulated and monitored operation under specific behavioral cases, 2) verifying simulation output against monitored data in three to seven day periods, and 3) ensuring simulation outputs match monitored data over the full year of monitored data. When compared to one year of data for three different magnitude draw profiles[1], Flexi-HPWH outputs were within -5.4 to 1.2% of monitored data for annual electricity consumption and 2.8 to 9.1% of annual 2nd stage electric resistance energy consumption. The reduction in annual peak period electricity consumption was within 2.2 to -11.9% for the three cases studied.

Simulation Model Findings

The Flexi-HPWH model was used to evaluate annual HPWH performance under different control strategies, three different magnitude hot water draw profiles (**L**ow, **M**ed, and **H**igh), climate zones, and HPWH design choices. This included testing different control strategies designed to optimize electricity consumption at different times of day, evaluating the impact of number of dwellings served by each HPWH, projecting HPWH performance in different California climate zones, and evaluating HPWHs with different storage tank and/or compressor sizes. Key findings from the simulation study include:

- Assuming a HPWH serving four apartments, the preferred load-shifting mode has the potential to reduce annual 4-9 PM on-peak electricity consumption by 57 to 73% depending on the hot water load magnitude.
- Implementing load-shifting by abruptly increasing the HPWH set temperature will cause 2nd stage heating and dramatically increase electricity consumption. Utilizing a stepped strategy, where the set temperature increases gradually, reduces this effect substantially. The preferred stepped load-shifting strategy is projected to reduce electric resistance usage by 53 to 84% across the L to H load profiles when compared to a sudden set point change load-shifting strategy.
- HPWH performance is highly impacted by climates with colder air and colder inlet water temperatures, resulting in more 2nd stage resistance heating and lower efficiencies. HPWHs in California's coldest climate zone (16) are expected to use approximately twice as much electricity under the M load profile than units installed in the coastal Los Angeles climate zone (6) when implementing load-shifting.
- Simulations using a larger 1 ton compressor are projected to reduce annual shared configuration electricity consumption (relative to nominal compressor size) in fixed 125°F set point operation by 11-14%, electric resistance consumption by 69-76%, 10-13% reductions in annual CO_2 emissions, and small impacts on on-peak consumption. The annual on-peak kWh reductions in the preferred load-shifting mode under M and H load profiles was found to be 33% relative to the load-shifting

[1] Low (L), medium (M), and high (H) hot water usage profiles at 67, 92, and 120 gal/day, respectively.

shared HPWH with a standard compressor, indicating that the larger compressor capacity enables improved load-shifting performance.

- Annual utility bill projections for 50 gallon HPWHs serving each apartment indicates that preferred load-shifting controls will increase annual utility costs by an average of 12% with the PG&E TOU-C rate structure, and by 4% with a hypothetical more aggressive TOU schedule. Improved TOU rate structures and better control of 2^{nd} stage heating during periods of overheating tank storage will improve these results.

Assessment of Shared HPWH Configuration

The shared HPWH approach implemented at Creekside offers first cost reductions against both central gas water heating and individual 50 gallon HPWHs for each apartment. Costs provided by the developer for the Creekside project and another related project indicate that plumbing costs for the Creekside shared designs should be ~$1,600 (central gas) to $1,850 lower (individual HPWH) per apartment. This will vary with the building design. Replacement and maintenance costs should also be lower over time as there are fewer water heaters to maintain. Potential downsides include greater potential for hot water loads exceeding heating capacity (i.e. run outs) and more occupants impacted by equipment failure (four apartments impacted rather than one).

The 4 apartment shared HPWH performance projections were compared to individual 50 gallon HPWHs for the L, M, and H hot water load cases at 125°F fixed set point. In terms of annual energy use, the shared configuration reduced per apartment kWh by 32%, 13%, and 14% for L/M/H, respectively. Additional comparisons between the shared HPWH operated in the optimal load-shifting mode relative to the fixed 125°F individual HPWH showed significant benefits. Simulations projected annual kWh reductions of 24% and 2%, for the L and M cases, respectively, with a 1% increase for the H case. 4-9 PM on-peak kWh reductions ranged from 63-81%. Projected annual CO_2 reductions were much higher in the L case (36%) due to the relative magnitude of standby loss impacts, with M and H CO_2 reductions projected at 5-11%. Changing from a 4 apartment per HPWH scenario to a 3 apartment assumption, resulted in minor improvements in energy usage and CO_2 due to the reduced loading triggering 2^{nd} stage heating less frequently.

Lessons Learned

Key findings related to the Creekside project include:

- The HPWHs at Creekside were installed in small closets with limited air volume and flow. Early operation in May 2020 confirmed that an exhaust duct was needed to avoid cold exhaust air recirculation into the evaporator to improve system performance. Uninsulated flex duct (due to closet physical constraints) was installed in June 2020 on all units and all monitoring results presented here include the impact of the ducted configuration. Appendix B contains an assessment of cases with and without ducting. Although the Creekside ducted configuration reduces evaporator airflow, the ducting was projected to reduce annual energy consumption by 14% relative to a non-ducted cramped closet case. Further lab work on closet performance is underway as part of a Northwest Energy Efficiency Alliance project.
- The shared configuration at Creekside has benefits including reduced first cost, elimination of additional water heaters (including associated embodied energy with less equipment), and close proximity to the apartment eliminating any need for recirculation loops. Performance for some of the highest loaded units was clearly

impacted, indicating that further research guiding high-performance shared HPWH system design is needed.
- Simulation algorithms for closet performance (with and without ducting) and shared configurations are needed, especially for Title 24 compliance software.
- The highly variable hot water usage from the ten monitored HPWHs highlights the importance of continuing to expand the dataset of multi-family hot water load profile data to improve both energy usage modeling and HPWH sizing tools.
- The manufacturer's Application Programming Interface (API) for remote scheduling and onboard data downloading needs improvement to be a fully reliable and secure system. CTA-2045, a modular device communication interface from the Consumer Technology Association, includes a new Advanced Load-Up control option which may perform better.

PROJECT RECOMMENDATIONS

Shared HPWHs and load-shifting are both new technologies that are not well understood by industry. A design guide providing sizing and control recommendations by climate and number of dwellings would support industry adoption. Additionally, further study is needed to better understand current industry practices for multi-family building types.

Flexi-HPWH is a publicly available[2], flexible simulation model for HPWHs. Improving identified limitations or expanding Flexi-HPWH's capabilities would yield more accurate results. Additional lab and field testing could provide data sets to:

- Verify or improve the in-tank heat transfer and COP calculations;
- Better understand the currently ambiguous control logic elements and update Flexi-HPWH accordingly;
- Collect performance and control data on HPWHs from other manufacturers and add them to Flexi-HPWHs library.

Laboratory testing can expand the findings from this project by evaluating performance in a controlled environment. Laboratory testing should evaluate:

- The impacts of various closet ventilation solutions;
- Evaluate the performance of products from multiple manufacturers including developing performance maps, understanding water flows inside the tank, and emulating the logic of their on-board controllers;
- Test CTA-2045's Advanced Load-Up feature and the impacts of using that communication strategy to implement load shifting;
- Compare shared vs. individual HPWHs in a controlled setting; and
- Determine the benefits of using either a drain water heat recovery device, solar thermal, or an additional HPWH (per apartment building) to pre-heat water and reduce the heating load on all (or only the most heavily loaded) HPWHs.

Simulation results indicate that the shared configuration offers significant benefits relative to individual HPWHs in a multi-family application. The capability to model this configuration should be added within the Title 24 compliance models.

2 https://github.com/PeterGrant/Flexi-HPWH

INTRODUCTION

Heat pump water heaters (HPWHs) represent an important technology that will play a central role in California's aggressive move towards electrification of the building sector. There is currently considerable effort underway to promote the technology, accelerate market uptake through incentives, and other initiatives to address market barriers. The California Public Utilities Commission (CPUC) sponsored TECH program is underway and provides $120 million in funding to advance California's move to carbon neutrality in 2045 by leading market transformation efforts in promoting HPWHs and space conditioning heat pumps[3]. Other programs such as the CPUC's Self Generation Incentive Program (SGIP) which will add a HPWH program in 2022[4], as well as various utility programs[5] which continue to promote and incentivize HPWH installations.

Unitary HPWHs are complex products, with two distinct modes of heating: compressor only which provides all heating via the heat pump, and 2nd stage operation which utilizes electric resistance elements to supplement compressor output. HPWH controls rapidly change the operating mode and the resulting operating efficiency, depending upon the operating environment, tank conditions, and hot water demands. The heat pump compressor in most available products is typically rated at 400-600 W. Depending on the water and air temperatures available, the compressor operates at a Coefficient of Performance (COP) ranging from 1.1 – 5 (Grant, Peter; Huestis, Eddie, 2018) . Efficiency generally improves with warmer surrounding air temperatures and cooler tank temperatures, and decreases with colder surrounding air and hotter tank temperatures. A compounding factor affecting performance is the pattern and intensity of hot water loads. Moderate hot water loading with demands reasonably spaced out allow the ~1/3 ton capacity compressor to perform most or all of the heating. If loads are too high and concentrated, the HPWH controls will energize 2nd stage heating which adds resistance element operation (nominally 4.5 kW) to the compressor output heating the water in the tank quickly, but greatly reduces operating efficiency. Second stage operation is most commonly used when the heat pump compressor is not able to provide enough heat to avoid sending cool water to the occupants, but can also be used in case of compressor failure or under low ambient air conditions (when the compressor is locked out to avoid freezing the coil).

A HPWH's storage volume (50-80 gallons for unitary equipment) and availability of an efficient compressor allows for the units to operate under load-shifting control strategies. It is entirely possible to adjust the HPWH tank set point such that the onboard controller prioritizes use of the highly efficient compressor to preferentially increase the temperature in the tank. This could occur in late morning to early afternoon periods, which are generally off-peak under current California residential utility rate structures, and also coincide with high levels of photovoltaic generation on the grid. This pre-heating would allow for later reducing the tank set temperature during the evening peak period while allowing occupants

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[3] https://energy-solution.com/tech/

[4] https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/self-generation-incentive-program

[5] https://www.smud.org/en/Corporate/Landing-Pages/PowerMinder

access to additional stored hot water, significantly reducing heating operation during the peak period.

Understanding the impacts and benefits of HPWH load-shifting performance in the field is an important step as California moves to widespread building electrification. This project explores load-shifting performance by monitoring ten HPWHs at an affordable multifamily project located in Davis, California. Three aspects of this project make it especially unique:

1. The installed HPWHs each served four single occupant apartments rather than utilizing a more conventional multifamily design of either a central hot water system or a "per apartment" water heater configuration. This semi-central approach coupled with the apartment design results in a compact hot water distribution configuration eliminating the need for a hot water recirculation system. In addition to the distribution system performance impacts advantages associated with the shared configuration, there are also construction, replacement, and operating cost benefits.
2. The development of a detailed simulation tool to model both fixed setpoint control and a range of load-shifting control strategies. The model is able to utilize either high resolution monitored input data (hot water usage, ambient air conditions, inlet water temperatures, etc.) or can utilize standardized input data from simulation models, such as the CBECC-Res Title 24 compliance software.
3. The integration of greenhouse gas (GHG) emissions data from the California Independent System Operator (CAISO), corresponding to the monitoring period duration, was used to assess the "real time" GHG impacts of the various strategies.

BACKGROUND

Residential unitary HPWHs have been a niche water heating technology in this country for thirty years or more, but in recent years the technology has started to gain traction as the most recent Department of Energy standards require consumer electric storage tanks greater than 55 gallons to have heat pump technology (i.e. compressor driven). Nationally roughly half of the 8.7 million residential water heaters sold in the United States (AHRI 2018) each year are natural gas with the remainder electric (primarily electric storage). An estimated 72,000 HPWHs were sold in the United States in 2017 (Granda 2019), indicating that the HPWH market is still in its infancy. In California, widespread natural gas availability, a historical Title 24, Part 6 push toward gas water heating, and favorable natural gas rates in much of the state (relative to electric rates) have contributed to a statewide residential gas water heater saturation rate of 86 percent (DNV GL Energy Insights USA, Inc., 2020).

Figure 1 presents a schematic showing the basic configuration of most unitary HPWHs currently on the market. The right side of the image depicts the HPWH with a cutout showing the inside of the tank with the various heating elements (tank wrap-around heat exchanger and immersion electric elements) and the water and air flow paths when the system is in use. The image to the left shows an expanded view of the heat pump vapor compression components, physically contained in the space above the hot water storage tank. When the HPWH's compressor is operating, ambient air is forced across the evaporator coil, extracting heat and therefore cooling the evaporator outlet air stream. Heat extracted at the evaporator coupled with the mechanical work of the compressor generates the heat that is transferred to the storage tank with efficiencies much higher than a conventional electric storage water heater.

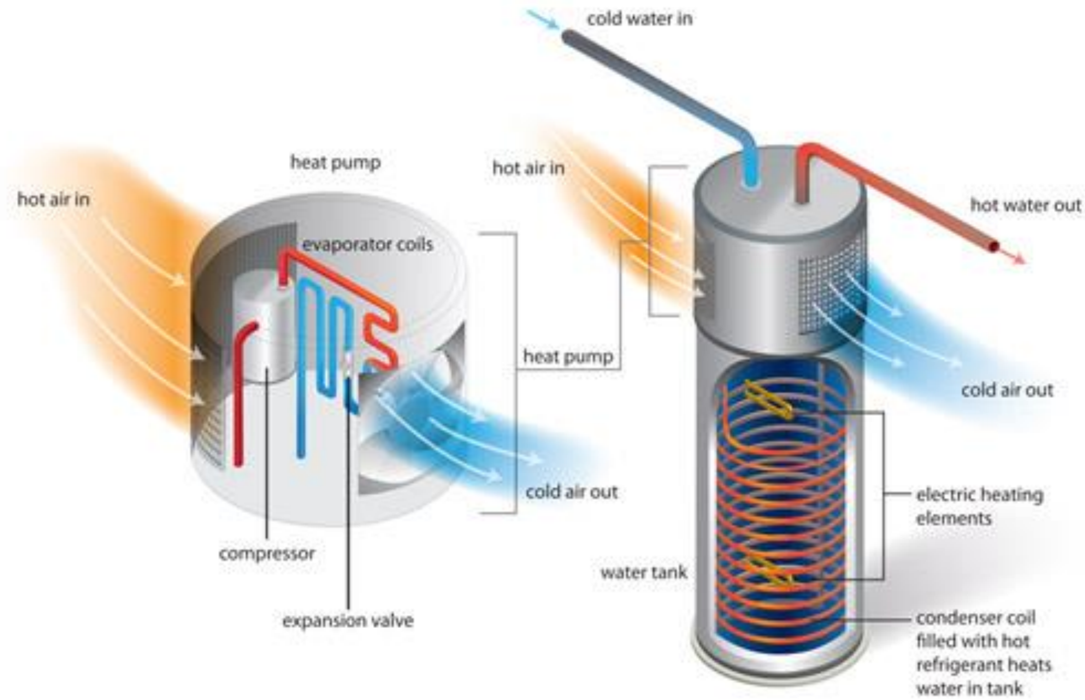

FIGURE 1: HPWH SCHEMATIC
IMAGE CREDIT: MARJORIE SCHOTT/NREL

Since unitary HPWHs generally feature small compressors, operating cycles are considerably longer than conventional water heating technologies (on the order of hours per cycle versus partial hours for a gas water heater). Both gas water heaters and electric resistance storage water heaters have greater heating capacities than the HPWH compressor. If the compressor alone is unable to maintain tank temperature during high hot water draw events, supplemental electric resistance heating is energized (i.e. 2nd stage operation)[6]. The HPWH's integrated storage offers the potential of utilizing that volume for load-shifting by biasing electrical demand away from utility peak load events. Load-shifting operation could bias operation to the middle of the day (around solar noon) to maximize the use of available renewable generation resources on the California grid and reduce the later on-peak use of non-renewable generation resources. When operated in this manner, storage can ideally be charged efficiently beyond the normal set point using exclusively the HPWH compressor. With load-shifting, a tempering valve is a necessary feature to ensure that the delivered hot

[6] For the HPWH studied here, 2nd stage operation can be both independent of or coincident with compressor operation, depending upon inputs to the control algorithm and operating conditions.

water is maintained at a safe temperature. The tempering valve is set at approximately 120°F and will mix cold water with hot tank water as needed.

Most HPWHs have multiple user-selectable control modes including "hybrid", "electric only", and "heat pump only" which alter the control (and the resulting efficiency) of the heating operation. Hybrid is the generally preferred mode for most customers and also the default mode, as it gives priority to the efficient compressor operation while allowing the controls to select backup electric supplemental heating to better ensure that adequate hot water delivery is maintained. These transitions from compressor operation to 2nd stage heating can occur with a tipping point event (minor hot water draw at the wrong time), resulting in excessive energy usage when it is not really necessary. Hence, patterns of hot water usage and intensity have a strong influence on system performance. Finally, "electric only" operation provides for a similar resource as the conventional electric storage water heater, but with no efficiency advantages.

Significant work has been completed in recent years on the impacts and benefits of load-shifting with HPWHs. The Electric Power Research Institute (EPRI) has been actively involved in testing and evaluating the technology as well as developing the standardized Consumer Technology Association CTA-2045 communications protocols to facilitate grid interconnectivity (Electric Power Research Institute 2015). A Pacific Gas and Electric (PG&E) funded laboratory test evaluated four HPWHs in a variety of modes to assess performance impacts of boosted temperature storage, response of HPWH controls to different test conditions, and impact of load-shifting utilizing 2016 TDV values (Grant and Huestis 2018). A 2018 American Council for an Energy Efficient Economy Hot Water Forum presentation by the National Resources Defense Council (NRDC) and Ecotope on HPWH demand flexibility (Delforge and Larson 2018) focused on the modeling of different load-shifting strategies utilizing the detailed Ecotope HPWH simulation model.[7] Findings indicated that when load-shifting is driven by utility marginal costs (rather than the Time Dependent Value -TDV- metric), greater value can be realized since marginal costs are more volatile than TDV values. Finally, a large Bonneville Power Administration (BPA) field study in the Pacific Northwest tested 277 electric storage and HPWHs in a large demand response demonstration pilot to assess the capabilities and impacts of water heater demand response control utilizing CTA-2045 (Bonneville Power Administration 2018). The BPA study was significant in demonstrating the benefits in a larger pilot study including load-shifting impact, occupant satisfaction, and effectiveness of the CTA-2045 communications strategy in controlling HPWH load-shifting operation.

Under the 2016 Title 24, Part 6 Standards development process, a detailed HPWH modeling methodology developed by Ecotope was added to the CBECC-Res compliance software (Kvaltine, N; Logsdon, M; Larson, B 2016). This significantly enhanced the modeling capabilities of the compliance software as it was derived from detailed model-specific lab testing sponsored by the Northwest Energy Efficiency Alliance to support utility program efforts in the Pacific Northwest. The new model improved the recognition of HPWHs relative to gas water heating under Title 24, but the use of a gas tankless water heater as the prescriptive standard still contributed to compliance challenges for HPWHs.

[7] The model is currently integrated in CBECC-Res for modeling of standard HPWH operation.

Under 2019 Title 24, Part 6 Standards activities, the Energy Commission developed an electric baseline, which allowed electric water heating to be compared to a minimum efficiency HPWH rather than a gas tankless water heater. This, in conjunction with increasing interests among many California municipalities to adopt policies supporting electrification (Building Decarbonization Coalition 2019), has spurred attention towards HPWHs heading into the 2022 Title 24 code development cycle.

California utilities are also initiating pilots and programs to move the load-shifting HPWH (LSHPWH) approach into the marketplace. The Sacramento Municipal Utility District (SMUD) currently has a pilot project underway (Sacramento Municipal Utility District 2019) with plans to start a full-fledged LSHPWH program in the coming years (Rasin 2019), and PG&E expects to begin a five-year program with a 5 MW load-shift goal in 2022 (Brown 2019).

In July 2022, the California Energy Commission adopted JA13 which outlines the requirements of a unitary HPWH that qualifies as a demand management system capable of shifting electrical demand from on-peak periods to off-peak periods (California Energy Commission, 2020). The motivation for adoption was the Energy Commission's understanding that as the building sector continues to move toward electrification, it is critically important that the new electrical load to be added is compatible with an electric grid that relies heavily on renewables driven by daytime PV generation. Pre-heating strategies that raise the tank temperature prior to utility peak periods are required to "avoid use of electric resistance elements unless user needs cannot be met", highlighting the importance of achieving load-shifting in an efficient manner.

A recent California field research study on advanced unitary and central HPWH performance in multi-family applications was completed in mid-2021 (Dryden, Brooks, & Duff, 2021). This California Energy Commission Electric Program Investment Charge (EPIC) funded project was led by the Association of Energy Affordability. One of the four projects featured unitary HPWHs each serving an individual apartment. Findings from the study provide an interesting reference case to some of the Creekside project findings presented later in this report.

The need for load-shifting with HPWHs and other controllable appliances is highlighted by Figure 2 which shows the increase in monthly curtailed renewable generation output as reported by the California Independent System Operator (CAISO).[8] As the statewide push for electrification in California increases market penetration of space conditioning heat pumps and HPWHs, peak period grid electrical demand will increase dramatically. HPWHs can be scheduled to bias operation to the mid-day (non-peak) periods when much of this curtailment is occurring. As renewables come on-line each day (most significantly during the 8 AM to 4 PM solar generation peak), HPWHs can be used to operate during these times to maximize the benefit of the low carbon generation and minimize the amount of curtailed energy.

[8] http://www.caiso.com/informed/Pages/ManagingOversupply.aspx Note: change in color bars in the plot are just to distinguish one year from the next.

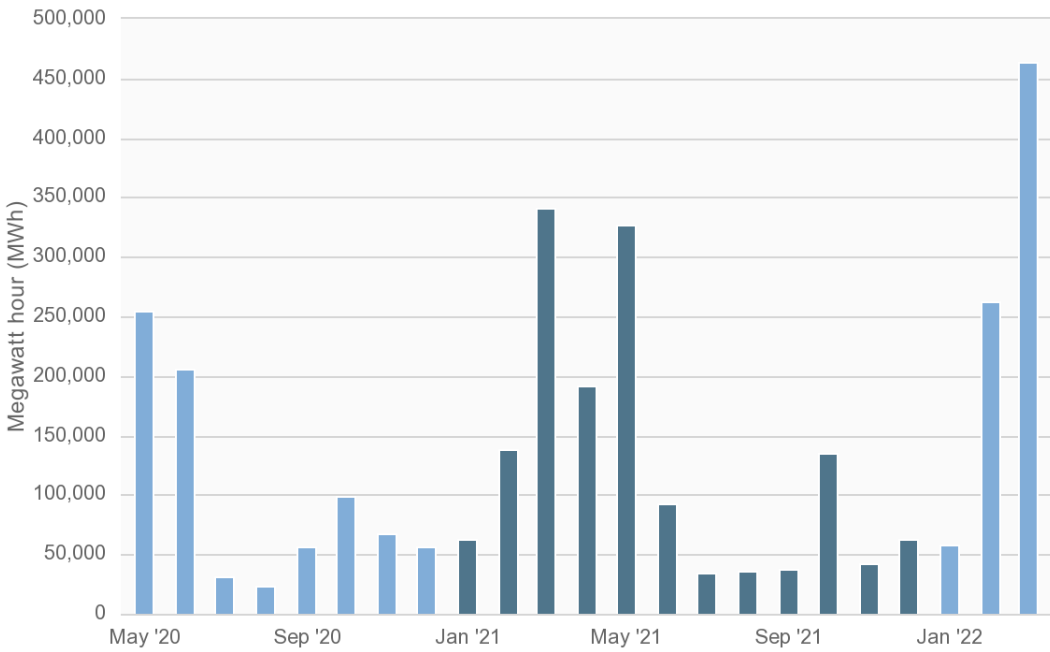

FIGURE 2: CAISO CURTAILED WIND AND SOLAR GENERATION BY MONTH

ASSESSMENT OBJECTIVES

Frontier Energy was funded by PG&E in 2017 to provide Zero Net Energy design consulting support, to the project developers (Neighborhood Partners LLC) and general contractor (Brown Construction), for the 90-unit Creekside affordable multi-family project in Davis, CA. The resident population targeted for the project was planned to include 25% extremely low-income occupants with 40% of the units prioritized for individuals who are disabled, currently homeless, or have other special needs. Over 90% of the apartments are single bedroom (single occupant) units with the remainder being two bedroom units.

With the goal of being the first affordable all-electric ZNE project in Davis, Frontier Energy worked with Neighborhood Partners LLC and Brown Construction to complete building energy modeling and cost-effectiveness analysis to help develop a workable, efficient, and cost-effective design solution. The evaluation findings[9] suggest a range of energy efficiency measures including mini-split heat pumps and high performance windows, as well as a novel

[9] https://title24stakeholders.com/wp-content/uploads/2019/06/Creekside-Frontier-Design-Analysis-Report-v032022-formatting-2.pdf

"shared" HPWH strategy whereby four adjacent apartments would share a single 80-gallon unitary HPWH located in close proximity. This design approach reduces costs by eliminating three water heaters (relative to a "per apartment" conventional design) and the associated construction costs to support the individual water heater installation. It also reduces distribution losses by eliminating the need for a recirculation pumped loop (relative to a conventional central water heating design or HPWHs located remotely). Additional benefits include reducing maintenance and replacement costs, as well as the standby storage losses associated with the three water heaters. Potential disadvantages of the shared strategy include the magnified impact of the mechanical failure of a single water heater on four apartments, and the potential for reduced HPWH operating efficiency due to having four hot water users overload the delivery capabilities of a single HPWH.

At the conclusion of the design process, PG&E was interested in testing the performance of the proposed shared configuration, as well as understanding how load-shifting operation in this configuration would impact both operating efficiency and HPWH demand profiles under real world conditions.

In late 2018, PG&E funded Frontier to instrument and monitor 10 of the 23 installed HPWHs in the project and monitor the units in detail over an 18-month period. In addition, modeling work was to be completed to evaluate various base case and load-shifting scenarios under standardized input assumptions (inlet air and hot water load patterns) to determine demand impacts, operating costs, and greenhouse gas impacts.

Key elements of the project included:

- Development of a monitoring plan;
- Installation, commissioning, and maintenance of monitoring equipment;
- Development of an automated communication strategy to remotely communicate with the HPWHs via an application programming interface (API) and change the unit's operating schedule to facilitate load-shifting operation;
- Monitoring over an 18 month period;
- Coordination with project site contacts as needed;
- Quarterly summary performance reporting;
- Development and validation of a detailed simulation tool able to work with high resolution input data (loads, ambient conditions, and control mode);
- Simulation studies expanding the study to other California climate zones, evaluating the annual performance of load-shifting controls, and exploring HPWH design changes for this installation configuration; and
- A final report documenting all project activities.

TECHNICAL APPROACH/TEST METHODOLOGY

This project was originally comprised of the following main elements to assess the impacts of load-shifting HPWH strategies in a multi-family application where the HPWH was shared among four apartments:

- Develop a reliable communications approach to be able to efficiently modify the operating schedule of remote HPWHs to facilitate field evaluation of load-shifting controls;
- Monitor ten HPWHs in standard fixed setpoint and different load-shifting modes to gain an understanding of field performance under varying hot water load and seasonal operating conditions over an 18 month period;
- Utilize existing HPWH simulation software to simulate performance of various operating strategies and report on energy usage, operating costs (under TOU rates), and time dependent valuation parameters;
- Document any findings related to installation and operational issues that would help inform best practices; and
- Document project findings.

As the project evolved from 2019 through late 2021, several modifications were made to respond to the interim data collection findings and new information gleaned over the multi-year project. These changes included:

- Development and validation of a flexible HPWH simulation model to allow for direct use of high resolution monitoring data (ambient conditions, hot water loads, inlet water temperature) and easily adjusted load-shifting control strategies to drive the simulation model.
- Addition of CAISO five-minute interval data characterizing the carbon content of the grid over the time period corresponding to the monitoring data. Coupled with the temporally aligned monitoring data, this approach provides a direct assessment of greenhouse gas emissions aligned with weather data for different installation and control strategies.
- Implementation of a ducting fix for the HPWHs which were installed in cramped water heater closets. The original installation recycled heat pump exhaust air in the space cooling the closet and reducing HPWH performance. The ducting significantly improved performance by directing heat pump exhaust air outdoors, avoiding cooling the closet. A preliminary modeling evaluation of various small closet scenarios was completed in a companion project (results included in this study as well).
- Comparative costing was obtained from the developer to compare Creekside plumber bid costs relative to a more recent project from the same developer with a similar building design, but with central gas water heating. Frontier approximated costs for a conventional "single HPWH per apartment" strategy to provide a rough assessment of three different design options.

The Creekside field evaluation was undertaken upon completion of construction in April 2020. The timing of project completion coincided with the start of the COVID-19 pandemic complicating early efforts of getting tenants into the apartments.

Figure 3 provides a site plan for the project with the community center building in the upper middle, the A and B buildings on the upper right, the C Building on the bottom right, and the D building on the bottom left. Figure 4 provides an aerial view of the completed project from a south vantage point.

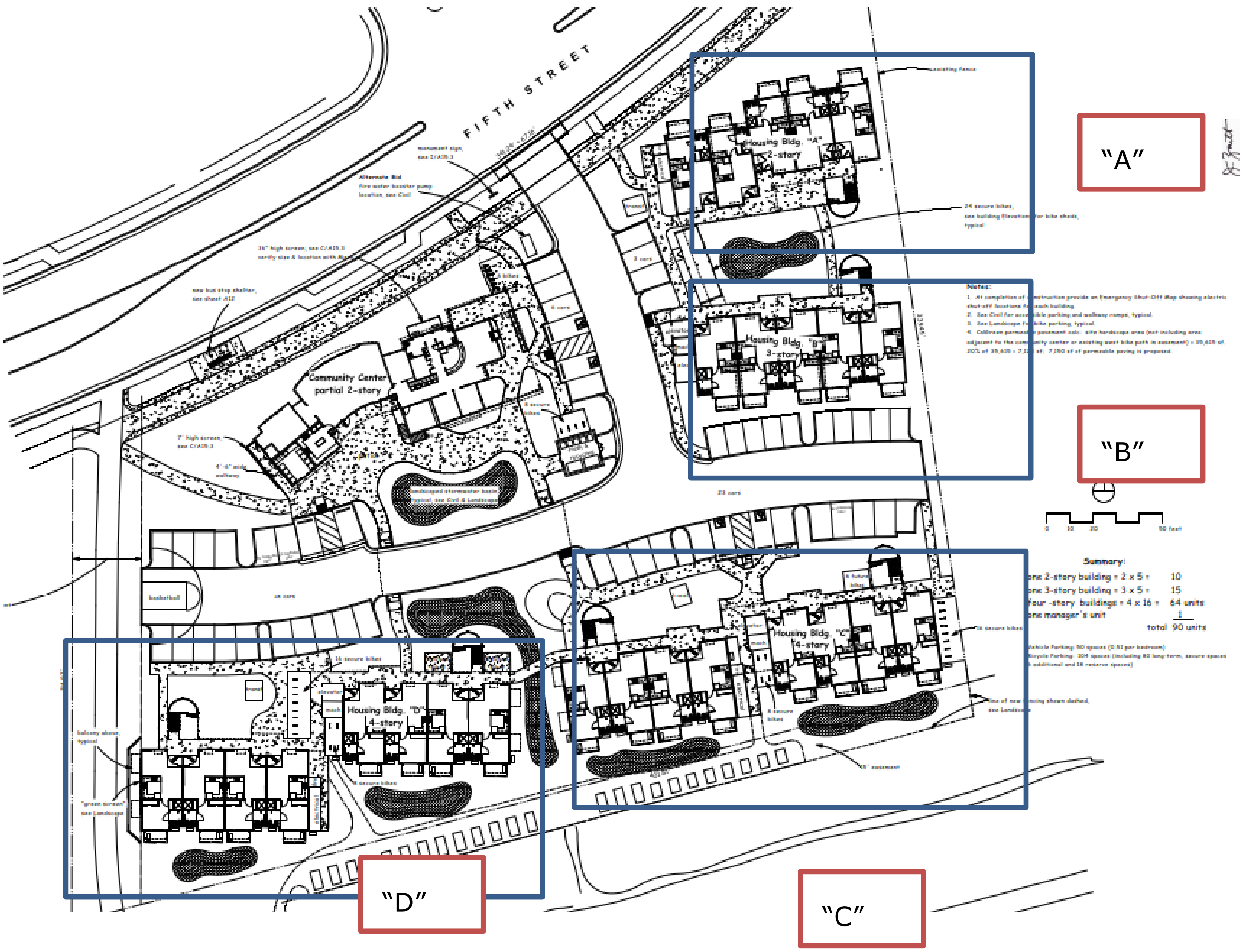

FIGURE 3: CREEKSIDE PROJECT SITE PLAN

FIGURE 4: CREEKSIDE PROJECT AERIAL VIEW (D AND C BUILDINGS SHOWN)
IMAGE CREDIT: JIM ZANETTO

The configuration of the buildings allowed for location of the HPWHs in exterior closets at the front of the apartment adjacent to two neighboring apartments. The water heater on the ground floor was plumbed to serve the two adjacent apartments (water heater location highlighted with red arrows in Figure 5) and the two second floor apartments immediately above. This configuration was also applied on the third floor to serve the third and fourth floors. The compact hot water distribution system served the kitchen sink, bathroom sink and the wheelchair accessible shower stall. No dishwasher, clothes washer, or tubs were included in the apartments. The C and D buildings are each comprised of 29 one bedroom apartments and 3 two bedroom apartments. The ten monitored HPWHs were in the D building (8 HPWHs) and the westmost segment of the C building (2 HPWHs).

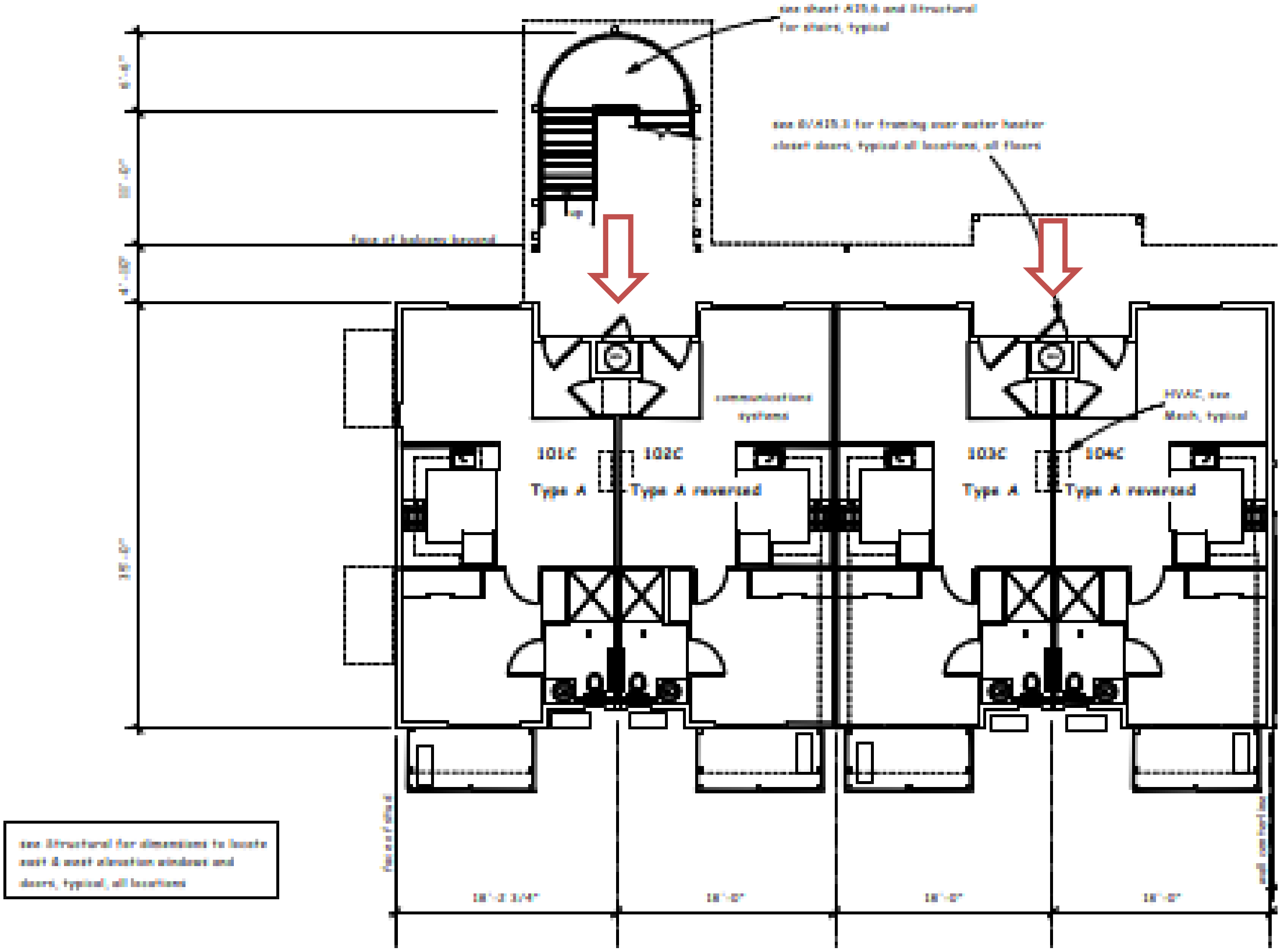

FIGURE 5: TYPICAL HPWH CONFIGURATION WITH ONE BEDROOM APARTMENTS

Prior to construction completion in the early spring of 2020, Frontier was actively coordinating with the plumber and the construction team on the integration of the monitoring components with the water heater. This involved coordination with the plumber and the electrician. Frontier prefabricated monitoring boxes containing the datalogger power monitor, and cellular modem and provided the hardware to the electrician for installation. During this coordination phase, Frontier field staff noted both the lack of pipe insulation (which was subsequently addressed) and the cramped size of the water heater closet (Figure 6). The cramped closet configuration would clearly create a circulation problem with evaporator exhaust air. Consultation with the project architect and construction team confirmed that the installed louvered door was consistent with manufacturers requirements at the time.

FIGURE 6: TYPICAL HPWH WATER HEATER CLOSET INSTALLATION

INSTRUMENTATION PLAN

The field experimental design was focused on testing ten identical 80-gallon HPWHs, each serving four apartments. Hot water distribution piping runs are short eliminating the need for any hot water recirculation system, further improving overall system efficiency.

Each HPWH was provided with a dedicated monitoring system and cellular modem for communication with the Frontier monitoring server. Data was collected on 15-second (or shorter) intervals and included:

- HPWH thermal energy delivered (integrated Btus over 15-second intervals);
- Average water heater cold water inlet temperature during flow events;
- Average mixing valve hot water outlet temperature during flow events;
- Average mixed water flow provided to the distribution system;
- HPWH total electricity consumed;
- Water heater closet ambient air dry-bulb temperature; and
- Water heater closet ambient air relative humidity.

Weather data was collected from National Oceanic and Atmospheric Administration's Meteorological Assimilation Data Ingest System (MADIS) in Davis, CA. Although not located on the site, the weather data was sufficient for characterizing local weather conditions during the full monitoring period. Since the HPWHs were located in closets, the closet or inlet air temperature was influenced by the weather, heat transfers to/from adjacent apartments, and HPWH tank storage losses. The evaporator air inlet condition (i.e., closet temperature) is therefore a bit different than a more typical garage or basement location where impacts from tank losses and system operation are not as impactful on ambient conditions due to the larger space for thermal mixing.

The HPWHs were operated through a variety of control modes during the 18-month monitoring period spanning May 2020 through October 2021. At the start of the project, there was a general understanding that tested operating modes would include standard fixed setpoint operation at different temperatures (125°F and a higher setting) and various load-shifting modes that would prioritize operation around solar noon, while also aligning with current PG&E time of use rate windows (on-peak periods for 4-9 PM for the TOU-C rate and 2-9 PM for the TOU-EV rate. These load-shifting modes use the manufacturer's API to change the set temperature and boost the tank temperature from the nominal 125°F setting to a higher setting, typically in the 130-140°F range. Each HPWH had a tempering valve installed to maintain outlet temperatures flowing to the four apartments at a maximum temperature of ~120°F.

The strategy of using the manufacturer's API to directly adjust the HPWHs set temperature to implement load-shifting was chosen for a few reasons. This strategy enables increasing the temperature of water in the tank beyond the user-specified set temperature, increasing the energy stored in the tank beyond typical limitations and enhancing load-shifting performance. At the start of this project the CTA-2045 communication protocol only included a command to bring the water to the set temperature and was not capable of this increased load-shifting performance. At the start of this project CTA-2045 was not yet a well adopted technology and the HPWHs selected by Brown Construction were not yet CTA-2045 compliant.

At the start of the project there was interest in exploring whether the higher pre-peak set point temperature could be accomplished in heat pump only mode. This was explored, but quickly abandoned as the highly variable hot water loads from the four apartments could frequently overwhelm the compressor output and result in loss of tank set point temperature maintenance. This finding may not necessarily be true for unitary HPWHs installed in single family homes due to the lower hot water demands in those installations.

Each of the modes of operation were implemented for several days at a time. By rotating the ten HPWHs through standard (fixed tank setpoint) operation and the various load-shifting strategies, each HPWH will collect a dataset under each operating mode under all seasons. This data was essential in developing and validating the simulation tool developed in this project.

Table 1 shows the installed monitoring equipment specifications and sensor accuracy. The Btu meter meets EN1434 class 1 requirements, the highest level for European thermal metering devices for energy submetering. The configuration of the monitoring is conveyed in the installation schematic (Figure 7).

TABLE 1. MONITORING EQUIPMENT

SENSOR	DESCRIPTION	SPAN	ACCURACY
Btu meter (water heater flow, hot and cold water temperatures, and integrated energy flow)	Onicon System 40 Modbus Btu meter Calibrated platinum RTDs which meet EN1434 Class 1 requirements (computation error ≤ 0.09% at 30°F temperature difference)	-13 to 131°F operating temperature range 32 to 250 °F operating fluid temperature range Flow rate:1-25 gpm	Matched platinum RTDs certified to a differential measurement uncertainty of ± 0.18 °F 1% accuracy for 1-25 gpm flow rate; 2% accuracy for 0.25 - 25 gpm
Power Monitors	WattNode Module for Modbus revenue grade monitors & 50 amp CTs		Meets ANSI C12.1 and CZ12.20 class 0.5 accuracy (0.5%)
Wireless Temp/ RH Sensor (water heater closet evaporator inlet air condition)	Onset Hobo MX1101 Data Logger	-4 to 158 °F 1 to 90 % RH	±0.38 °F ±2% RH

Raw 15-second, or shorter duration[10], interval data was stored locally and transferred periodically to Frontier Energy's server through a cellular modem. Local data was stored as hourly CSV files for each monitored HPWH. Each file contained all the logged data which was uploaded daily to Frontier's secure servers via SFTP. Data was stored in binary files for analysis and in daily CSVs for data quality control purposes.

Data processing scripts were developed to check the status of the file transfer and perform a range check to identify defective sensors or unusual conditions. The close proximity of the field site to Frontier's Davis, CA office facilitated correcting any monitoring issues.

A brief preliminary observation report was provided to PG&E after the first full month of monitoring to provide an initial summary of the data collected and any early observed issues. Quarterly monitoring reports (six total through the 18-month project) provided more detailed monitoring results with tabular summaries and graphs. Tabular data disaggregated performance between the different control modes and reported on hot water consumption, kWh consumption by time of use, daily average COP, and other metrics.

[10] Towards the end of the field monitoring phase, PG&E's code readiness consultant (2050 Partners) expressed interest in gathering higher resolution hot water usage data as part of a multi-family hot water use pattern data collection effort, so the sampling interval was reduced to 2-second.

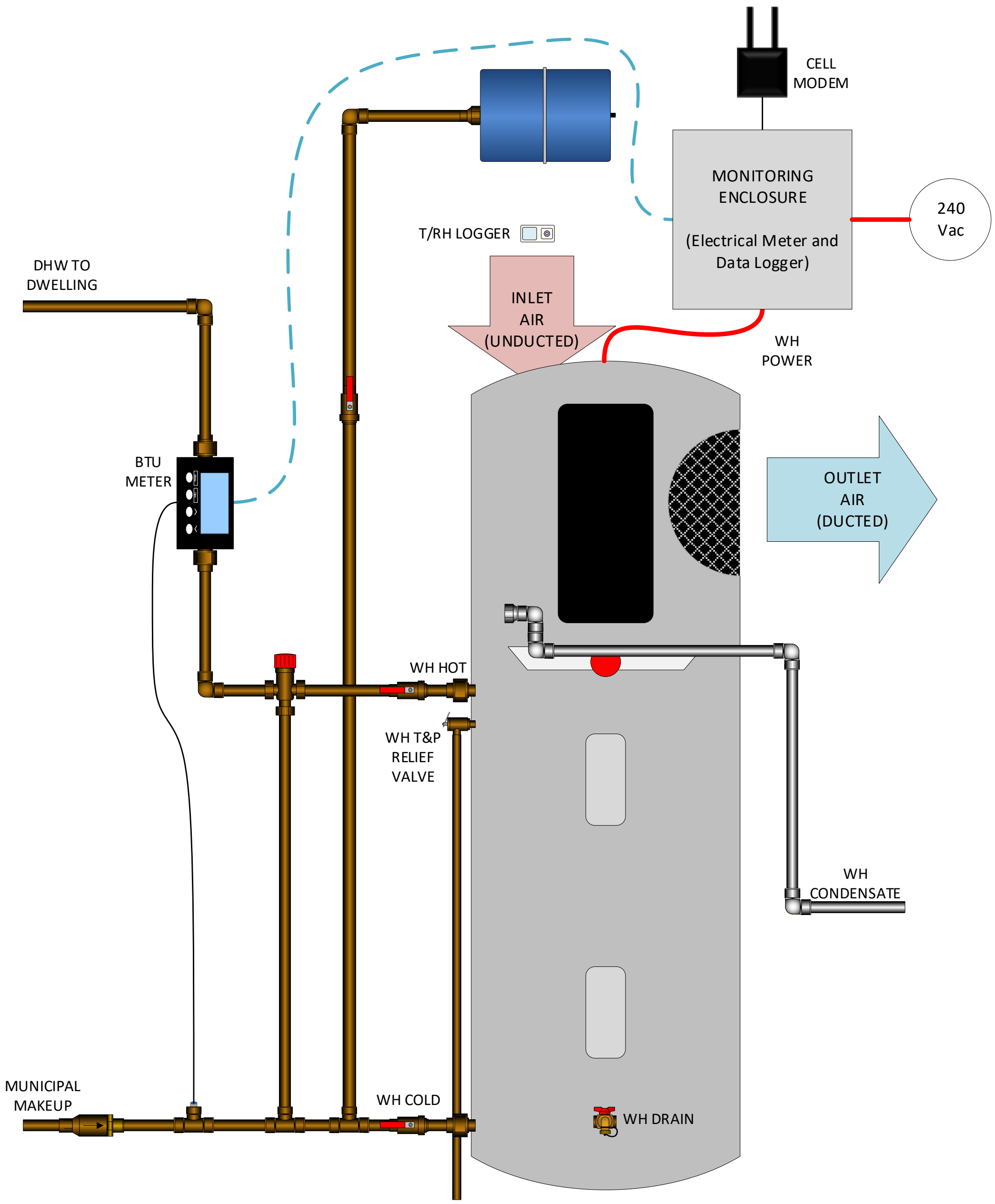

FIGURE 7: MONITORING CONFIGURATION SCHEMATIC

MODEL DEVELOPMENT AND VALIDATION

In addition to the detailed data collection efforts, simulation efforts extended the findings from an uncontrolled real world environment to a simulation environment where loads and other performance impacting parameters could be standardized to allow for direct performance comparisons between fixed and load-shifting operating modes. The Flexible

HPWH Performance Predictor (Flexi-HPWH), a multi-node HPWH simulation tool, was developed exclusively for this project. The model is designed both to be able to simulate various HPWH control logic strategies, such as load-shifting controls, and also perform simulations with a range of input assumptions and input data. It has the following capabilities:

- The ability to utilize variable time step monitored data (ambient air, inlet water, hot water loads) as simulation inputs with minimal data manipulation;
- The ability to read simulation hot water draw profiles, such as the CBECC-Res dataset;
- The option to either read the HPWH set temperature from a monitored data set or use a library of functions implementing different static setpoint or dynamic load-shifting control strategies;
- A library of field-derived functions adjusting the evaporator inlet air temperature to more accurately predict performance in different installation configurations such as an unconstrained HPWH in open space, a small water heater closet with inadequate ventilation, or with ducts directing the exhaust air out of the closet[11];
- A user-specified, multiple node model of the storage tank to better represent stratification and draw impacts on water temperatures at different heights in the storage tank;
- Control logic emulating the observed performance of the on-board controller in the Creekside project;
- Second order, multi-variable regressions describing the heat pumps heat addition and electricity consumption rates as a function of the tank and surrounding air temperatures;
- Equations calculating the rate of heat loss from the water in the tank to the surrounding air; and
- Calculations identifying the temperature of water in each node as a result of hot water draws, cold water entering the tank, and tank storage losses.

Flexi-HPWH performs calculations predicting all thermal and control phenomena occurring in HPWHs, including emulating the on-board control logic of the HPWHs monitored in the Creekside project. The model obtains the water flow and temperature conditions from a specified data file (either monitored or simulation assumption) and obtains the parameters describing the specific HPWH from a configuration file. Flexi-HPWH includes a configuration file describing the HPWHs installed at Creekside, facilitating simulation of those units.

The heat pump is modeled as a variable-capacity heat source with heat input below the stratification layer in the tank. The heating capacity is based on the rated heating capacity of the heat pump and modified using a second order regression based on the stored water and surrounding air temperatures. It also utilizes a second order regression based on the stored water temperature and surrounding air temperature to determine the electricity consumption of the heat pump compressor. Both regressions were calculated by matching

[11] The latter two configurations are based on observed performance characteristics from the Creekside monitoring.

simulation outputs to Creekside monitoring data, as discussed in more detail in the Flexi-HPWH Parameterization section.

The electric resistance elements are modeled as two separate heating elements, one at the top of the tank and the other near the bottom. These elements are simulated with a total heating capacity of 3.8 kW, a 99% efficiency, and control logic as observed at Creekside. Monitoring data during the project showed that 2nd stage resistance heating (RH) usually starts as the compressor heating the bottom of the tank and the upper resistance element heating the top. When the temperature at the upper thermostat reaches the set temperature, the HPWH switches to using the compressor and lower resistance elements. The element continues to heat the bottom of the tank until the entire tank reaches the set temperature. Flexi-HPWH replicates this operation.

Flexi-HPWH implements three different deadbands to represent the observed control logic of the monitored HPWHs. The three deadbands are:

- **Heat Pump Activation Deadband**: This deadband determines the heat pump activation control logic. When the lower thermostat temperature records water temperatures colder than the set temperature minus the deadband the HPWH activates the heat pump compressor to heat the tank back up to the set temperature.
- **2nd Stage RH Activation Deadband**: This deadband determines the 2nd stage RH heating control logic. If the upper thermostat records a water temperature colder than the set temperature minus this deadband, the HPWH will activate 2nd stage heating RH to bring the tank back up to the set temperature.
- **2nd Stage RH Activation Deadband, Heat Pump Active**: This deadband determines the 2nd stage heating RH control logic in cases when the heat pump compressor is already heating the water. It is a higher value, meaning that 2nd stage heating RH is delayed until the water at the upper thermostat is colder than if the heat pump were not actively heating. The HPWH activates 2nd stage heating RH to bring the tank back up to the set temperature if the upper thermostat records water temperatures colder than the set temperature minus this deadband.

The three deadbands are stored in the configuration file representing the monitored HPWHs and were identified by observing the specific behavior of the installed HPWH as observed in monitoring data. It is important to note that this control logic may be unique to HPWHs produced by the same manufacturer as those used at Creekside and may or may not be applicable to HPWHs from other manufacturers.

The monitored HPWHs also have a low temperature shutoff to protect the heat pump compressor when there is a risk of freezing and damaging the coils due to low evaporator air inlet temperatures. The on-board controller locks out the compressor and relies on the electric resistance elements to provide heating when the ambient air temperature falls below this threshold. Flexi-HPWH replicates this behavior by using the electric resistance elements as the only heating source when the evaporator air inlet temperature is colder than the manufacturer specified cutoff temperature.

Monitoring data showed that the HPWH will not heat the water if the upper thermostat temperature is above the set temperature. In typical water heater operation this does not have a significant impact on control logic decisions, but it is a frequent occurrence in load-shifting scenarios as load-shifting controls return the set temperature from an elevated value to the lower user-defined value at the start of the peak period. Reducing the set temperature typically cause the upper thermostat temperature to be above the new set temperature due to the prior preheating. Flexi-HPWH's control logic includes this lockout enabling more accurate prediction of load-shifting performance.

Jacket losses are calculated using the industry-standard approach of dividing a "UA" value for the entire tank by the number of tank nodes to find the heat loss coefficient per node, and multiplying the UA value for an individual node by the temperature difference between that node and the surrounding air. This method enables identifying the heat loss from each node of the tank. It is likely that the top and bottom nodes should have higher heat loss than the more internal loads, as they have higher surface areas (top and bottom of tank) connected to the surrounding air.

The heat transfer caused by water flow is calculated assuming plug flow during a timestep, and perfect mixing at the end of the timestep. During a draw the colder water from a lower node enters the node above. That calculation is performed simultaneously for each node. Flexi-HPWH then assumes the colder water entering the node mixes completely with the rest of the water in the node, reducing the temperature of each node. The inlet water temperature is delivered to the bottom node during draws.

It is important to note an important distinction between the monitoring data and the simulation output data. HPWH energy monitoring was completed using a single revenue grade power monitor, as opposed to separately monitoring electric resistance heating (RH) usage separately from total HPWH demand. Sections of the report that discuss monitoring results present 2^{nd} stage operation as the total energy consumed by the HPWH. Simulation results disaggregate compressor consumption from RH consumption.

Flexi-HPWH Parameterization

To ensure that Flexi-HPWH can accurately simulate the different control strategies and installation configurations to be studied, the project team identified parameters describing the operation of the HPWHs installed at Creekside. This process included two different strategies to identify different types of parameters. The strategies were:

- **Manual Identification**: Some of the parameters were identifiable using a manual inspection of the monitoring data set or product rating sheets. These parameters included the deadbands for the heating sources, the rated heating capacity of the heating sources, the cutoff air temperature below which the heat pump will not activate, and the thermostat locations in the tank. The rated heating capacity of the heating sources and cutoff air temperature were identified from the product specification sheet. The thermostat locations were identified by observing the location of the resistance elements relative to the inlet and outlet water pipes. The heating deadband temperatures were identified by reviewing monitoring data and comparing the water temperatures to the set temperature when the on-board controller activated the heating sources.
- **Error minimization**: The other parameters were not easily identifiable either due to the non-discrete impact they have on the HPWH, such as the UA coefficient describing the heat losses from the tank to the surrounding air, or were too complex to identify manually, such as the coefficients describing the heat addition rate and electricity consumption of the heat pump. The project team utilized a minimization algorithm to identify these parameters. The minimization algorithm guessed the value of the parameters, performed a simulation using the new parameters, and

calculated the difference between the simulation results and monitored data to determine the error when using the guessed parameter set. The minimization algorithm repeatedly adjusted the parameters and performed simulations until it minimized the difference between the simulation outputs and the monitored data. For the heat addition rate the error function was the root mean squared error (RMSE) between the monitored and simulated lower thermostat temperature. For the UA coefficient and heat pump electricity consumption coefficients the error function was the RMSE between the monitored and simulated heat pump electricity consumption.

The automated error minimization process consisted of two steps. The first step identified the heat addition coefficients that minimized the difference between the monitored and simulated water temperatures. The second step adjusted the electricity consumption multiplier of the heat pump, thus changing the electricity consumption, until the monitored and simulated electricity consumed by the HPWH closely matched.

To ensure that this process yielded an accurate performance curve it was necessary to create a dataset with the following characteristics:

- The dataset could only include heat pump compressor operation, not 2nd stage RH operation. Periods of electric resistance operation would impact the tank differently from independent heat pump operation, potentially causing differences between the modeled and monitored data. The minimization algorithm would make adjustments to minimize that error which would force the model to more closely fit the observed data, but less accurately predict the performance of the heat pump.
- Only include periods where the heat pump compressor was active for the same reason as above. Including periods where the heat pump was inactive would introduce minor differences caused by control logic choices, not by heat pump performance. The minimization algorithm would minimize the total error in the simulation, making up for errors in the controls by inaccurately predicting the performance of the heat pump.
- Include periods that span the entire range of tank water and ambient air temperatures encountered during operation. This includes periods where the water was cold after large draws in the winter, to times when the water temperature reached 140°F during load-shifting periods. It also included periods of cold and hot surrounding air temperatures. It was important to cover a broad range of conditions to create a complete performance map predicting heat pump compressor performance, and to avoid extrapolating a 2nd order regression to conditions outside of the calibration range.

The parameterization process used 28 different data periods to meet those criteria. To equally include the different ambient air temperatures at least two periods from each of the 12 monitored months were included. Seventeen of the days included load-shifting operation up to 140°F ensuring representation of a full range of water temperatures.

FLEXI-HPWH VALIDATION

To ensure that Flexi-HPWH accurately predicts the performance of HPWHs utilizing both standard and load-shifting controls, simulation outputs were compared to the measured data. The validation process included three phases:

- **Visual Inspection**: The simulation model outputs were visually compared to monitored data to ensure that Flexi-HPWHs control logic accurately captured the algorithms employed by the on-board controller. This included identifying behavioral aspects such as operation below the low-temperature cutoff, on-board controller responses to changes in the set temperature, and HPWH response to the upper thermostat temperature being above the set point.
- **Targeted Numerical Validation**: The simulation model outputs were numerically compared to the monitored data over short periods of time evaluating the control logic decisions, timing of operation, and total electricity consumption. These tests were used to ensure that the model was predicting accurate amounts and timing of electricity consumption over 1-7 day periods. Tests included both load-shifting and non-load-shifting scenarios.
- **Annual Performance Verification**: The final test was comparing annual Flexi-HPWH performance when predicting the response to Low, Medium, and High hot water use cases while using the same control strategies. The simulation model was tested to identify 1) total annual electricity consumption (kWh), 2) total annual 2nd stage RH consumption, 3) peak period electricity consumption when utilizing a static 125°F set temperature, 4) peak period electricity consumption when utilizing a 125 to 133°F, stepped load-shifting strategy, and 5) the reduction in peak period kWh consumed when load-shifting.

CAISO Greenhouse Gas Data

CAISO provides a wealth of data related to operations on the electric grid related to real time and historical grid supply conditions, sources of generation, projected and actual demand, and estimated greenhouse gas (GHG) emissions based on the mix of resources supplying the grid at any time. Five-minute interval demand and emissions data are available for download at the CAISO website. Frontier staff downloaded the data for the full monitoring period and processed the data to develop hourly profiles over the October 2020 through November 2021 time period. The data was used in conjunction with the Flexi-HPWH energy usage output to provide annual CO_2 impacts of each of the scenarios. Figure 8 plots a selected set of data showing the time of day variations in GHG output based on an annual average day, the months with minimum and maximum average content (May 2021 and October 2020, respectively), and the two days of the year with the minimum and maximum hourly values (May 2nd and March 25th, respectively). The data shown in Figure 8 are represented in terms of metric tons per MWh. Later CO_2 emissions calculations based on simulation model projected energy usage will present results in terms of lbs/year.

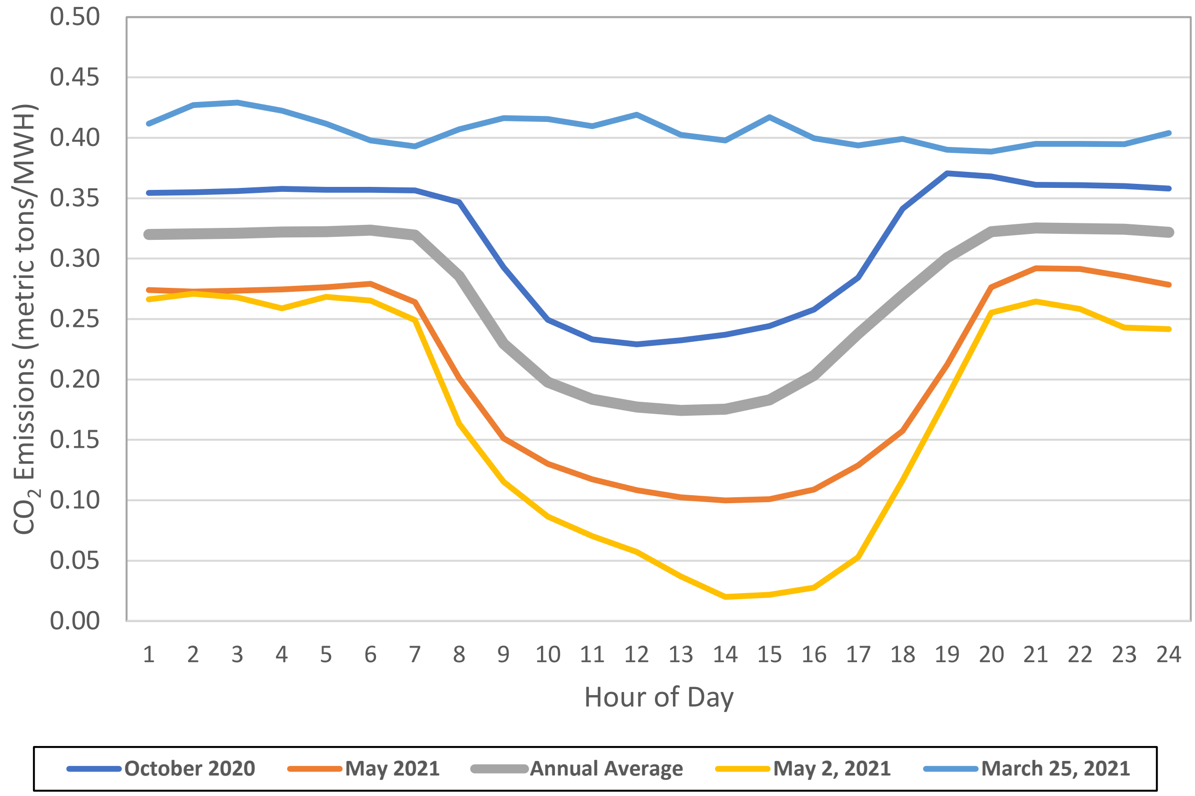

FIGURE 8: CAISO GHG AVERAGE PLOTS BY TIME OF DAY

SIMULATION MODELING PLAN

To expand on the findings from the Creekside monitoring data, the project team used simulation modeling to extrapolate the findings and answer additional research questions. The questions studied via simulation are:

1. How would the tested load-shifting control strategies perform if implemented annually? Which control strategies yield the lowest occupant electricity costs, peak period electricity consumption, and carbon emissions?
2. How does the performance of the load-shifting controls change with differences in hot water loads and patterns? Do some control strategies perform better in high use cases while others perform better in low use cases?
3. How does the performance of a HPWH shared between three or four apartments compare to the performance of one HPWH for each apartment?
4. How well do the shared HPWH installations and load-shifting controls perform in climates other than the monitored Davis location? Are there California

climate zones where these approaches perform well and others where they perform poorly?

5. Would a HPWH with a larger 100 gallon tank, a larger one ton compressor, or both, perform better than the monitored unit? Which of these changes is most impactful?

The project team addressed these questions using annual Flexi-HPWH simulations with varying inputs and parameters. The inputs were varied to describe different installation scenarios, such as site location or number of apartments served by each HPWH, and the Flexi-HPWH parameters were adjusted to describe changes in HPWH design, such as a one ton compressor.

To ensure that the simulation data covered a representative range of potential usage levels, the project team identified low, medium, and high water heating load cases from among the monitored HPWHs. These load cases were selected based on defining a reasonable range of hot water consumption, as well as maintaining a relatively consistent pattern of consumption, indicating that there was not a drastic change in occupancy.

To address the first two questions the project team used the low, medium, and high load cases to drive annual simulations studying the performance of seven different control strategies. All control strategies were tested on the medium use case to determine the impacts of all control strategies, and a targeted set of the most important control strategies were tested on the low and high use cases. The seven control strategies are as follows:

1. **Fixed 125°F**: A constant set temperature of 125°F for all hours.
2. **Fixed 130°F**: A constant set temperature of 130°F for all hours.
3. **Fixed 140°F**: A constant set temperature of 140°F for all hours.
4. **125 to 140°F Load-Shifting**: A load-shifting control strategy with a base set temperature of 125°F and an elevated set temperature during the pre-peak load-up period of 140°F. The load-up period was 8 AM to 4 PM with a defined peak period of 4 PM to 9 PM[12].
5. **125 to 140°F Load-Shifting, Stepped**: A load-shifting control strategy with a base set temperature 125°F and a gradual, stepped increase to 140°F during the pre-peak load-up period. The modeled set temperature was increased by 1.875°F per hour during the load-up period. The load-up period was 8 AM to 4 PM with a peak period of 4 PM to 9 PM.
6. **125 to 133°F Load-Shifting**: A load-shifting control strategy with a base set temperature of 125°F and an elevated set temperature of 133°F during the pre-peak load up period. There were two variants of this control strategy. One used a load-up period of 8 AM to 4 PM with a peak period of 4 PM to 9 PM. The second used a load-up period of 8 AM to 2 PM and a peak period of 2 PM to 9 PM[13].

[12] This corresponds to PG&E's on-peak period under the current TOU-C rate.

[13] The 2-9 PM period corresponds to PG&E's on-peak period under the current TOU-EV2-A rate.

7. **125°F to 133°F Load-Shifting, Stepped**: A load-shifting control strategy with a base set temperature of 125°F and a gradual, stepped increase to 133°F during the pre-peak load up period. The set temperature target reached 133°F one hour before the end of the peak period. This control strategy used the same two variants as 125°F to 133°F Load-shifting, one with a 4 PM to 9 PM peak period and a second with a 2 to 9 PM peak period.

To address the performance of fixed operation and load-shifting with HPWHs serving a single apartment, the simulations assumed reduced hot water loads and a HPWH with a 50 gallon storage tank. The hot water volumes were reduced to 25% of the measured total to represent this configuration. The volume of the tank was reduced to a nominal 50 gallons, and the jacket heat loss coefficient was reduced to 83% to match the geometric differences between the 80 gallon and 50 gallon HPWHs. The project team used these assumptions to drive annual simulations using the control strategies described above.

Further simulations studied the performance of the four apartment shared installation configuration and load-shifting controls in California Energy Commission Climate zones 3, 6, 10, 12, 15, 16. These climate zones were selected to represent both areas of high population and areas of extreme climates within the state of California. Climate zones 3, 6, 10, and 12 represent the high population Bay Area (Oakland), Los Angeles, Riverside, and Sacramento regions. Climate zone 15 covers a hot/dry southern California climate (Palmdale), and climate zone 16 represents the cold mountainous region of eastern California (Blue Canyon). These simulations evaluated the impact of local air and water temperatures on HPWH and load-shifting control performance. The project team used simulation assumptions from CBECC-Res to overwrite the monitored inlet water and outdoor air temperatures in lieu of Creekside data, in conjunction with the identified Medium hot water usage profile.

To evaluate the performance of the shared HPWH installation and the load-shifting controls when serving three apartments the project team performed annual simulations reducing the hot water volume in the low, medium, and high use cases to 75% of the monitored volume.

The final simulations evaluated the performance of the shared HPWH installation and load-shifting controls with 100 gallon tank size and/or 1 ton compressor by changing the parameters describing the HPWH. The changes included increasing the storage tank volume to a nominal 100 gallons, increasing the jacket loss coefficient accordingly, and increasing the compressor size to 1 ton. The project team performed simulations using the medium load case with targeted load-shifting control strategies. The COP relationship for the HPWH remained the same with the 1 ton compressor case, assuming linear scaling of heat exchanger components and evaporator airflow consistent with the compressor capacity increase.

The simulation results were used to estimate the total electricity consumption, 2nd stage electricity consumption (RH usage only), peak-period electricity consumption, electricity cost, and carbon emissions of each design configuration and control strategy. Electricity consumption values were taken directly from the simulation results.

Electricity costs were calculated using both the PG&E TOU-C (effective January 1, 2022) and a hypothetical alternative TOU rate with a wider on- to off-peak rate differential. The latter rate was modeled for on-peak to off-peak rate differentials in the current Southern

California Edison TOU-D 4 to 9 PM rate[14]. Since only domestic hot water energy consumption is being modeled in this study, several assumptions had to be made in defining how the rates and baseline quantities (and credits) would be applied. Based on prior evaluations as part of Frontier's Reach code modeling activities, it was assumed that typical total apartment usage in a month would always fall under the baseline usage quantity. This means that the baseline credit (currently $0.0826 per kWh would apply to all HPWH energy consumed for both rates). A second complication is that the shared HPWH configuration implies that the HPWH usage is billed to a separate account, not one connected to an apartment. How the shared HPWHs are metered in any particular project will vary on a variety of factors including building configuration and HPWH sharing ratio. Clearly the shared HPWH is a challenging case to provide bill estimates for, without bundling all the other usage on that meter into the total.

Both the TOU-C and hypothetical rate assumes a 4-9 PM on-peak period each day of the year. Table 2 provides the actual TOU-C rates and the assumed hypothetical rate. No meter charges or California climate credit rebates were included in the rate calculations.

TABLE 2. ASSUMED UTILITY RATES (COST PER KWH)

PERIOD	PG&E TOU-C RATE	ALTERNATIVE PG&E TOU RATE
Winter On-peak	$0.3843	$0.3940
Winter Off-peak	$0.3333	$0.2900
Summer On-peak	$0.4477	$0.5112
Summer Off-peak	$0.3843	$0.3208

Note: Rates shown do not included baseline credits

RESULTS

OVERVIEW

This section of the report focuses on the field data results, the Flexi-HPWH validation process and findings, and results from the full year simulation runs. The results discussion begins with characterization of observed hot water loads amongst the ten monitored HPWHs and additional details on the patterns of usage and how the loading impacted the ability to deliver adequate supply water temperatures to the individual apartments. The data presented then focuses on higher level monitoring findings on operational efficiencies and energy usage (total usage and time of use) that convey seasonality impacts, load impacts,

[14] https://www.sce.com/residential/rates/Time-Of-Use-Residential-Rate-Plans

and the influence of fixed set point operation versus load-shifting operation. The high degree of day-to-day load variability and changing operating modes with the ten HPWHs makes it challenging to compare monitoring results in a more refined and systematic fashion. The authors rely on the validated Flexi-HPWH model to draw these conclusions as the simulation runs provide for standardized hot water load and operating conditions comparison while running the HPWH in a single mode of operation.

Much of the monitoring data presented uses evaporator air inlet temperature as the independent variable in plots. This parameter is specific to the Creekside installation as it represents the specific thermal impact of the water heater closets impacted by both the neighboring apartments and the outdoor environment, as well as the impacts of tank storage losses, and any cooling from the uninsulated evaporator exhaust ducting. Evaporator air inlet temperature is a meaningful input as it simultaneously 1) impacts HPWH control logic decision, heat pump COP, and HPWH jacket losses, and 2) captures the diurnal and seasonal changes that drive HPWH performance. The resulting energy use performance reflects the impact of the installed ducting on evaporator airflow and duct heat transfer to the closet.

CONSTRUCTION COST REVIEW OF SHARED HPWH STRATEGY

An important aspect in the development of construction documents for any project is developing a design that is consistent with overall project goals (in this case an affordable ZNE design), provides the needed amenities and features, and fits within any overall funding constraints. The Creekside developer and architect have been working together for many years developing projects that effectively integrated energy efficiency elements and solar thermal or PV technologies. Implementation of HPWHs was a new aspect for the team, but a key design element to achieve the stated all-electric ZNE goal. Frontier's prior working relationships with the architect, general contractor and plumbing contractor allowed for Frontier to access cost data that was useful in providing a comparison between the shared HPWH operation implemented at Creekside and a more conventional central gas water heating design.

In late 2020 the Creekside developer (Neighborhood Partners LLC) was going to bid on a similar apartment design for the Dixon California Heritage Commons Phase III affordable project (consisting of 43 one bedroom rental units and a single manager unit in four separate buildings). The general building layout and apartment floor plan were similar to Creekside suggesting that in-unit plumbing design costs should be roughly comparable.

The Creekside project, which went to bid in October 2018, had a total plumbing bid of $1,449,000 inclusive of all work. The Creekside architect estimated that $200,000 of that cost was associated with the Community Center building, resulting in $13,900 cost per apartment ($1,249,000 divided by 90 apartments). The Dixon Phase III development was designed to include central gas water heating in each of the four buildings. The December 2020 plumber's total bid for the Dixon project (exclusive of solar water heating costs), totaled $760,000 or $17,300 per apartment.

With two years of elapsed time between the two bids, adjustments for construction cost inflation are necessary. A 2020 study from the Terner Center for Housing Innovation at UC Berkeley (Reid, 2020) provides insights into recent construction cost escalation for affordable housing. The study notes that between 2016 and 2019, the costs to develop a new affordable apartment unit under the Low-Income Housing Tax Credit program increased

13% total. Applying half that increase (6.5%) to the Creekside project costs should align the 2018 Creekside bid to the 2020 Phase III bid price.

A final piece of the comparison between the central gas case and the shared HPWH approach involves electrical costs for connecting the HPWHs to the electrical panel. The authors estimate $2,000 per HPWH for electrician costs (wiring, circuit breaker, conduit, etc.). An additional $200 was assumed for the louvered water heater closet door. These costs are apportioned over four apartments, adding $550 to the per apartment costs. Other incidental costs include the closet ducting and an expansion tank. Adding these incidental costs to the base plumber bid increases the per apartment cost from $13,900 to $15,700, which is still 10% lower than the more recently bid central gas water heating per-apartment cost ($17,300).

With movement towards electrification in many localities in California, the more mainstream HPWH configuration for multi-family applications would be the individual HPWH per apartment. For comparative purposes a rough cost comparison is provided here, although there are many installation nuances that could impact the assumptions presented here. For the "per apartment" configuration, most likely a 50 gallon HPWH would substitute for the 80 gallon unit used at Creekside. Recent big box pricing for these size HPWHs (with a 30% plumber overhead and profit included) results in added HPWH costs for the individual scenario of $1,170 per apartment. In addition, the authors are presuming an exterior closet application which has associated costs of added electrical, louvered door, closet construction, expansion tanks, added water heater plumbing, etc. Many of these costs are challenging to pin down without a specific design, so the authors have used engineering judgement in estimating these costs at an additional $680 per apartment. The resulting total cost increase for the individual HPWH scenario is $1,850 per apartment, after adjusting for the substitution of the four units for the single 80 gallon unit. Adding this to the prior shared HPWH cost of $15,700 results in a total cost of $17,550 per apartment, or 1.5% higher than the nominal central gas system cost.

These cost estimates will vary with building configuration and details of the overall design. It is however evident that the shared HPWH approach is a less expensive first cost approach than either of the other two scenarios (~$1,600 per apartment less than the central gas design and $1,850 less than the individual HPWHs). Although there is some added risk in a shared configuration with the rare occurrence of equipment failure, the first costs, maintenance costs, and replacement costs would all be significantly lower than an individual HPWH strategy.

MONITORING STARTUP AND OTHER OPERATIONAL ISSUES

The field data collection began in late April 2020, but due to the challenges with COVID, initial occupancy of the apartments was very low and slow to pick up. Throughout the course of the monitoring phase, regular inquiries with the onsite property manager provided a reasonable reflection of occupancy for the 40 apartments served by the ten monitored HPWHs. Figure 9 plots the monthly average occupancy data based on these updates. By October 2020, ~85% of the apartments were occupied. Occupancy remained above 90% for the rest of the monitoring period.

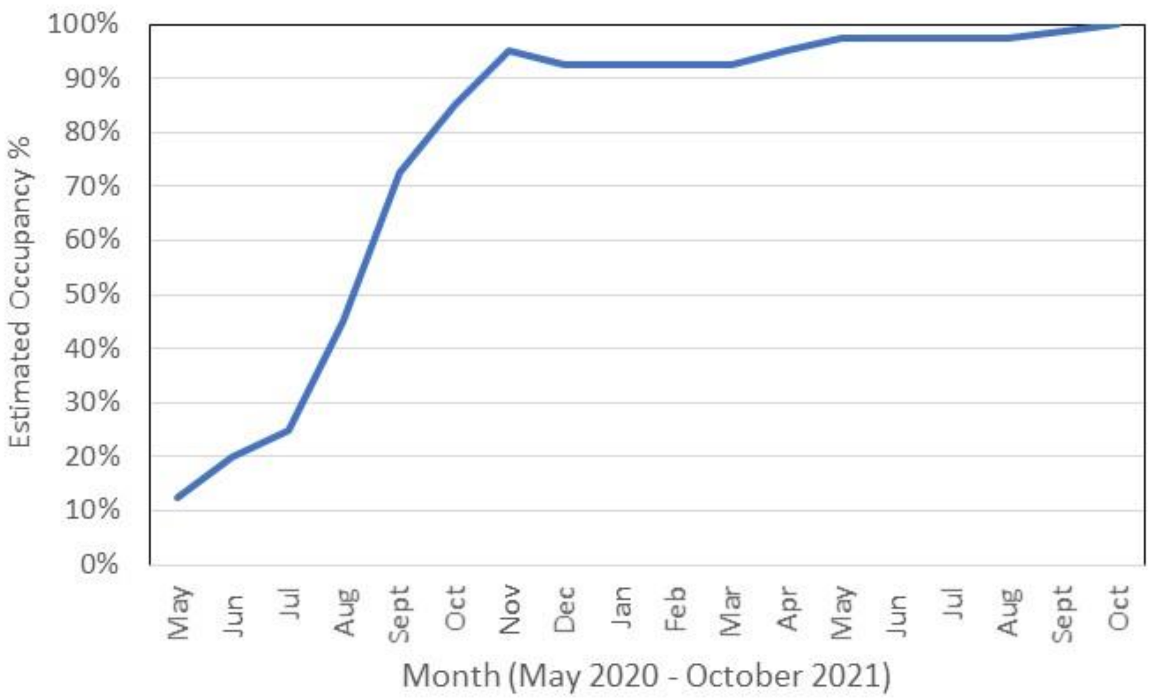

FIGURE 9: ESTIMATED MONTHLY AVERAGE OCCUPANCY PERCENTAGE BASED ON SITE MANAGER COMMUNICATIONS

Project early data collection efforts were useful in identifying the standby energy consumption of the largely unloaded HPWHs. This data characterizes the standby consumption of the HPWH to maintain the tank volume at temperature. During these early April and May 2020 months, average daily HPWH energy usage was found to be 0.51 kWh/day for HPWHs with zero or near zero hot water loads with average outdoor temperatures of 73°F and average closet temperatures of 79°F. Although this consumption level is small, it is important to keep in mind in comparing the energy use of a shared HPWH configuration with an individual HPWH approach where multiple units are continually consuming energy just to offset standby losses.

CRAMPED CLOSET HPWH INSTALLATION

As occupancy started to pick up slowly in May 2020, it quickly became apparent that the cramped water heater closets were woefully insufficient in providing enough outdoor airflow to counteract the cooling effect from the evaporator exhaust, even with the installed louvered doors. Data showed that prior to a HPWH operating cycle, the May closet temperature was generally warmer than outdoor air (due to tank heat losses to the closet), but the closet temperature commonly fell 35°F over a typical three hour heat pump heating cycle. This observation was clearly a concern and reported to the project team in the start up memo attached in Appendix A. Communications with the developer and the architect (who reached out to the HPWH manufacturer representative) indicated that the cramped closet louvered door requirements were not clearly conveyed during the design process. New manufacturer installation requirements specified 240 in^2 of net free area for the louvered door, but this information was not available to the architect during the design phase[15]. Frontier, the architect, and developer reviewed remediation strategies and implemented a trial fix for the problem, which significantly improved the situation by directing the exhaust air to an exterior portion of the louvered door with rigid sheet metal ducting. At this point, the project HVAC contractor was brought in and proposed a modified ducting approach. This was implemented in the middle two weeks of June 2020 on all 23 installed HPWHs, with partial funding support from PG&E. Most of the 18 month data collection period included the impact of the ducting fix, but the early pre-retrofit data provided for some useful data on non-ducted closet performance.

Small closet HPWH operation is an issue that has performance implications for HPWHs as the HPWH market grows. Multi-family individual HPWHs (per apartment) may often have closet installations, depending upon the building construction configuration. Similarly single family HPWH retrofits in older homes may involve either interior or exterior closet water heater locations. Understanding the impact of cramped closet performance both with and without ducting is an important activity. During the course of the Creekside project, PG&E's code readiness consultant, 2050 Partners, engaged Frontier in the summer of 2021 to complete a limited modeling assessment of ducted vs. non-ducted cramped closet performance based on the data collected at the Creekside project. More details on this can be found in the Evaporator Airflow Impacts section of this report. The Northwest Energy Efficiency Alliance (NEEA) is also currently in the process of lab testing HPWH closet performance, primarily focused on closet size but also looking at some cases with and without ducting[16].

WORKING WITH MANUFACTURER'S API

The manufacturer's API can be used to communicate directly with the HPWH, enabling remote changes to the operating mode or set temperature. These capabilities enable load-shift or shed events by controlling the energy stored in the HPWH storage tank. While any HPWH from the manufacturer can connect to the internet and be controlled through the API, only units that have been certified to have been installed with thermostatic mixing valves can participate in utility programs.

The API only facilitates scheduling commands (changing mode or setpoint) to the HPWHs. The HPWHs themselves do not store schedules and do not respond to the API server that the command was received. This can cause issues if the internet connection of the HPWH is not constant, or if connection to the API is not constant.

This was an issue found during 2019 lab testing completed prior to the field demonstration at Creekside. During the lab testing the HPWH frequently lost connection with the API, despite not actually losing internet connection. In this case, the current set point would be maintained until connection is restored. Manufacturer technical support staff claimed that the API was still under development at this stage and would improve in time for the field tests.

[15] The installed dual-panel (interior & exterior louvers) louvered doors had 110 in^2 of net free area.

[16] Personal communication from Ben Larson (August 24, 2021).

Supply Voltage Impacts

As occupancy increased and the seasons progressed from fall into early winter 2020, the amount of observed 2nd stage operation increased significantly, particularly for one heavily loaded HPWH unit. Frontier studied the increased energy consumption in detail and noted that the logged 2nd stage electrical demand was considerably less than the nominal 4.5 kW of the installed electrical elements. After further investigation and communications with the project developers, it was determined that the electrical service to the project was 208 Wye rather than the assumed 240 Volt three phase service. Although it is not uncommon for projects of this type to have 240 Volt service, the presence of elevators at Creekside likely contributed to the use of 208 Wye service. Observed voltages at the HPWHs were seen at 210-215 Volts, which resulted in the capacity degradation of the resistive elements. Instead of supplying 4.5 kW, the units were supplying ~3.5 kW. Although the compressor is negligibly impacted by a change in voltage, the reduced 2nd stage output contributes to lower heating output and a greater likelihood of storage tank depletion during high hot water load events.

Closet Condensation Issues

Although ducting was installed in later June 2020 to address the cramped closet issue, the tight closet configuration required uninsulated flex duct to be used due to closet constraints and impinging piping associated with condensate and pressure/temperature relief valve piping. Uninsulated flex duct results in less thermal resistance between the cooled HPWH exhaust air and the closet ambient air, increasing both heat transfer and the potential for condensation on the ducting and other fittings. Condensation potential is further exacerbated by the impact of ducting on airflow due to increased static pressure. The property management team's regular[17] site maintenance activities observed some level of condensation on most, but not all of the HPWHs. Frontier staff toured the project in April 2021 with the property management staff, developer, and architect to review the situation. Although limited condensation was evident on several units, it was determined that the issue was not severe and that an observation and maintenance plan would be the best approach moving forward. As reported by the site maintenance lead, the condensation was a seasonal issue during the colder months when HPWH run hours are longer and the evaporator inlet and outlet air temperatures are lower, increasing condensation potential. No condensation has been observed on the walls of the closet. In hindsight, a slightly larger closet would have allowed for a modified orientation of the HPWH which would have provided sufficient room on the HPWH evaporator exhaust outlet to install insulated ducting, leading to reduced condensation potential.

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[17] Approximately monthly

DATA ANALYSIS

OVERVIEW

This section of the report focuses on the field data results, the Flexi-HPWH validation findings, and results from the full year simulation runs. The results discussion begins with characterization of observed hot water loads amongst the ten monitored HPWHs and additional details on the patterns of usage and how the loading impacted the ability to deliver adequate supply water temperatures to the individual apartments. The data presented then focuses on higher level monitoring findings on operational efficiencies and energy usage (total and time of use) that convey seasonality impacts, load impacts, and the influence of fixed set point operation (i.e. conventional operating mode) versus load-shifting operation. Additional data of selected sample days with high resolution HPWH operation in both fixed and load-shifting modes can be found in Appendix C. The high degree of day-to-day load variability and changing conditions and operating modes with the ten monitoring HPWHs makes it challenging to compare monitoring results in a more refined manner. The authors rely on the validated Flexi-HPWH model to draw these conclusions as the simulation runs fully standardize the input hot water loads and operating conditions.

A key focus of this report is to evaluate the performance and energy impacts of the Creekside shared configuration. Readers should take the findings presented here in that context and accordingly exercise caution in extending the results to a broader perspective.

OBSERVED HOT WATER LOAD CHARACTERISTICS

As occupancy was building during the summer of 2020, hot water loads on the ten monitored HPWHs also increased. Frontier developed a naming convention for the ten HPWHs based on the address of the Raspberry Pi datalogger. The ten HPWHs are denoted as: B9AE, 3CFA, BD13, BA3A, 3DDD, BC4D, 3E98, 3D95, 3E82, and 3D8C.

Table 3 shows that during the prime monitoring period of October 2020 through September 2021, average usage was 92.0 gal/day, or 23.0 gal/day per apartment. The apartments did not have dishwashers, bath tubs, or clothes washers, so the hot water load is comprised solely of showering and bath/kitchen sink use. The average of 23.0 gal/day per apartment is 9% higher than typical mean consumption of 21.1 gal/day for a one bedroom apartment in the Ecosizer tool (Kinter, Banks, Spielman, Grist, & Heller, 2020). The Ecosizer assumptions are based on an extensive historical dataset of hot water usage that is incorporated in the CBECC-Res hot water simulation model. The Creekside apartments did not have bath tubs nor in-unit laundry facilities, making this 9% deviation in reality even larger. The authors surmise that since part of the Creekside tenants are disabled, higher than normal shower consumption may be a factor in explaining higher hot water consumption.

The recent Association for Energy Affordabilty (AEA) EPIC study monitored four separate affordable multi-family projects located in the cities of Calistoga, Cloverdale, Atascadero, and Sunnyvale. The average daily hot water usage over the four projects was 17.7 gal/day per person (23% lower than Creekside).The Atascadero site with unitary HPWHs averaged 14.3 gal/day per person (Dryden, Brooks, & Duff, 2021). Three of the four EPIC monitored sites were farmworker housing with the fourth being low income. It is plausible that Creekside's population of disabled occupants resulted in higher hot water usage.

Average hot water usage by HPWH varied from a low of 52.6 gal/day to a high of 168.9 gal/day, which is a large range given that the four apartment shared configuration already provides an element of load diversity. Although it is difficult to understand how usage between HPWHs could vary by a ratio of three, one factor could be related to the fact that water heating operating costs are paid by the project management company (the John Stewart Company) resulting in some occupants having little concern about their usage. When queried about whether submetering of hot water usage by apartment is a valid approach to controlling occupant hot water usage, the project developer indicated that the John Stewart Company has no interest in the increased administrative burden and headaches associated with managing that issue in their low income projects. If a water usage bill goes unpaid and hot water is cut off to that apartment, the tenant may escalate issues with the on-site manager. Additionally, the bad public relations attention received from cutting off hot water to a family with children, a disabled individual, or a senior is not constructive in maintaining positive relationships with potential renters.

TABLE 3. HOT WATER USAGE SUMMARY BY HPWH

HPWH	AVG USAGE -- GAL/DAY (OCT 2020-SEPT 2021)	STANDARD DEVIATION IN DAILY GAL/DAY
B9AE	168.9	65.5
3CFA	70.6	35.3
BD13	78.9	37.3
BA3A	119.5	49.9
3DDD	81.2	37.7
BC4D	65.1	34.2
3E98	67.4	27.0
3D95	123.3	49.3
3E82	52.6	22.6
3D8C	92.0	44.6
Average	92.0	65.5

Note: 3D95 usage only through late May 2021 due to Btu meter issues on 5/25/21

The monitored data from three of the HPWHs were selected as the low, medium, and high draw profiles for use in the simulation study. As previously mentioned, these draw profiles were selected based on a combination of exhibiting a representative range in hot water consumption, and having fairly steady use patterns during the full year period. The three selected HPWHs were:

- 3E98 was selected for the low use draw profile. It had the third lowest average daily hot water consumption at 67.4 gal/day (16.9 gallons per apartment), and no dramatic changes in consumption during the monitoring period. 3E82 and BC4D both showed lower daily hot water consumption at 52.6 and 65.1 gal/day, but also showed sudden changes in hot water consumption likely indicating changes in occupancy.

- 3D8C was selected for the medium use draw profile as the 92.0 gal/day (23.0 gallons per apartment) hot water consumption in that HPWH matched the daily average hot water consumption in the entire data set. Additionally, the changes in hot water consumption followed smooth seasonal trends indicating no changes in occupancy.
- BA3A was selected for the high use draw profile. At 119.5 gal/day (29.9 gallons per apartment) this was the third highest consuming draw profile. B9AE was highest at 168.9 gal/day (42.2 gallons per apartment), but that draw profile exceeded the average by more than three standard deviations and was considered an outlier. 3D95 had the second highest consumption at 123.3 gal/day (30.8 gallons per apartment), but was excluded because the Btu meter started delivering anomalous data beginning in May 2021.

Figure 10 plots the hot water usage profile by season and time of day, averaged across all HPWHs and all modes of operation. Seasonality effects are evident with noticeably higher usage in winter months than in summer. Interestingly, in comparison with the AEA EPIC data from the Atascadero unitary HPWH site (Dryden, Brooks, & Duff, 2021), only 4.6% of the Atascadero hot water usage was observed to occur between midnight and 5 AM vs. 10.5% for the Creekside monitored units. Clearly different types of multi-family housing will have slightly different profiles. Potentially Creekside's greater fraction of unemployed and disabled occupants likely contribute to the flatter usage profile.

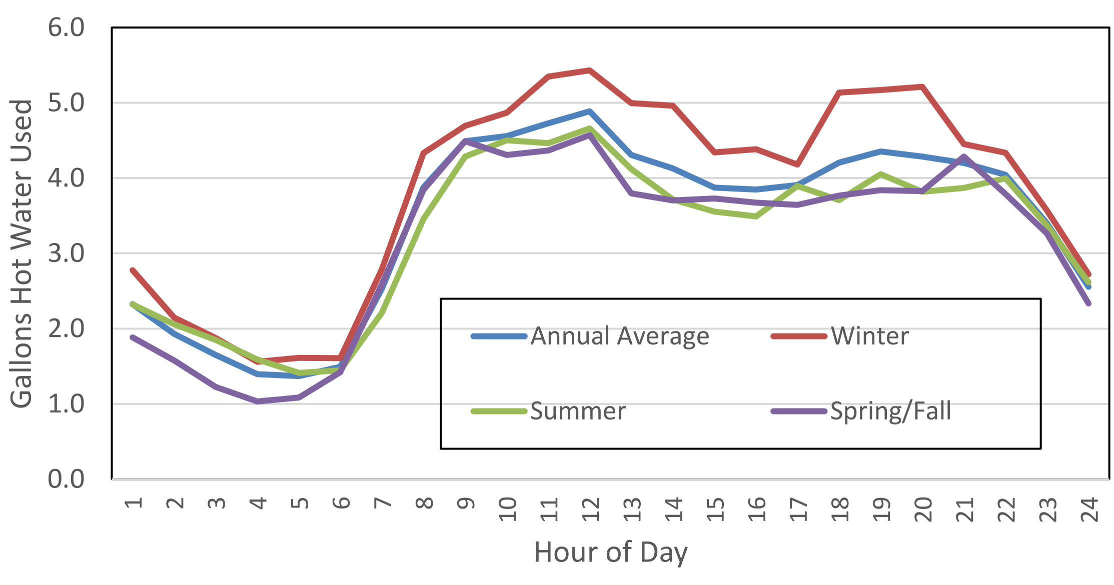


FIGURE 10: AVERAGED TIME OF DAY HOT WATER USAGE (OCT 2020-SEPT 2021)

Figure 11 provides additional insight on hot water usage as it might influence load-shifting operating modes by looking at when hot water loads occur for each HPWH. The plotted data represents the baseline fixed 125°F tank set point for the full 12 month monitoring period. It breaks down the average hot water usage by time periods: the 10 AM – 4 PM pre-peak time period, the nominal 4-9 PM peak period, and the remaining hours of the day. The pre-peak period is the time when a load-shifting HPWH would ideally be biasing operation to boost the tank temperature up to the target to allow for coasting during the peak period. Similarly peak hot water loads characterize how much stored energy is needed during the peak period. On average, 33% of the hot water demand occurs in the pre-peak period and 26% in the 4-9 PM peak period, but the variation is significant with the high use B9AE unit having over three times the hot water demand during the pre-peak period and over double the gallons during the peak relative to the low use 3CFA unit. This variability clearly places significantly different demands on a HPWH when it comes to effectively performing load-shifting.

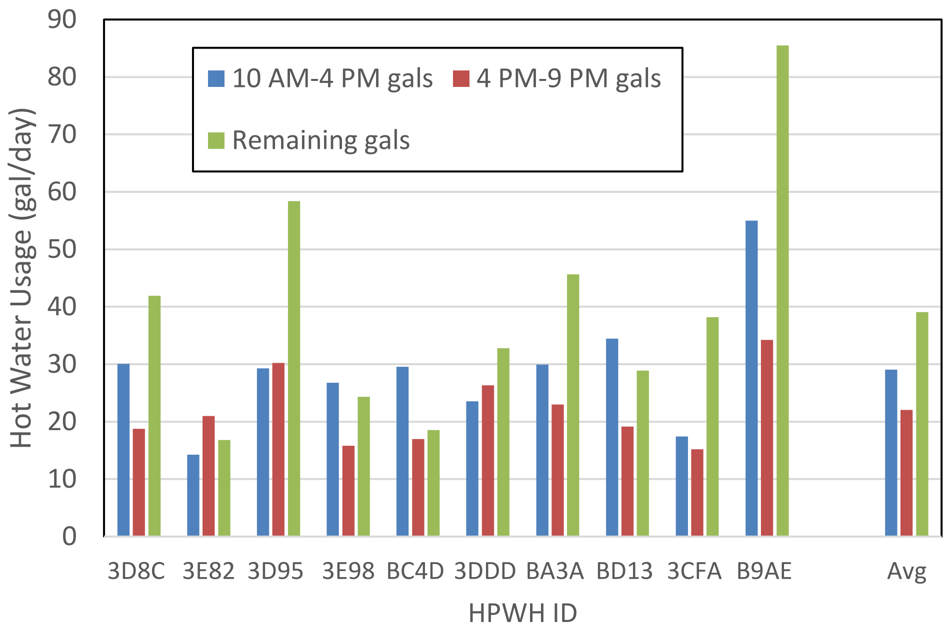


FIGURE 11: COMPARISON OF HOT WATER LOADING PATTERNS ON THE TEN HPWHS

Seasonal variability in hot water usage is highlighted in Figure 12 which includes the daily average in blue and a 15-day trendline in red. Plotting the average hot water demand on the HPWHs from June 2020 (as occupancy was starting to increase) through October 2021 shows a climbing hot water load which peaks at around 110 gal/day in mid-February 2021. Loads in summer 2021 are lower, falling to around 75 gal/day. Changes in the trend line are due to various factors including changes in occupants, as roughly 15% of the apartments experienced new tenants moving into previously occupied units. The yellow vertical line shows the rough timing of "full" occupancy at the site.

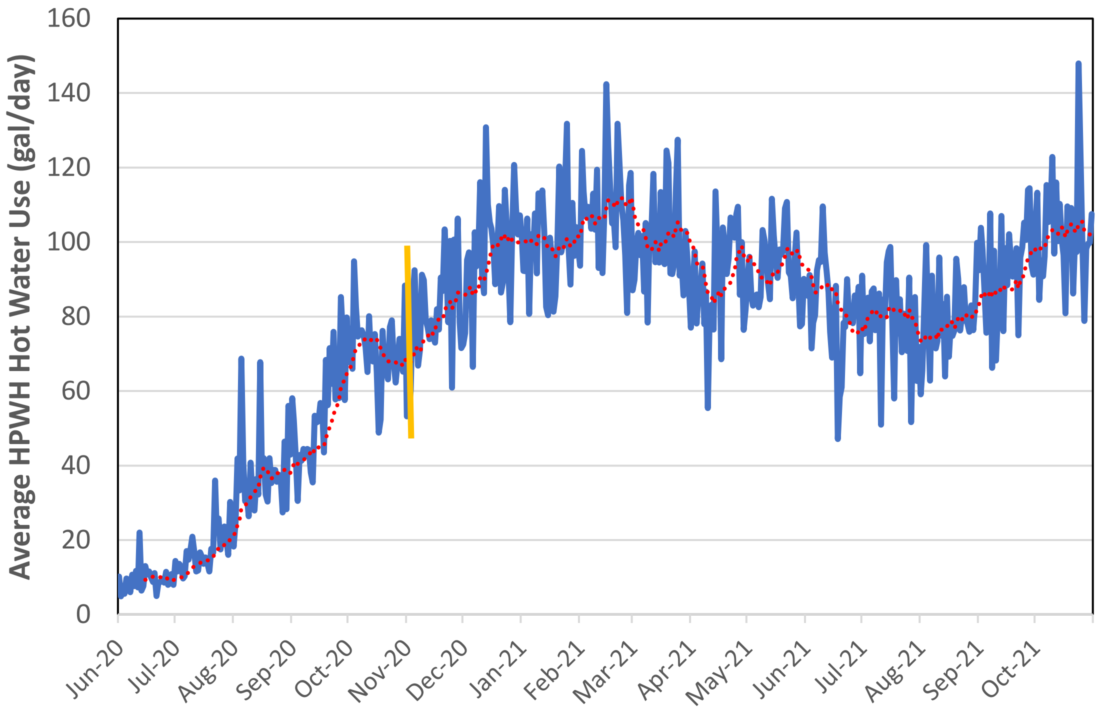


FIGURE 12: AVERAGE HPWH GAL/DAY HOT WATER USAGE

Figure 13 provides similar data, but compares the high user B9AE and the "typical use" 3D8C. Both show the general trend of increasing winter usage and lower summer usage, although that trend is clearer for B9AE. B9AE has regular daily excursions above 200 gal/day usage and rarely falls under 100. 3D8C is regularly below 100 gal/day, but does also have sporadic high usage days.

The energy removed from the storage tank is dependent upon the volume of water removed, and the difference between the HPWH inlet and outlet temperatures. In addition, there are seasonal effects for some uses such as showers in that winter showers will require a higher flow rate of hot water to offset the colder water being mixed at the shower valve. This latter effect is often not fully recognized, but has a significant impact on the hot water use seasonality and the input energy required to satisfy the load[18].

[18] A gallon of hot water delivered in a Lake Tahoe winter day requires considerably more input energy than a gallon in Palm Springs.

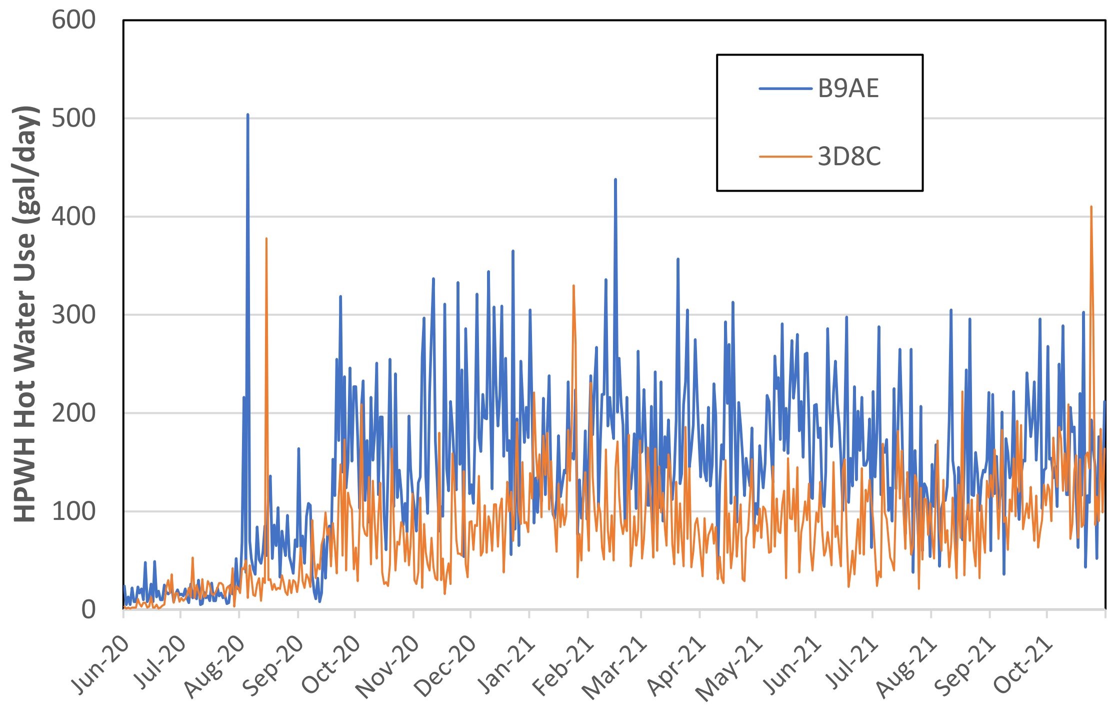


FIGURE 13: COMPARISON OF HIGHEST USE HPWH AND TYPICAL USAGE HPWH

Figure 14 plots daily average inlet water temperature, only while there is active flow from the water heaters, across all ten HPWHs for the period of October 2020 through October 2021. Also plotted are the average daily outdoor temperatures and the standard deviation between the ten HPWHs on the right hand axis. Inlet water temperatures peak around 85°F (late July 2020) and reach a minimum just below 55°F in early January 2021. Interestingly the weather influences on the monitored inlet water temperatures can amount to several degrees of temperature change, as spikes or dips in the daily average ambient temperature has clear impact on the inlet water readings. This type of variability is not uncommon and is a function of climate and water source (well or surface water). Hotter parts of California will see elevated inlet water temperatures throughout the year, while mountainous areas will see colder temperatures. This will impact water heating loads and operating efficiency, especially for technologies like HPWHs, which have a non-linear efficiency with load. Changes in cold water inlet temperature also impact the mixing of hot and cold water for shower draws as well as the mixing at the tempering valve adjacent to the HPWH, since colder water requires more hot water to achieve an adequate mixed temperature.

Also shown on the plot is the assumed cold water inlet temperature used by the CBECC-Res Title 24 compliance software for climate zone 12 (Sacramento area). The hourly CBECC-Res data is plotted against the monitored data from 11/1/20 to 10/31/21. For much of the year the assumed inlet water temperature is more than 10°F lower than the monitored Creekside data. This is most pronounced in early to mid-summer when the deviation is as high as 15°F. On an annual basis, the Creekside data shows an average inlet water temperature of 69.1°F while the CBECC-Res data averages 61.6°F. This difference impacts the magnitude of energy needed for water heating as well as the mixing ratio at end use points such as showers. This variation between monitored and presumed inlet water temperatures has been observed in other monitoring studies (Hoeschele & Weitzel, 2013), which suggests that an improved compliance software algorithm is warranted to improve the accuracy of annual water heating load estimation.

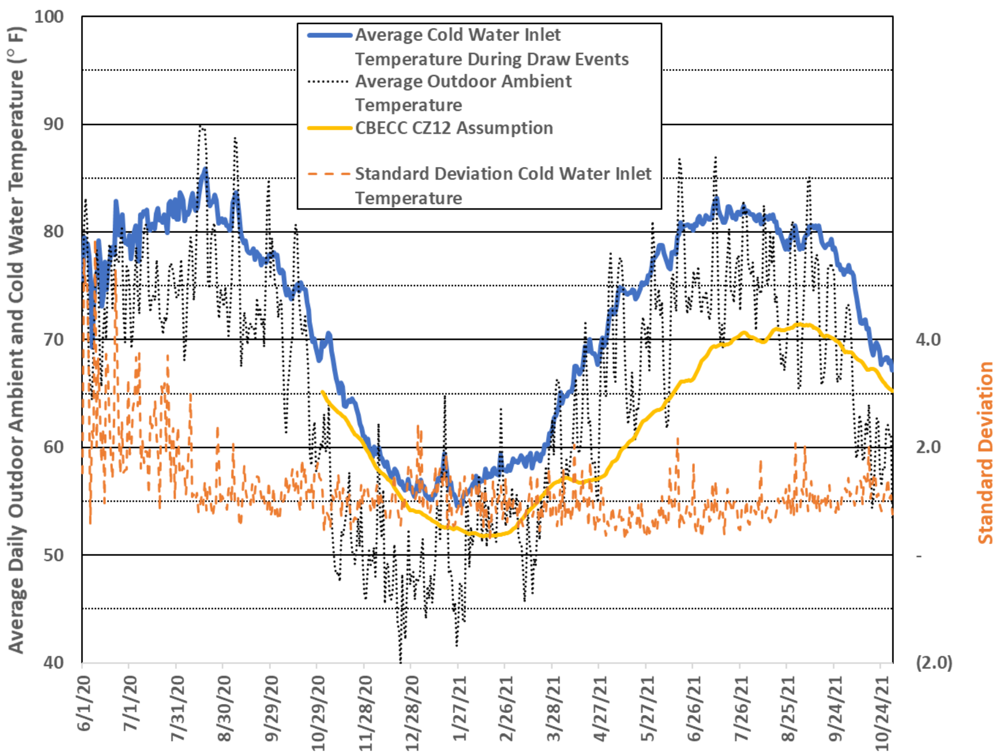


FIGURE 14: MONITORED DAILY AVERAGE INLET WATER TEMPERATURE DURING HOT WATER FLOW EVENTS

Further understanding hot water loads variability is important for characterizing HPWH performance, which entails either efficient compressor only operation, or a much lower 2nd stage efficiency with primary reliance on electric resistance heating. Although the controls on the various HPWH products on the market differ, each model can be found in a control mode where even a small hot water draw might trigger the switch to 2nd stage operation. Of more significance is the impact of extended, high volume, high intensity hot water loads. Figure 15 plots the percentage of all hot water usage that is associated with large volume (> 30 gallon) continuous draw events[19]. The data is disaggregated by HPWH and in two month increments to show changing seasonal effects. Not surprisingly, the highest loaded HPWH (B9AE) has the greatest fraction of usage associated with the large draw volume events, ranging from 17% to 28% of all hot water drawn from the tank. Other HPWHs, such as 3E98 show very few large draw events and no seasonal variation. Also, 3DDD has some

[19] Note: 3D95 Btu meter issues results in no data reporting after May 2021.

initial events, but after January, there were no more events recorded (presumably a change in occupancy). From a seasonal perspective, these events tended to diminish during the summer.

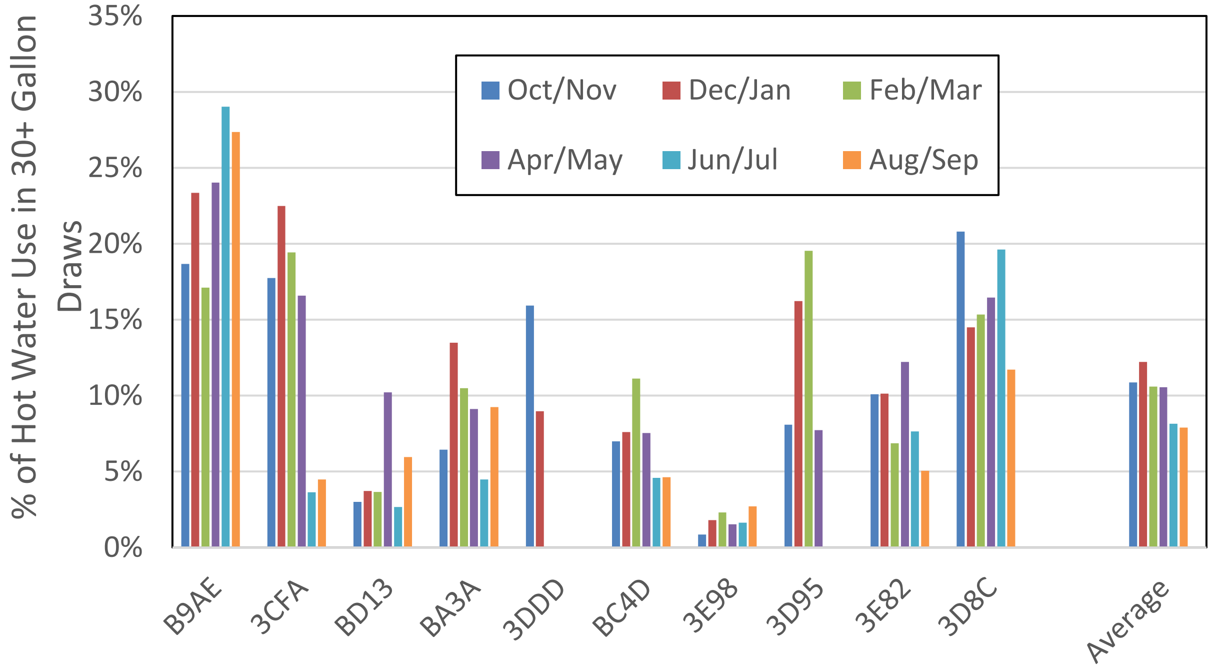


FIGURE 15: PERCENTAGE OF HOT WATER FLOW EVENTS WITH FLOW VOLUMES > 30 GALLONS

These different draw patterns and usage magnitudes not only impacts performance, but also has implications for satisfactory hot water delivery. In the spring of 2020 all of the HPWH units had their mixing valves set at nominally 120°F. Since tank temperatures in all modes of operation were always at a minimum of 125°F, this resulted in an expected 5°F cushion in the tank temperature. Residential electric storage water heaters relative to gas water heaters are anecdotally recognized as having a greater likelihood of experiencing hot water runouts[20], since the input capacity of a typical residential electric water heater is 4.5 kW (~15,400 Btu/hour) vs. the 30,000 to 40,000 Btu/hour input rate of a typical gas storage water heater. HPWHs, which rely primarily on the compressor stage, may have a slightly higher propensity of runouts due to the timing of 2nd stage operation and potential time delays in sensing the added heating capacity result in improved tank outlet water temperature. This impact is exacerbated by the use of 208 volt Wye electrical service at Creekside, which further reduced the resistance heating capacity to 3.8 kW. Figure 16 plots the percentage of hot water leaving the water heater that is less than a 112°F cutoff (eight

[20] Runouts are instances when the hot water outlet temperature falls below a "useful" limit (~ in the 110°F range at the use points).

degrees below the mixing valve setting). The data is disaggregated by HPWH and binned in two month groupings to reflect seasonal effects. Again, high use B9AE shows the largest degraded outlet temperatures, ranging between 6-12% (average of 9.3%) of all hot water flow below the threshold. Averaged across the other nine HPWHs, the annual rate is 4.7% with consistently lower percentages in the warmer months. Runouts are problematic for any water heater, more so for a shared water heater configuration where multiple apartments are impacted. This data compares to a sample of eight data points from the AEA study (Dryden, Brooks, & Duff, 2021) where an average of 2.7% of hot water flow leaving the water heaters was at temperatures less than 105°F (range of 0.3% to 5.8%). The 105°F threshold is more lenient than the 112°F cutoff, and excluding the B9AE data point, the findings are roughly in line.

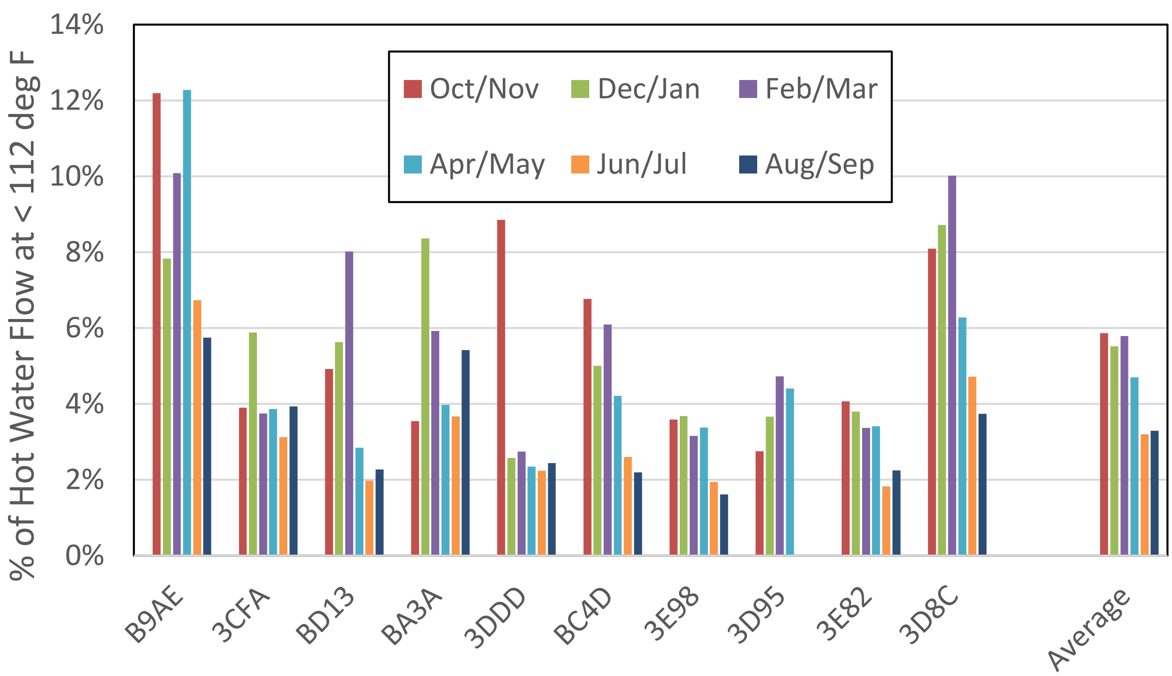


Figure 16: Percentage of Hot Water leaving Mixing Valve at Less Than 112°F

Evaporator Airflow Impacts

The original installation of the HPWHs relied on the louvered door to provide sufficient access to ambient outdoor air, as per manufacturer's instructions at the time of the project design. As discussed later in the report (see Cramped Closet HPWH Installation) the louvered door did not provide for adequate airflow. Early in the project, all 23 closet HPWHs at the site were retrofitted with a flex duct design that allowed the closet doors to be opened for inspection and servicing, while maintaining a robust physical connection to the door. The length and the path of the flex duct from evaporator air exhaust fitting to the door varied slightly by unit based on the orientation of the HPWH in the closet, location of HPWH condensate drain line, and other factors. In general, the installed ductwork was 8-10 feet of 8 inch duct. In some cases, the location of the condensate line imposed an added constriction on the flex duct, further increasing to the airflow resistance.

In the summer of 2021, at the direction of PG&E's Code Readiness consultant (2050 Partners), Frontier completed airflow measurements on the ten monitored HPWHs as well as on an unducted HPWH unit located in the common area building. The goal of this work was to collect field data to support development of Flexi-HPWH algorithms that could allow for model evaluations of ducted, non-ducted, and idealized HPWH performance. Full details on the evaluation effort and findings can be found in Appendix B, with a brief summary below.

The Creekside common area building HPWH unit served as the reference for expected nominal airflow. Airflow measurements on the ducted units were completed using a pressure balanced Duct Blaster configuration, as shown in Figure 17. The unducted "reference" HPWH airflow was measured at 133 cfm. The ten ducted units averaged 73 cfm (ranging from 64 to 77 cfm), or 55% of "nominal" airflow. The reduction in airflow should result in a corresponding increase in the temperature drop between evaporator inlet and outlet air temperature. The measured difference between evaporator inlet and outlet air temperature was found to be 16.2°F for the unducted unit and 31°F for the ducted units. The 58% ratio in air temperatures (16.2/31) is in line with the observed 55% airflow measurement. With the ducted system's lower airflow, the average evaporator temperature is degraded to maintain equivalent evaporator heat transfer. With a 15 degree larger temperature drop in the ducted configuration, the average evaporator temperature is reduced by 7.5°F, negating some of the benefits of the duct remediation effort.

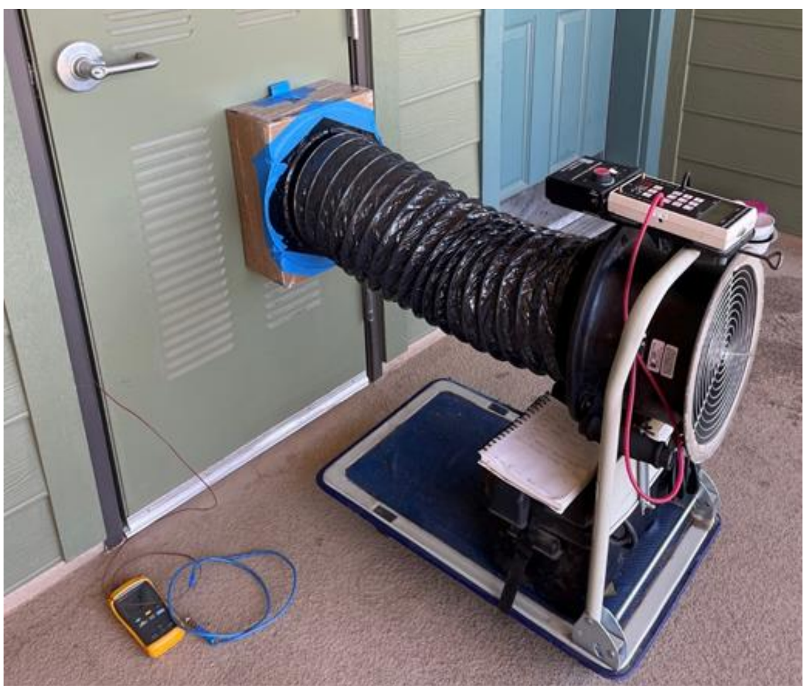


FIGURE 17: DUCTED AIRFLOW MEASUREMENT SETUP

In addition to the impact of the ducting, data collected prior to the ducting retrofit was available to characterize HPWH performance if the HPWH operated in a small closet with a louvered door. Flexi-HPWH approximated the cooling effect of the HPWH in the closet by reducing the closet air temperature by 11 °F, based on the average observed difference in the monitored data. Full year modeling was completed using a Creekside hot water load case with a 90 gal/day average hot water load. A new algorithm representing the impacts of the Creekside ducting installation was added to Flexi-HPWH, implementing the 7.5°F decrease in evaporator air inlet temperature when the exhaust is ducted to the outdoor environment. The results of the analysis indicate that relative to the HPWH operating in a cramped closet without ducting, the Creekside ducting retrofit as described above, would reduce annual energy consumption by 14%. An idealized scenario with no assumed recycled air thermal impacts (i.e. a very large closet space) was found to reduce annual energy usage by 22% relative to the non-ducted case. The ducted performance algorithm was used in all subsequent performance modeling efforts in this study to represent the observed Creekside configuration. Although there are certainly different multi-family building configuration which may facilitate operation in more open environments where exhaust air recycling is not a concern, it most likely would involve HPWHs further from the apartments leading to increased piping distribution losses and the need for recirculation pumps.

Alternative HPWH closet or enclosure designs for multi-family applications will have different thermal influences. For example, the unitary HPWHs installed at the Atascadero EPIC project (Dryden, Brooks, & Duff, 2021) were housed in a large metal shed enclosure on the roof of the building. In comparison to the cramped Creekside closet, the Atascadero configuration is more exposed to daytime solar effects and nighttime exposure to colder temperatures and night sky radiation. These two configurations experienced very different relationships to outdoor conditions. The EPIC report indicates that nighttime shed temperatures were typically zero to 3°F colder than outdoors and summer mid-day shed temperatures were 4-8°F warmer than outdoors. This contrasts with Creekside findings where the average closet temperature during HPWH operation was ~10°F warmer during non-solar night hours and roughly equal to outdoors during the mid afternoon in winter, and ~5°F cooler than the outdoor temperature in mid-summer[21]. Clearly different closet/shed configurations, climates, and need for ducting will have significant impacts on evaporator air inlet conditions.

HPWH Modes Of Operation

During the course of the field monitoring, the HPWHs were operated in a variety of modes to observe performance under different control settings, as well as evaluate seasonal performance impacts in the different modes. Load-shifting operation was focused on raising set points and building load during the period from early morning at 8 AM to the start of the on-peak period, generally at 4 PM but in some cases 2 PM, and then relaxing set point to the nominal 125°F setting for the remaining hours. Frontier coordinated with the Creekside property management staff in implementing modes. Their preference was to keep the systems at a "nominal" fixed set point of 125°F to minimize operating costs. Frontier was judicious in implementing changes based on their preferences, while satisfying the research

[21] See Figure 1 in Appendix B for Creekside data.

needs of the project. The following outlines most of the modes implemented during the monitoring period:

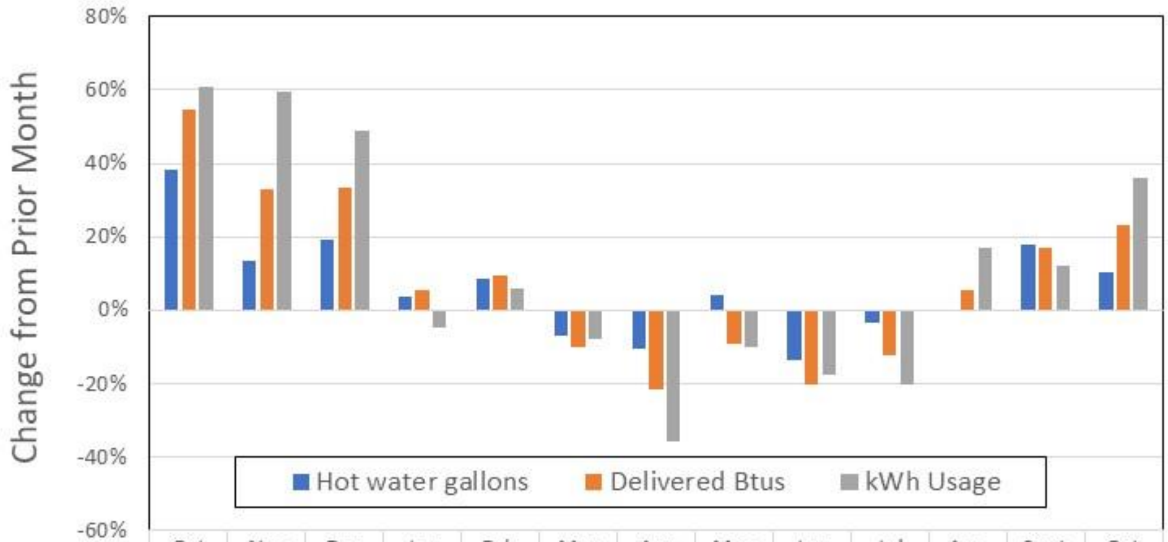
- **Mode 0**: Fixed 125°F set point for all hours;
- **Mode 0a**: Fixed 130°F set point for all hours;
- **Mode 0c**: Early AM boost (127°F from 2-3 AM, 129°F from 3-4 AM, 131°F from 4-5 AM), with all other hours at fixed 125°F set point[22] ;
- **Mode 1a**: Load-shifting with nominal 125°F set point, with jump to 140°F from 9 AM to 4 PM;
- **Mode 2**: Load-shifting with nominal 125°F set point, with jump to 140°F from 9 AM to 2 PM;
- **Mode 2b**: Load-shifting with nominal 125°F set point, with stepped increase to 140°F from 9 AM to 2 PM (9-11 AM, 132°F set point; 11 AM-1PM, 140°F set point);
- **Mode 3**: Load-shifting with nominal 125°F set point, with stepped increase to 140°F from 8 AM to 4 PM (8-10 AM, 128°F set point; 10 AM-12PM, 132°F set point; 12-2 PM, 136°F set point; 2-4 PM, 140°F set point); and
- **Mode 4**: Load-shifting with nominal 125°F set point, with stepped increase to 133°F from 8 AM to 4 PM (8-10 AM, 127°F set point; 10 AM-12PM, 129°F set point; 12-2 PM, 131°F set point; 2-4 PM, 133°F set point).

HPWH Operation: Control Impacts, Energy Usage, Efficiency

As previously noted, there is a strong seasonality in hot water usage due to various factors including changes in cold water inlet temperature, lower distribution losses, and potentially behavioral changes in how hot water is used between winter and summer. This variability is dependent on climate and also the source of water such as well water, surface water, or a mix as is the case at Creekside. Figure 18 plots the changes in monitored hot water use (gallons/day), thermal energy delivered in Btu's, and HPWH energy consumed. The plot averages the data across all HPWHs and does not distinguish between HPWH operating mode.

The plot is useful in highlighting some general trends. On the left side of the plot October 2020 shows a significant increase in all three metrics relative to September 2020, at least partly due to increases in occupancy. Additionally, the start of Fall results in declining inlet water temperatures, hence the delivered Btu's monthly increase is greater than the increase in gallons of hot water consumed. Roughly similar magnitude impacts are shown for November and December, as occupancy continues to build and inlet water temperatures are falling. January and February show small impacts, but March provides an indication that inlet water temperatures are starting to rise. Reductions in the three metrics continue through July. In August, although hot water volume is essentially identical to July, falling inlet water temperatures result in slightly increasing loads and energy usage.

[22] Implemented later in project at direction of PG&E code readiness consultant to look at the ability to mitigate 7-8 AM 2nd stage demand peaks during winter by overheating storage earlier in the night.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Hot water gallons	38.4%	13.6%	19.2%	3.5%	8.7%	-7.0%	-10.4%	4.3%	-13.7%	-3.4%	-0.1%	17.8%	10.6%
Delivered Btus	54.8%	32.8%	33.3%	5.3%	9.5%	-10.1%	-21.3%	-9.3%	-20.2%	-12.2%	5.4%	17.0%	23.2%
kWh Usage	60.8%	59.5%	48.8%	-4.7%	6.0%	-7.9%	-35.7%	-9.8%	-17.7%	-20.2%	17.0%	12.2%	35.9%

FIGURE 18: MONTH TO MONTH VARIATIONS IN USAGE IN ALL MODES (HOT WATER, BTUS, KWH)

The impact of water heater recovery load on operating efficiency for HPWHs has some similarities to other storage water heaters (both electric resistance or gas storage), but also some differences. Similar to any type of storage water heater, the energy required to offset standby losses is a primary performance degradation term. As hot water loads rise, system operating efficiencies will increase up to a point. For gas storage water heaters, annual efficiency will continue to increase and asymptotically reach a maximum as the standby energy becomes a smaller fraction of the total water heater recovery loads. For HPWHs, which are impacted by increasing likelihood of 2nd stage operation at higher water heating loads, long term efficiency will reach a maximum value at a certain gal/day level, and then start to decline as 2nd stage operation becomes increasingly necessary to satisfy the hot water loads. The peak efficiency will vary somewhat from one HPWH to the next depending upon on the precise hot water demand characteristics in terms of hot water flow rates and flow durations.

Figure 19 plots average operating COP of each HPWH versus average daily hot water load during the October 2020 to September 2021 period. The data shown are for all modes of operation and clearly indicate a downward performance trend as hot water loads exceed 125 gal/day. Average COP for all ten HPWHs was found to be 1.96. All the individual HPWHs, with the exception of two, were within 5% of the 1.96 average; HPWH BD13 at 78.9 gal/day was 11% higher than average, and the highest use B9AE HPWH was 19% below the average with an average COP of 1.58. It is interesting to note that BD13 had the second lowest level of large volume draws of >30 gallons and B9AE had by far the highest fraction of large draws (nearly 5 times higher than BD13).

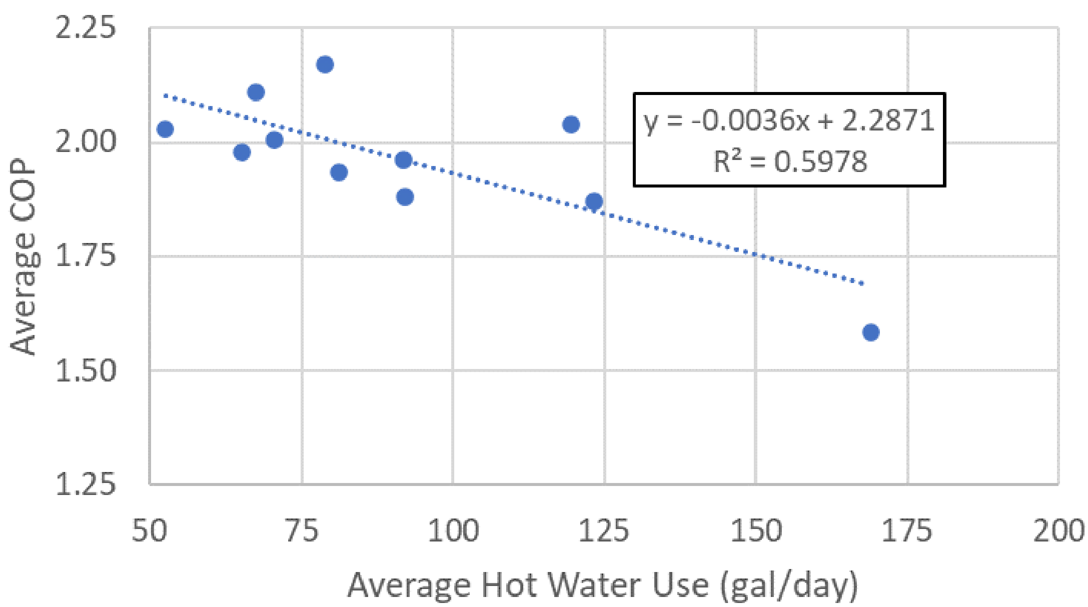


FIGURE 19: AVERAGE ANNUAL COP BY HPWH IN ALL MODES

Figure 20 provides a bit more precision by looking at only the default Mode (Mode 0) and presenting COP's by HPWH for both mid-summer (July and August 2021) and mid-winter (January and February 2021) periods of time. The plot reinforces several key characteristics of HPWH performance:

- Using the second order regression curve as a guide, average COPs range from 0.3 to 1.0 COP point higher in summer, depending on hot water load; and
- Hot water loads are considerably lower in summer with five HPWHs under an average of 75 gal/day in summer, but only one in winter.

Optimal efficiency as a function of load (based on the regression curve) suggests summer optimal efficiency is achieved at ~110 gal/day, while in winter the optimal efficiency is achieved at ~ 75 gal/day. The higher loading on the HPWH in winter due to colder inlet water temperatures and reduced evaporator air inlet temperature results in increased 2nd stage operation and reduced operating efficiency.

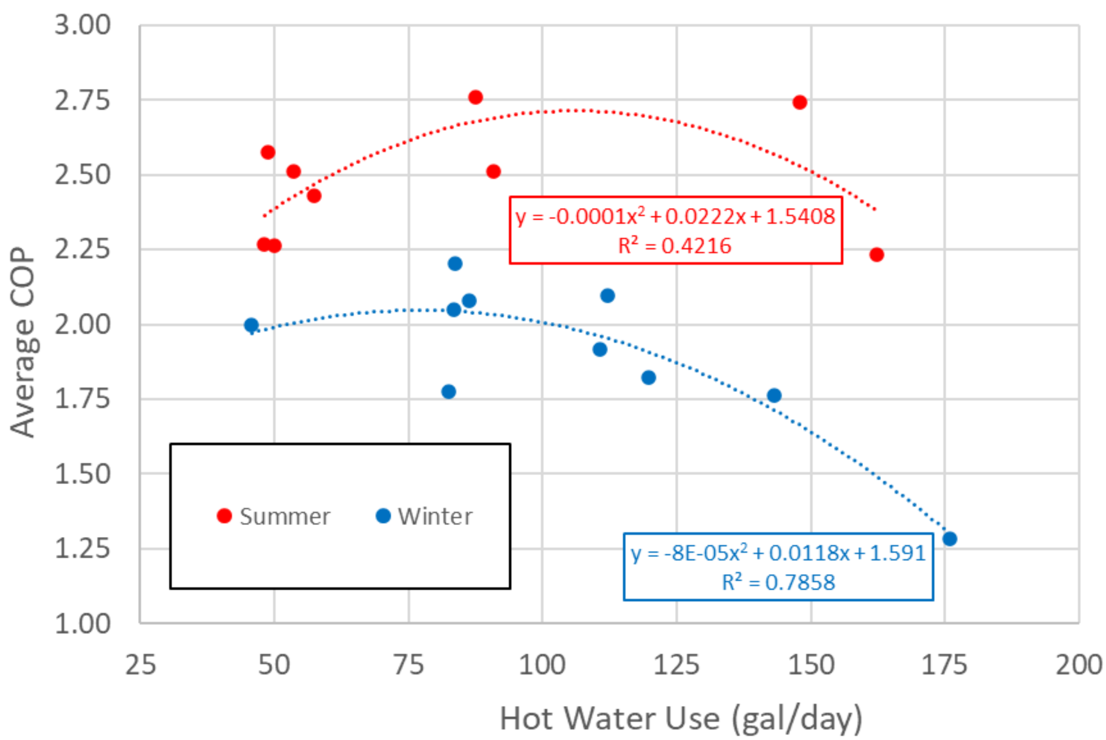


FIGURE 20: AVERAGE SEASONAL COP BY HPWH IN FIXED SETPOINT MODE 0

Figure 21 plots 2nd stage energy as a fraction of total energy versus average daily hot water loads in all modes of operation over the year. Keep in mind that for the monitored data, 2nd stage energy is comprised of all HPWH energy usage, compressor plus RH, unlike the modeling results which explicitly break out RH from total HPWH usage. Therefore as hot water usage increases, the percentage of 2nd stage usage also increases. The trend is fairly strong, with an exception being the HPWHs with annual usage around 70 gal/day. Two units (BD13 at 29% and 3CFA at 32%) are much higher than 3E98 which is at only 16%. This suggests that use pattern in terms of draw intensity may play a role in the difference. Of particular note is that 3E98 had by far the lowest rate of occurrence of high volume hot water draws (see Figure 15).

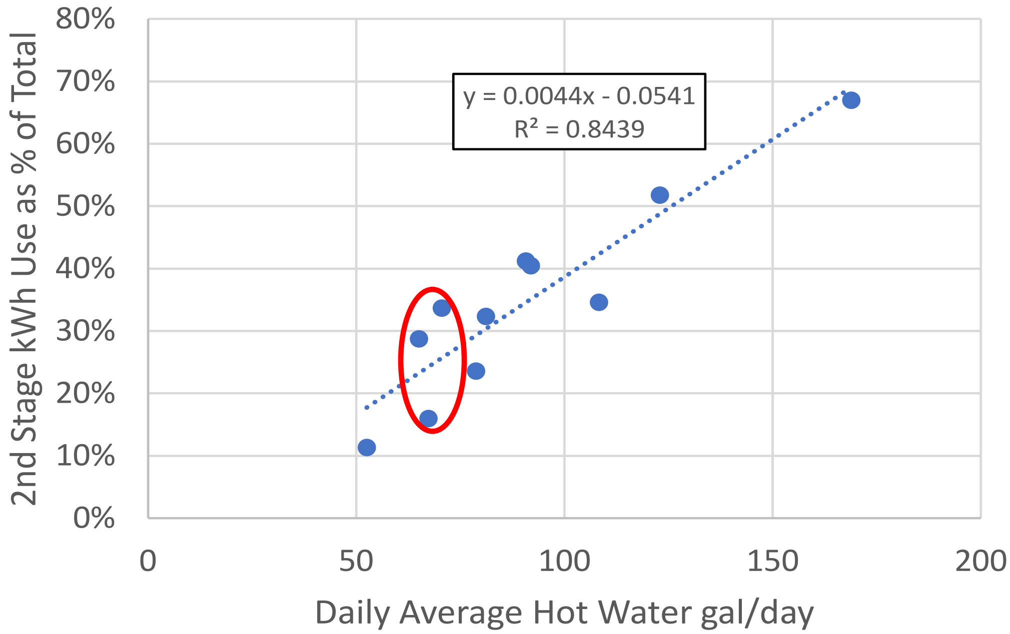


Figure 21: Fraction of 2nd Stage HPWH Electrical Consumption in all Modes

Results conveyed earlier in this report presented in detail the hot water load variability (both seasonally and between the ten HPWHs), patterns of hot water use, prevalence of large volume draws, and high level reporting of operating efficiency COP as a function of hot water load magnitude. With this study focusing on load-shifting, the monitoring data presented now transitions from a discussion of high level HPWH performance to a more targeted assessment of the differences between conventional operation of maintaining a fixed set point and various load-shifting strategies that were demonstrated. The variability in hot water loads in each mode of operation precludes drawing detailed conclusions from the monitoring data, but it is useful for conveying performance trends.

Table 4 aggregates all data across the ten HPWHs into the most common modes providing a high level assessment of hot water loads, performance, and impact on 2nd stage operation. Not all modes are shown since the number of days for some modes were limited. It is also important to note that although data collection over the 12 month period was nearly 100% continuous, nearly 25% of all days could not be fully assigned to a specific mode due primarily to API control problems[23] or unrelated communication issues. Additional items of note:

[23] API issues included the HPWH not following the scheduled set point changes, or only partially following those changes.

- Mode 0a (fixed 130F setpoint) was more commonly used in the winter, partially to provide additional stored energy during the highest load season. This winter-biased operation is reflected in the high hot water loads, low average evaporator air inlet temperature and resulting COP, and high 2nd stage energy use percentage.
- The two load-shifting modes of operation (2B and 3) show a significant reduction in the percentage of hot water at the mixing valve below the 112°F comfort temperature (4.1 to 4.6% vs. 5.8 to 7.2% for the fixed setpoint cases). This is presumably due to the storage tanks being at a higher average temperature due to the pre-peak load-shifting.

TABLE 4. CONDENSED SUMMARY OF OBSERVED HPWH PERFORMANCE BY KEY MODES

MODE	NUMBER OF DAYS	AVERAGE GAL/DAY	AVERAGE TINLET AIR TEMP (°F)	AVERAGE COP	2ND STAGE RH KWH %	% UNSATISFIED HOT WATER LOADS	% OF HOT WATER USE IN LARGE VOLUME DRAWS
0	1,011	88.7	67.4	2.10	31.6%	7.2%	11.5%
0A	335	109.1	63.2	1.64	56.9%	5.8%	16.4%
2B	195	93.9	73.2	2.07	32.2%	4.1%	11.9%
3	571	89.8	68.1	1.92	37.9%	4.6%	12.7%

To better convey performance trends, the monitoring data by operating mode was disaggregated by evaporator air inlet temperature, as a proxy for outdoor air temperature. Evaporator air inlet temperature is a primary parameter impacting performance and serves to characterize performance of the Creekside installations recognizing both the closet's and outdoor weather impact on the temperature, as well as the ducting's impact on airflow across the evaporator.

Figure 22 plots the average daily COPs in the various modes after binning the daily average operating evaporator inlet temperature into ~5°F temperature bins. Combining the two fixed setpoint Modes and the two load-shifting Modes provides for more clarity in the plots. At the low end of the inlet temperatures the average COPs are comparable but start to diverge as the evaporator temperature increases to the upper 80's. At 85°F inlet air temperature the fixed setpoint Modes operated at an average COP ~10% higher than the load-shifted cases.

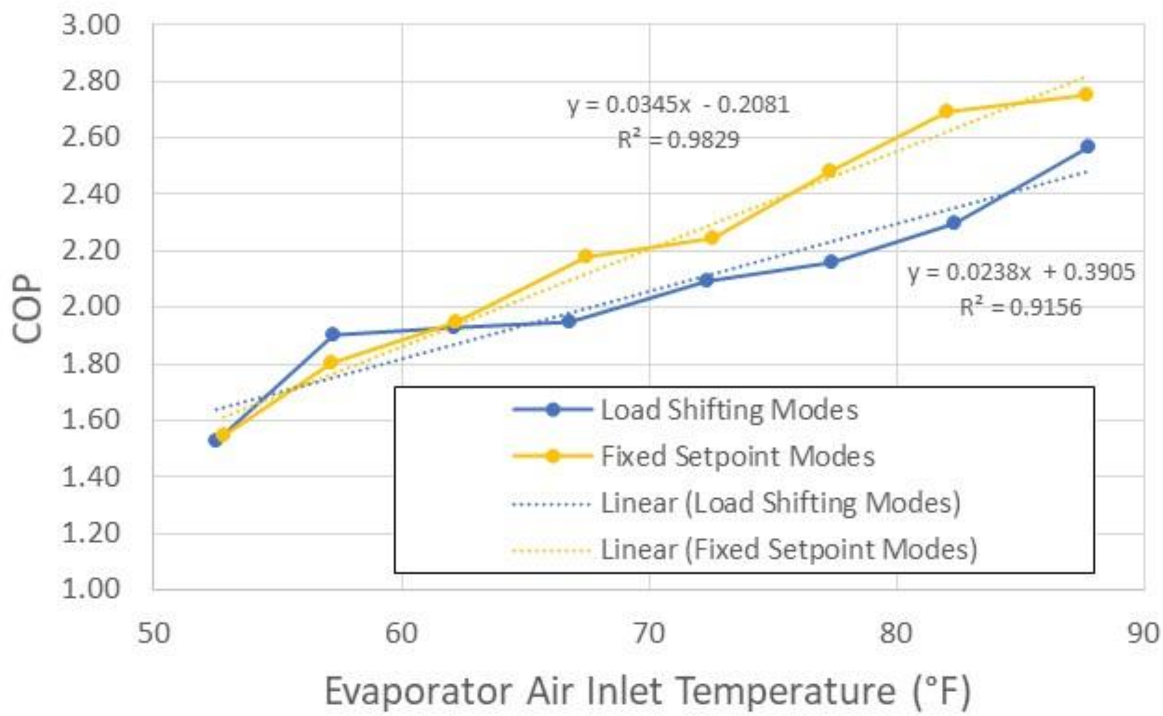


FIGURE 22: VARIATIONS IN COP AS A FUNCTION OF MODE AND EVAPORATOR AIR INLET TEMPERATURE

Figure 23 provides additional insight on this. Again, at low evaporator air inlet temperatures the trend lines indicate that roughly half the energy consumed by the HPWHs was in 2nd stage operation. However from inlet temperatures between the mid 60's to the high 80's, the load-shifting Modes showed consistently higher 2nd stage energy consumption than the Fixed Mode cases, presumably due to greater likelihood of triggering 2nd stage during the pre-peak tank ramp up periods where the deviation between the target setpoint and actual tank temperatures are increased. This factor likely contributed to the increasing COP discrepancy in Figure 22.

The variation in 2nd stage energy consumption with evaporator inlet temperature demonstrated in Figure 23 is clear and highlights the impact of climate on HPWH performance. Well over half the HPWH usage is 2nd stage at the coldest inlet air condition, but less than 10% at the warmest condition. These findings can be compared to the AEA EPIC monitoring of unitary HPWHs in the Atascadero, CA climate. In the AEA study 64% of the HPWH energy consumed in Energy Saver mode during the January to August period was 2nd stage electric resistance heating. This result is higher than observed in the Creekside data, and could be due to both warmer inlet air conditions at Creekside (due to the tempered closet relative to the exposed rooftop metal sheds at Atascadero) and also patterns of hot water usage.

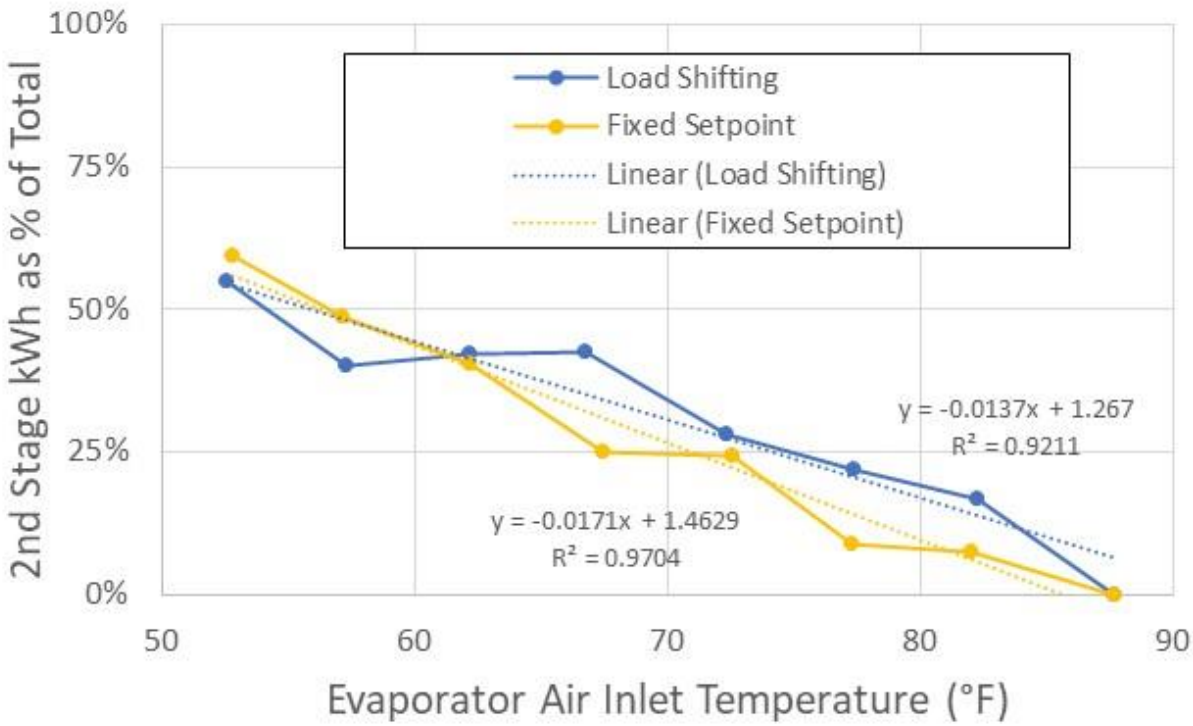


FIGURE 23: VARIATIONS IN 2ND STAGE ENERGY USE FRACTION AS A FUNCTION OF MODE AND EVAPORATOR AIR INLET TEMPERATURE

Figure 24 ties together the impacts of varying COP, percentage of 2nd stage operation, and HPWH inlet water temperature seasonality together in a graph showing the change in energy use intensity through the range of evaporator inlet air temperatures experienced during the Creekside monitoring. The graph clearly highlights the impact of 2nd stage operation as under the warmer inlet air conditions the energy intensity for the load-shifting mode was ~20% higher than the fixed set point cases. During the colder time of the year, where the evaporator air inlet temperature is ~65°F and below, there is no appreciable difference in this metric.

Averaged over all modes, HPWH electricity consumption ranged from 8.4 kWh/100 gallons hot water delivered at an average evaporator air inlet temperature of 53°F (mid-winter), to a low of about 3.0 kWh/100 gallons at an average evaporator air inlet temperature of 82°F (mid-summer). This range reflects the impact of warming inlet temperatures (both water and evaporator air) associated with summer operation, as well as the improved efficiency and reduced 2nd stage operation during warm weather. These seasonal energy use intensity findings are in line with the Atascadero EPIC data (Dryden, Brooks, & Duff, 2021)[24].

[24] See Figure 21.

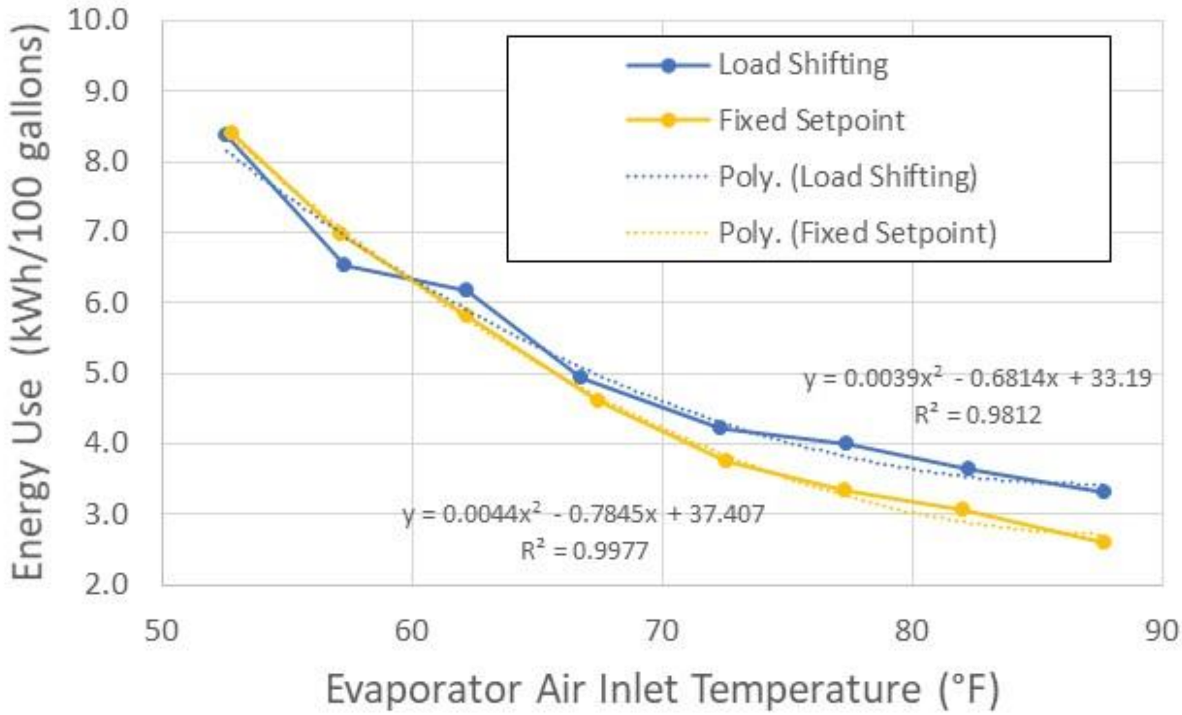


FIGURE 24: VARIATIONS IN ENERGY USE PER 100 GALLONS DELIVERED AS A FUNCTION OF MODE AND EVAPORATOR AIR INLET TEMPERATURE

Figure 25 plots the percentage of total HPWH monitored energy usage by three time periods: the nominal 4-9 PM peak period, the preferred pre-peak "solar available" period of 10 AM to 4 PM, and all other hours[25]. The data are aggregated for the two fixed setpoint modes (0 and 0A) and for the two predominant load-shifting modes (2B and 3). In terms of the 4-9 PM peak period usage, the red and orange lines convey the reduction in on-peak consumption with the load-shifting strategies. The shedding benefits are fairly consistent throughout the range of evaporator inlet air temperatures, with the one deviation occurring at the binned temperature around 57°F. In terms of load building during the 10 AM – 4 PM "solar availability" hours, the load-shifting cases increase the proportion of energy usage during these times, with some indication that the concentration of usage during these hours increases with evaporator air inlet temperatures above 70°F, presumably as the mid-summer conditions allow the HPWH's to more effectively bias usage to mid-day.

[25] As a percentage of total usage, this graphical representation does not account for differences in overall energy usage, but does convey load shifting and shedding trends.

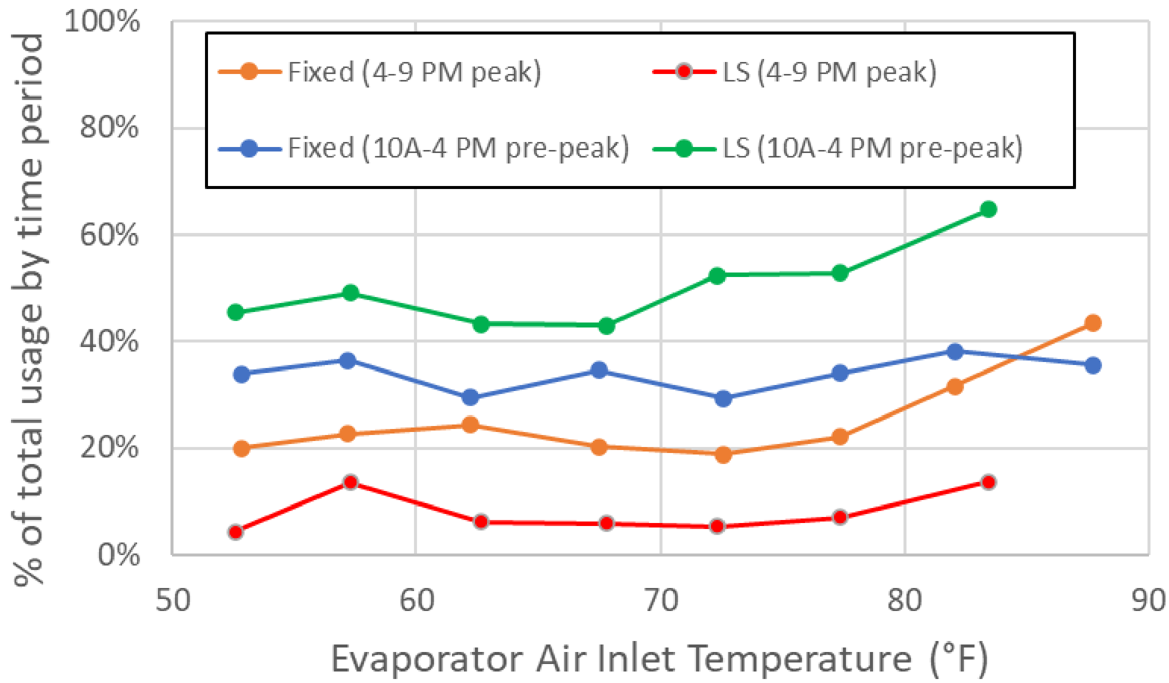


FIGURE 25: TIME OF USE ENERGY IMPACTS AS A FUNCTION OF MODE AND EVAPORATOR AIR INLET TEMPERATURE

Figure 26 plots the same data in an area plot with fixed and load-shift mode data for the same evaporator air inlet temperature binned side-by-side. The box on the left hand side of the graph highlights the initial pair of datapoints – fixed and load-shift – at the 52°F bin to facilitate comparisons. The remaining points follow the same pattern. This more clearly conveys the TOU impacts as inlet air temperatures rise. The first two data points shown in the highlighted box are for the lowest evaporator temperature bin (~52°F) and shows how pre-peak energy increases with load-shifting and on-peak energy decreases. The green area "peaks" correspond to load-shifting (minimized distance between green and orange) and "valleys" reflect fixed set point operation.

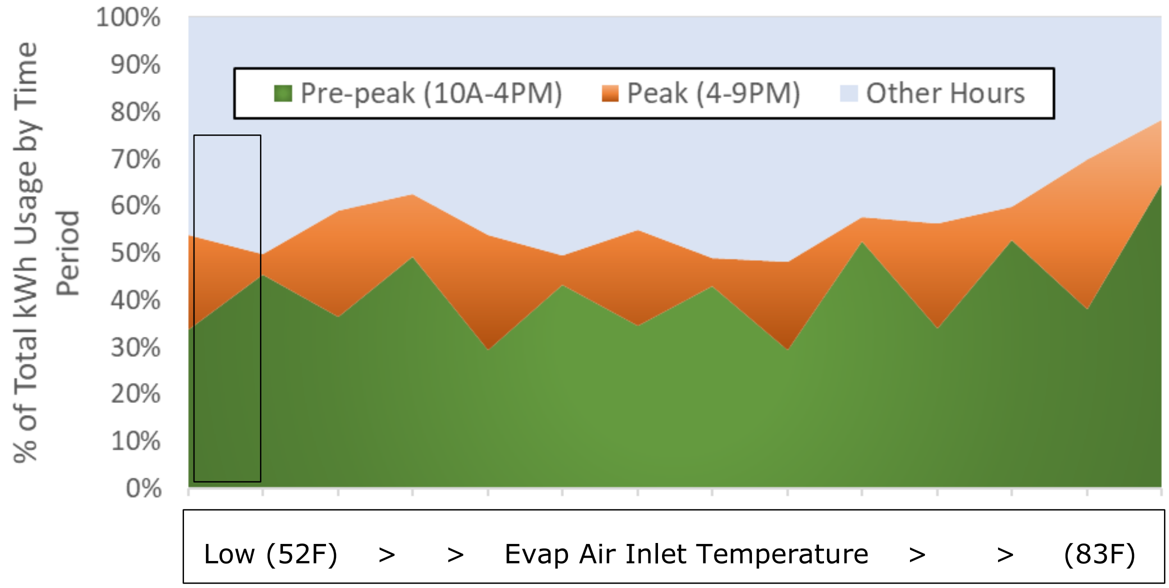


FIGURE 26: AREA PLOT OF TOU ENERGY IMPACTS AS A FUNCTION OF MODE AND EVAPORATOR AIR INLET TEMPERATURE

Further in-depth look at monitored fixed setpoint and load-shifting operation is provided in Figures 27-29. These figures average the demand profiles for all HPWHs in Fixed and Mode 3 operation for the months of February, April, and July 2021. The y-axis range of the three graphs (0-1.0 kW) are identical to better highlight seasonal differences between the three plots. Since different HPWHs operated a varying amount of time each month in different modes, this represents a qualitative picture of relative performance which doesn't account for variations in hot water load and other factors.

Figure 27 clearly shows the load-shifting operation beginning at 9 AM and continuing to 1 PM. In the hours immediately prior to the 4 PM peak, average HPWH demand between the two modes is fairly close, but for the full 9 AM to 4 PM period, the load-shifting mode consumed 29% more energy in total, while boosting the storage tank targets. During the 4-9 PM peak period, initial load shedding is good, but the high winter hot water loads result in increasing Mode 3 consumption in the later hours of the peak. For the full five hour peak period, average aggregated electrical demand in the 4-9 PM period is reduced by 54%.

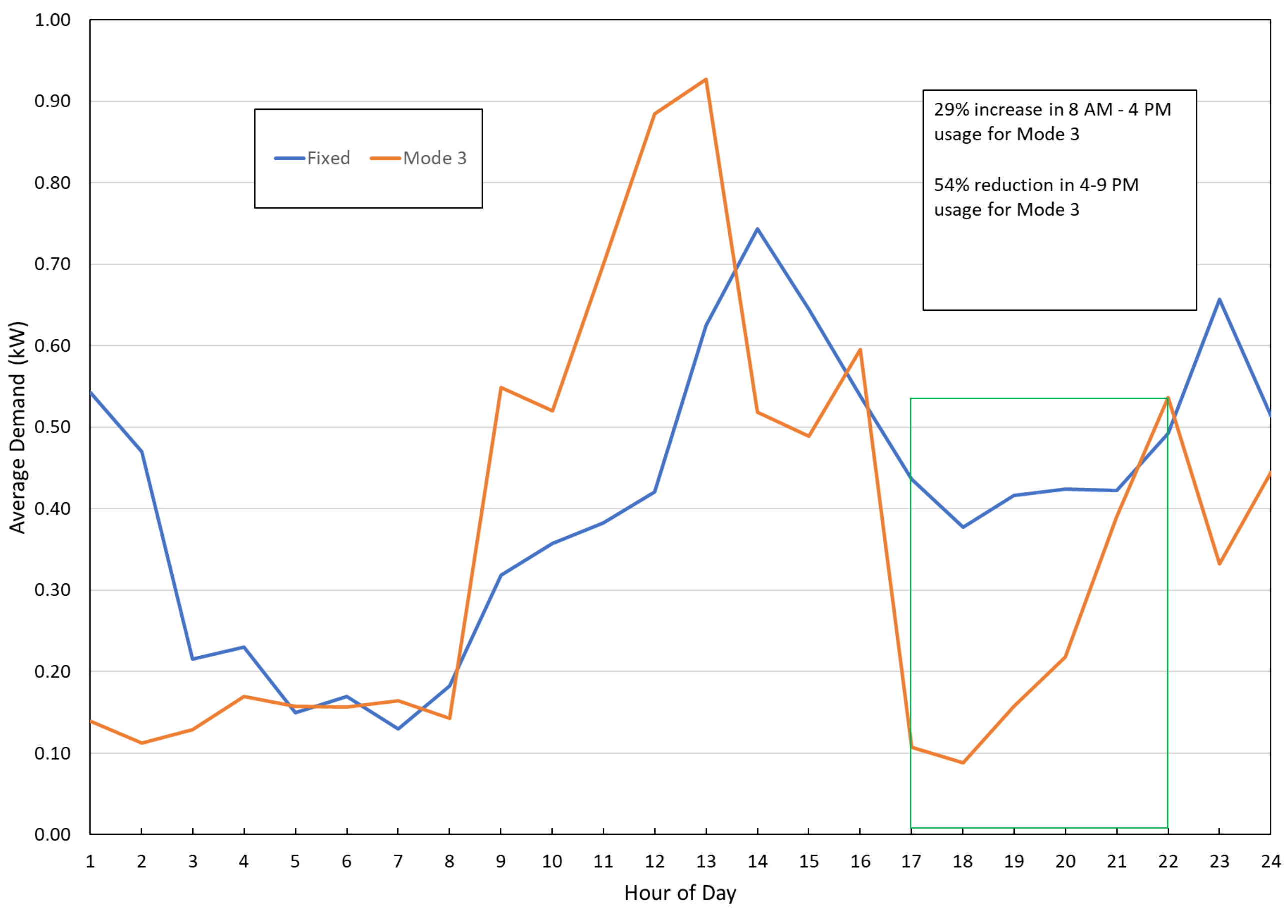


FIGURE 27: FEBRUARY 2021 COMPARISON OF AVERAGE DEMAND PROFILE FOR FIXED SETPOINT AND LOAD-SHIFTING MODES

Figure 28 and 29 provide similar data for April and July, respectively. In April, Fixed mode is flatter with peak hourly demand roughly half that of February. Load building consumption in the 8 AM to 4 PM period is evident, but also less pronounced. A 30% increase in pre-peak usage is tabulated. On-peak load shedding is more evident, with a more consistent reduction through the 4-9 PM peak (65% total reduction vs. Fixed operation).

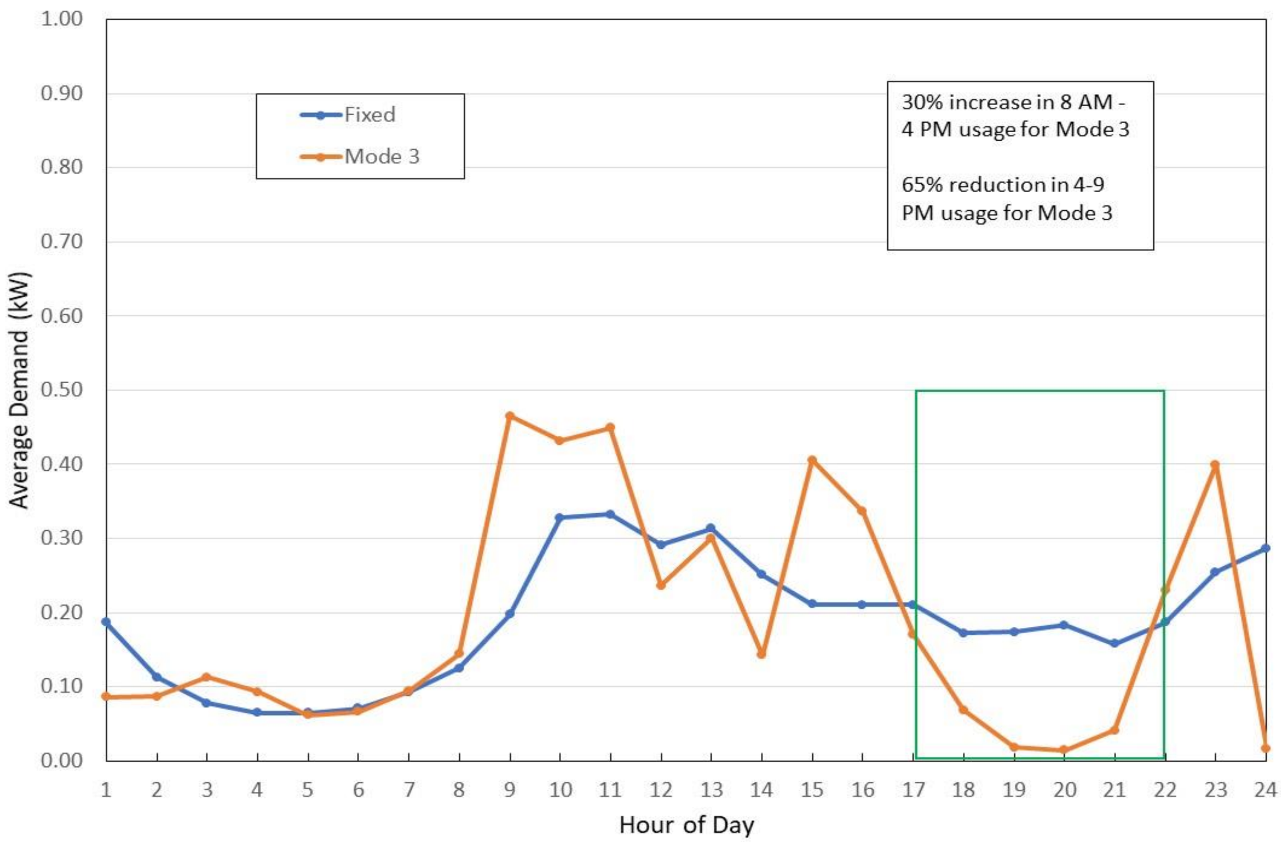


FIGURE 28: APRIL 2021 COMPARISON OF AVERAGE DEMAND PROFILE FOR FIXED SETPOINT AND LOAD-SHIFTING MODES

Figure 29 clearly shows the reduction in energy required to meet the summer water heating loads. The Fixed mode profile is a bit flatter than the prior months. Load building is evident with a 58% increase in 8 AM to 4 PM consumption. More impressively, the on-peak reduction is 95% with almost no operation shown.

The three graphs highlight the effectiveness of load-shifting during the hotter summer months (or for hotter climates), as well as the challenges of getting through a full five hour peak period under cold winter conditions. Since the electricity grid currently has a summertime peak challenge this result demonstrates that mitigation of peak demand is feasible. The authors reiterate that these average demand profiles do not account for deviations in hot water load nor operating conditions.

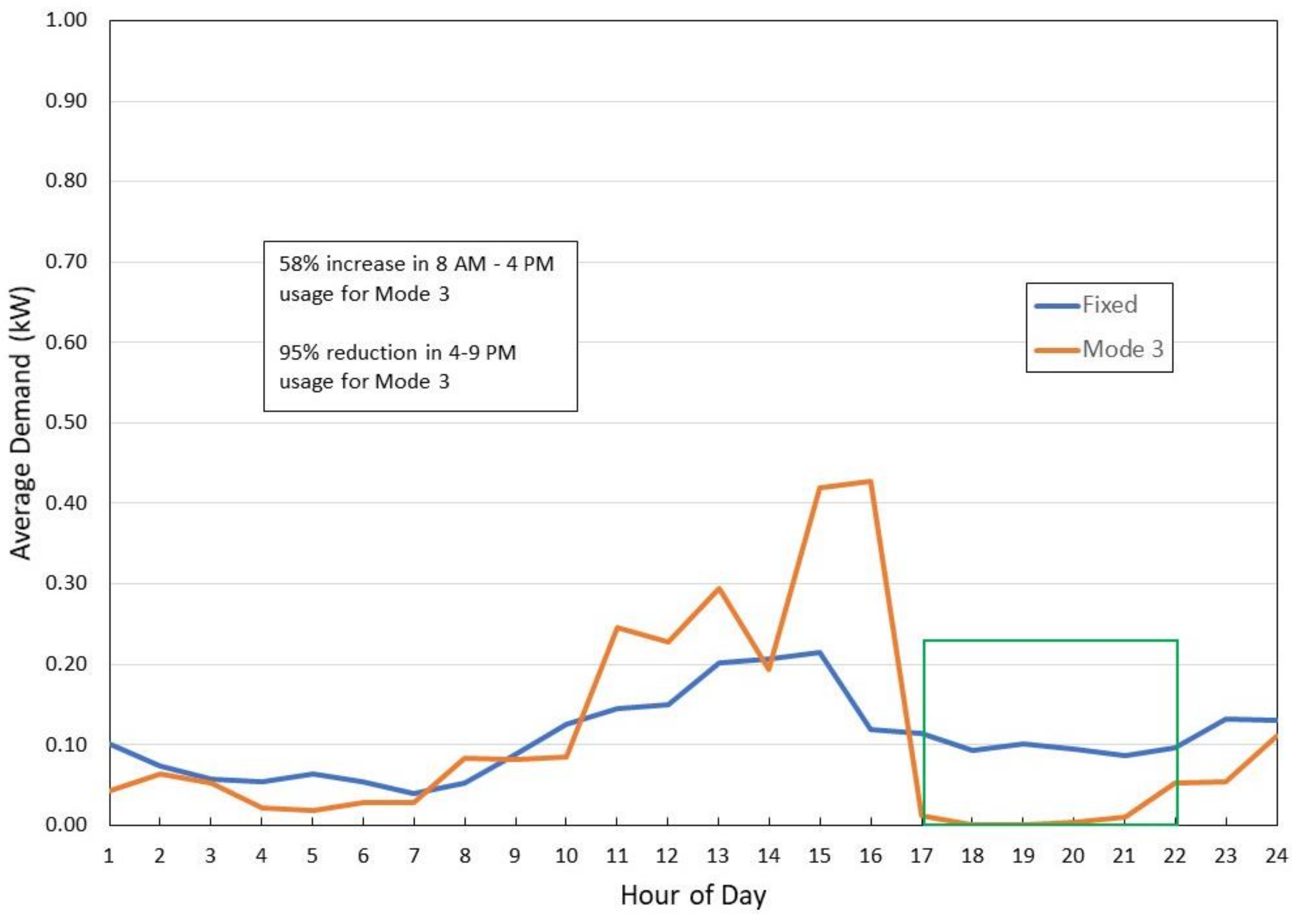


FIGURE 29: JULY 2021 COMPARISON OF AVERAGE DEMAND PROFILE FOR FIXED SETPOINT AND LOAD-SHIFTING MODES

FIELD OBSERVATIONS IN WORKING WITH THE MANUFACTURER API

Several issues have been identified with the API over the course of the field monitoring portion of the project. Specific issues include:

- **Poor documentation:** The documentation is missing critical information needed to effectively utilize this API, including such basics as explanations of method purposes and limitations. The API documentation has not been updated since the start of the project, despite changes to the API.
- **The API server did not automatically purge completed events:** The server has a limit of 100 stored events**.** Since old events do not get deleted, it is necessary to delete completed events in order to schedule new ones. This caused a host of issues, and Frontier revealed an error in the API where active events would be cancelled if a completed event was deleted, making continuous control of HPWH settings

impossible. In Q4 of 2021, the manufacturer changed this behavior so that older events are automatically deleted without interfering with active events.

- **Scheduled events are not always implemented.** This was found to be an ongoing issue that cannot be resolved because of the design of the communication module. The module does not contain sufficient memory to accept a schedule and load-shifting schedules must be implemented by an external computer sending control signals at the appropriate time. If there are any communication issues between the HPWH and the API server, the HPWH will not implement the schedule and also may not return to customer default settings at the conclusion of a load-shift event. If the API were to be used in a widescale utility program, there would be widescale incidents of water heaters continuing high setpoints and high energy use modes for far longer than intended.
- **API is open to significant security risks.** The API provides the partner application an access token and a refresh token which never expire. In a secure API, the access token expires after a set amount of time. The partner application using the API uses a refresh token to request a replacement access token just prior to the expiration of the current access token, allowing uninterrupted service of the application. If the current access token is compromised, an attack from a hacker can only last until the access token expires. For example, access tokens provided by ecobee's thermostat API expire every hour, and the refresh token lasts one year. APIs for essential infrastructure applications require new tokens after each use. Access tokens that never expire are significant security risks, and when they can be used to control water heaters, pose significant health and safety risks to utility customers.

While there has been considerable communication with the manufacturer, many issues continue to persist. The manufacturer has acknowledged that there are issues with the API and how it communicates with the water heaters. They have also indicated for at least a year that they are planning a new version of the API that will implement new security standards, but this has not yet happened as of early 2022.

FLEXI-HPWH MODEL VALIDATION

VISUAL COMPARISON OF RESULTS

Visual inspection of Flexi-HPWH outputs compared the model results to monitored data to ensure that the model correctly predicted the HPWH's control logic decisions in the following ways:

- Response to changes in the set temperature;
- Heating control logic decisions when the temperature recorded by the upper thermostat is higher than the set temperature; and
- The timing of activation of the electric resistance elements.

Figure 30 shows the monitored and simulated water temperatures from a monitored HPWH with average hot water draw volumes on October 9th, 2020. This day featured a stepped load-shifting schedule increasing the set temperature from 125°F to 137°F in increments of 3°F every two hours from 8AM to noon. The monitored HPWH activated the heat pump in response to the initial increase in set temperature, heating the water at the lower thermostat from 116°F to 129°F. When the lower water temperature passed the set temperature the HPWH deactivated the heat pump, and stopped heating. This behavior can be identified by the sudden decrease in the lower measured temperature at 9:50 AM. When the load-shifting control strategy increased the set temperature again at 10 AM the HPWH again activated the heat pump to bring the water to the new set temperature. This is contrary to typical behavior, when the HPWH waits until the lower thermostat temperature falls 23°F below the set temperature before activating, and indicates that the deadband is not utilized when the set temperature is changed.

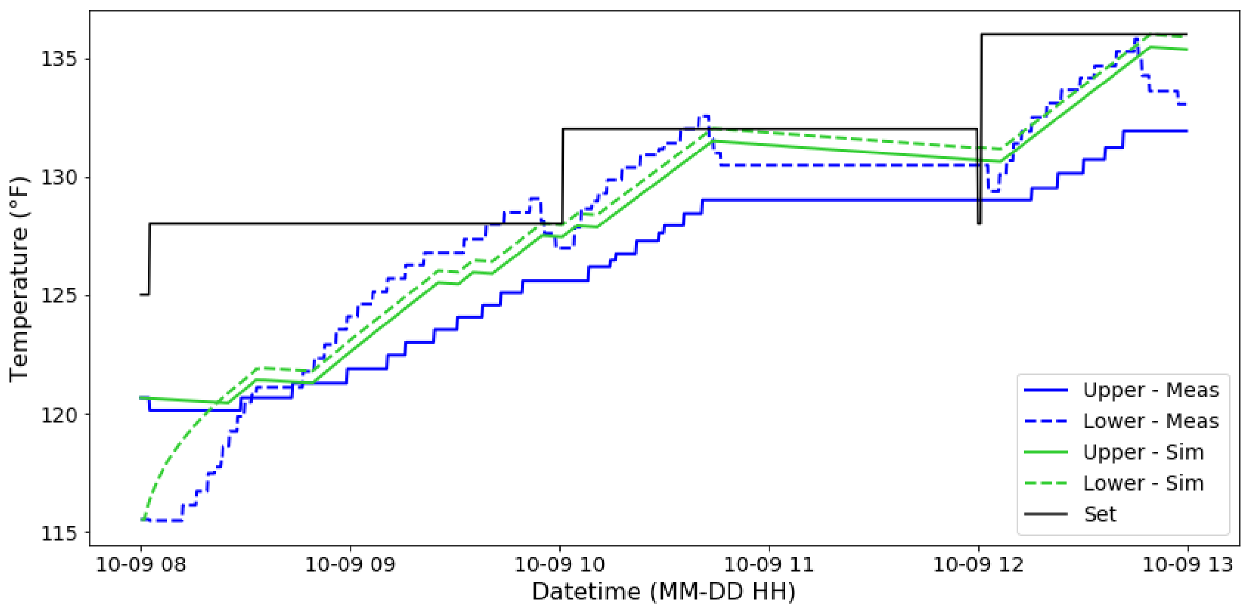


FIGURE 30: MONITORED AND SIMULATED WATER TEMPERATURES DURING LOAD-SHIFTING OPERATION ON OCT 9TH, 2020

Flexi-HPWH closely emulates the observed behavior. It activates the heat pump as soon as the set temperature is increased at 8 AM and starts heating the water to the set temperature. The simulated heat pump heats the water until it reaches the 128°F set temperature at 9:55 and deactivates the heat pump. The model then ceases heating until 10:00 AM when the set temperature is increased to 131°F. Flexi-HPWH then responds to the new change in set temperature by activating the heat pump and heating the water until it reaches the new set temperature.

Figure 31 shows the monitored and predicted electricity consumption during this period. Similar to Figure 30 it shows that Flexi-HPWH activated and deactivated the heat pump at similar times as the monitored HPWH. Additionally, the monitored and simulated electric power consumed by the heat pump are very similar. In both cases the electric power gradually increases as the temperature of water in the tank increases. The electricity consumed at each timestep is similar, with the monitored HPWH consuming an average of 407 W and the simulated HPWH consuming an average of 418 W.

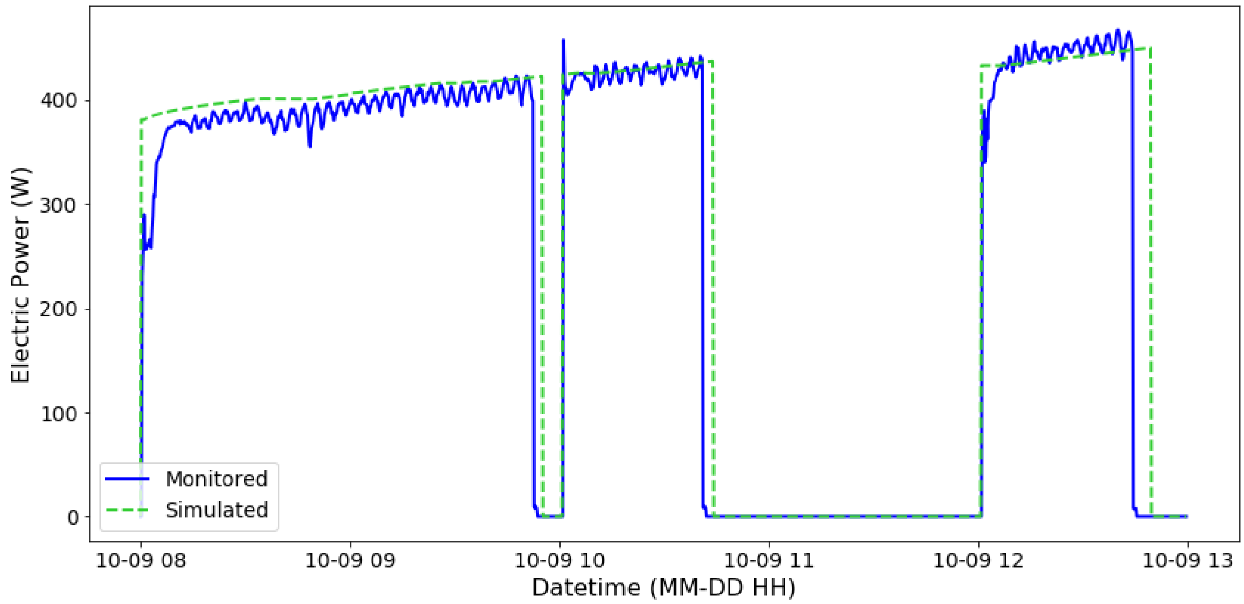


FIGURE 31: MONITORED AND SIMULATED ELECTRICITY CONSUMPTION ON OCT 9TH, 2020

Figure 32 shows simulated and monitored data from July 3rd, 2021 following load-shifting operation on July 2nd, 2021. As a result of the prior load-shifting operation, which increased tank temperatures to 140 °F, the upper thermostat temperature at the start of the period is 135°F, 10°F higher than the current set temperature. The initial lower thermostat temperature is 83°F. The deadband during normal operation is 23°F and the heat pump would activate to bring the water to the set temperature. Figure 32 shows that the heat pump does not activate and heat the water until the load-shifting controls increase the set temperature to 140°F at 9 AM, at which point the upper thermostat temperature is below the set temperature.

The simulated data shows that Flexi-HPWH is correctly emulating this control logic behavior. Similarly to the monitored data the simulated controller does not activate the heat pump until the load-shifting controls increase the set temperature at 9 AM. Once the set temperature increases the upper thermostat temperature is colder than the set temperature, enabling heat pump operation. Flexi-HPWH then activates the heat pump and heats the water until it reaches the elevated 140°F set temperature.

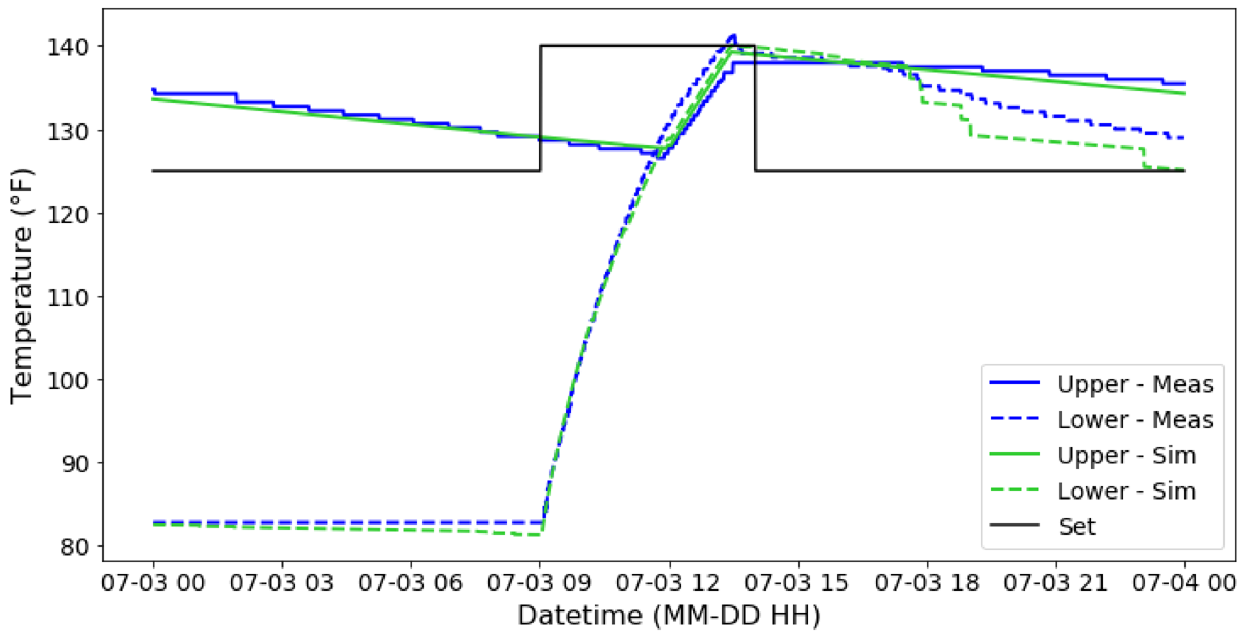


FIGURE 32: MONITORED AND SIMULATED WATER TEMPERATURES WITH ELEVATED WATER TEMPERATURES ON JULY 3, 2021

Figure 33 compares the monitored and simulated electricity consumption during a second stage heating event on November 11, 2020. The HPWH responded to cold water temperatures in the bottom of the tank by activating the heat pump at 7:56 AM. However, continued hot water uses meant that the heat pump could not provide enough heat to maintain tank water temperatures and the HPWH activated the resistance elements at 9:50 AM. The resistance elements have a power consumption of ~3,800 W (varying with voltage fluctuations), but the monitored data shows a gradual increase from 4,076 W to 4,319 W[26]. This shows that typical second stage heating in the monitored HPWH uses both the resistance elements and the heat pump simultaneously. The monitored HPWH uses second stage heating until the water reaches the set temperature at 11:07 AM.

The simulated data in Figure 33 shows the same trends as the monitored data. Flexi-HPWH activated the heat pump to heat the water at 7:52 AM. It continued using the heat pump until 9:50 AM, at which time the continued hot water use caused the water temperature measured by the upper thermostat to fall below the threshold activating second stage heating. Flexi-HPWH then used both the resistance elements and the heat pump compressor to bring the water in the tank up to the set temperature. The simulated water temperatures

[26] The monitored data also shows several transient dips from the typical power down to 2,900 – 3,500 W. The reason for these dips is not understood. The monitored HPWHs have been observed switching power between the upper and lower resistance elements, and the dips may be caused by temporary reductions in power consumption during those switches.

reached the set temperature at 11:12 AM, and Flexi-HPWH deactivated both the heat pump and the resistance elements at that time.

In this 2nd stage heating event the monitored HPWH consumed a total of 6.0 kWh over the simulated time period, and Flexi-HPWH predicted 6.4 kWh (prediction error of 7.8%).

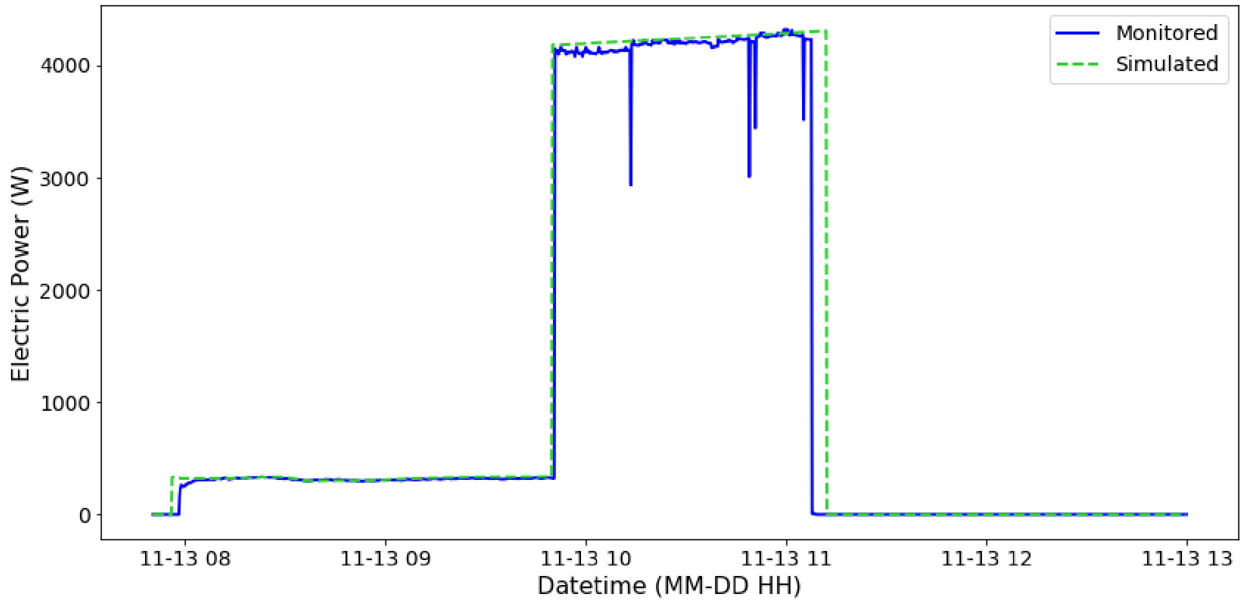


FIGURE 33: MONITORED AND SIMULATED ELECTRICITY CONSUMPTION DURING 2ND STAGE HEATING EVENT

TARGETED NUMERICAL VALIDATION

The targeted numerical validation process identified the performance of Flexi-HPWH over several multi-day periods to ensure that the accuracy of the control logic and heat pump performance map led to accurate predictions over longer periods of operation.

Figure 34 shows the monitored and simulated tank temperatures in one simulation ranging from June 16th to June 20th. This monitoring period included five days with load-shifting controls, typically stepping the set temperature from 125°F to 133°F or 140°F (prior to the peak). The data shows Flexi-HPWH closely emulating the behavior of the monitored HPWH. The simulated lower thermostat temperature closely matches the monitored lower thermostat temperature both when cooling off in response to hot water draws and heating up in response to HPWH heating cycles. The simulated upper thermostat temperature also closely matches the monitored data. Both the monitored and simulated HPWHs are responding to changes in set temperature by heating the water to the new set temperature.

There are some differences between the simulated and monitored HPWHs driven by imperfections in modeling the HPWH's tank temperatures and control logic decisions. The simulated HPWH activates the heat pump earlier than the modeled HPWH in a few instances. The data at the start of the load-shifting period on June 16th shows one example of this. The simulated HPWH activated the heat pump in response to the first increase in set temperature. However, the monitored HPWH only activated the heat pump in response to the second increase in set temperature. With the water at the bottom of the tank at 82°F the HPWH theoretically should have activated the heat pump in response to the first set temperature increase, as soon as the upper thermostat temperature was below the set temperature. This difference caused Flexi-HPWH to heat the water earlier than the real unit. This difference is not significant on June 16 as both the simulated and monitored tank temperatures reach 133°F before the end of the load-up period. However, the same behavior is observed with more significant impacts on June 20th. The simulated HPWH activates the heat pump earlier than the monitored HPWH. By activating the heat pump earlier the simulated HPWH is able to add more energy to the tank than the monitored HPWH. Since significant hot water was consumed during this period, as shown by the sudden decreases in water temperatures, the monitored HPWH was not able to meet the elevated set temperatures. Had operation started earlier it would have. The result is that Flexi-HPWH estimates the upper tank temperature to be 138°F at the end of the pre-peak period when it was actually 128°F.

This behavior is thought to be driven by imperfection in the HPWH measurements or controls. The data in Figure 34 shows the HPWH activating the heat pump later than expected; however, other instances have shown times when the monitored HPWH activated the heat pump slightly before the upper thermostat temperature fell below the set temperature. Since this behavior is not consistent, Flexi-HPWH uses the average and locks out heating operation until the set temperature falls below the set temperature. Since some examples show the physical HPWH not heating the water in response to set temperature changes, the project team expects load-shifting predictions with Flexi-HPWH to perform better than in the physical unit.

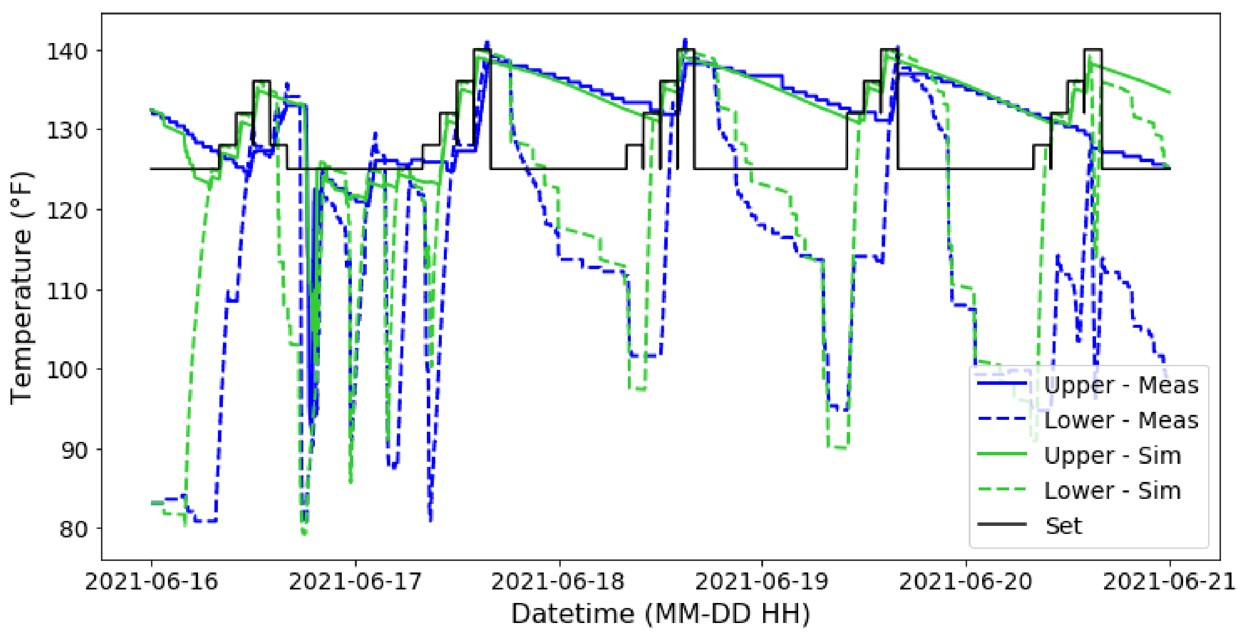


FIGURE 34: MONITORED AND SIMULATED WATER TEMPERATURES FROM JUNE 16TH TO JUNE 20TH, 2021

Figure 35 shows the cumulative monitored and simulated electricity consumption over the same time period. The data shows that the timing and amount of electricity consumption are generally in good agreement. Both the monitored and simulated HPWHs activate at similar times in response to set temperature changes, except in the cases described above.

Over the entire period the monitored HPWH used 14.9 kWh and the simulated HPWH used 14.4 kWh (prediction error of -3.9%.)

The monitored and simulated HPWH both implemented 2nd stage heating at the same time and consumed similar amounts of electricity. The monitored HPWH used 4.8 kWh of second stage heating on June 16 and the simulated HPWH used 4.3 kWh (prediction error of -8.7%). Consuming close to 10% less electricity during 2nd stage heating is a not uncommon issue in Flexi-HPWH, and is believed to be caused by limitations in the performance map. Since the performance map tuning process could not include periods of 2nd stage operation the performance map has not been tuned to be accurate at the appropriate water temperatures. It is believed that extrapolating the performance map to these temperatures causes the simulation to heat the water more efficiently than in reality and underpredict 2nd stage electricity consumption. Using laboratory data to develop a performance map over a broader range of temperatures, with finer measurement of water temperatures within the tank, would improve these predictions.

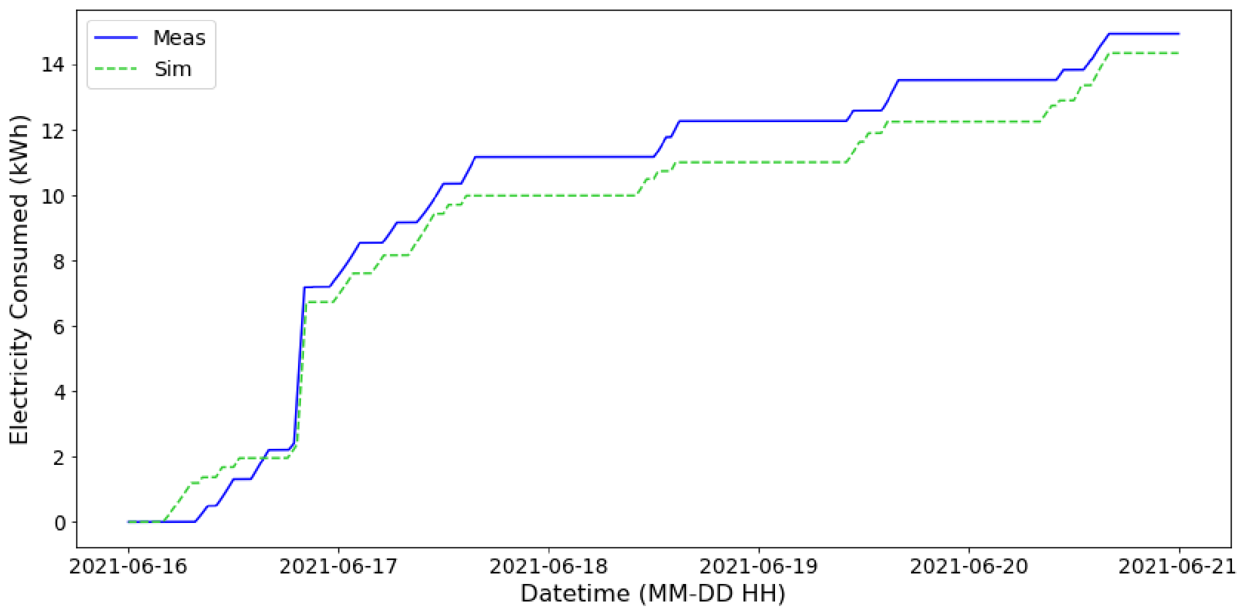


Figure 35: Monitored and Simulated Cumulative Electricty Consumption From June 16th to June 20th, 2021

Over the June 16th to June 20th period, the monitored HPWH consumed 5.0 kWh during the peak period, and Flexi-HPWH predicted 4.8 kWh. The error in predicting peak period electricity consumption during load-shifting operation was -4.3%.

Figure 36 shows the simulated and monitored electric power from April 8th to April 14th. This period did not include load-shifting, and used a static 125°F set temperature through the entire period. The results show that Flexi-HPWH predictions match the monitored data very closely. Flexi-HPWH very accurately predicts both the timing and consumption of 7 of the 12 heat pump heating cycles during the period. In some cases, including the third heating cycle on April 8th, Flexi-HPWH incorrectly predicted an earlier heating cycle and effectively breaks the heating cycle into two.

Flexi-HPWH also accurately predicts the 2nd stage heating cycle on April 14th, though with the same issue as identified in Figure 35. The monitored HPWH consumed an average of

4,124 W during 2nd stage heating with a minimum of 4,065 W and a maximum of 4,246 W. Flexi-HPWH predicted an average of 4,176 W with a minimum of 4,117 W and a maximum of 4,251 W. Similarly to in the June 16th to 20th dataset Flexi-HPWH underpredicted the total second stage heating by 10.5%, caused by differences in timing. The monitored HPWH used 2nd stage heating from 12:04 PM to 2:02 PM while Flexi-HPWH predicted 2nd stage heating from 12:13 PM to 13:57 PM. Since Flexi-HPWH heated the water too quickly it used 2nd stage heating for a shorter period of time despite consuming very similar amounts of electricity. This is believed to be a result of the heat pump performance map not being tuned for temperatures when 2nd stage is active leading to errors in predicting the heat added to the water by the heat pump. Lab testing data with more controlled conditions and additional water temperature measurements inside the tank would improve the prediction accuracy.

Over the April 8th to April 14th period the monitored HPWH consumed 22.0 kWh and Flexi-HPWH predicted 21.8 kWh. Despite the imperfections described, the error in total energy usage over the period was -0.8%.

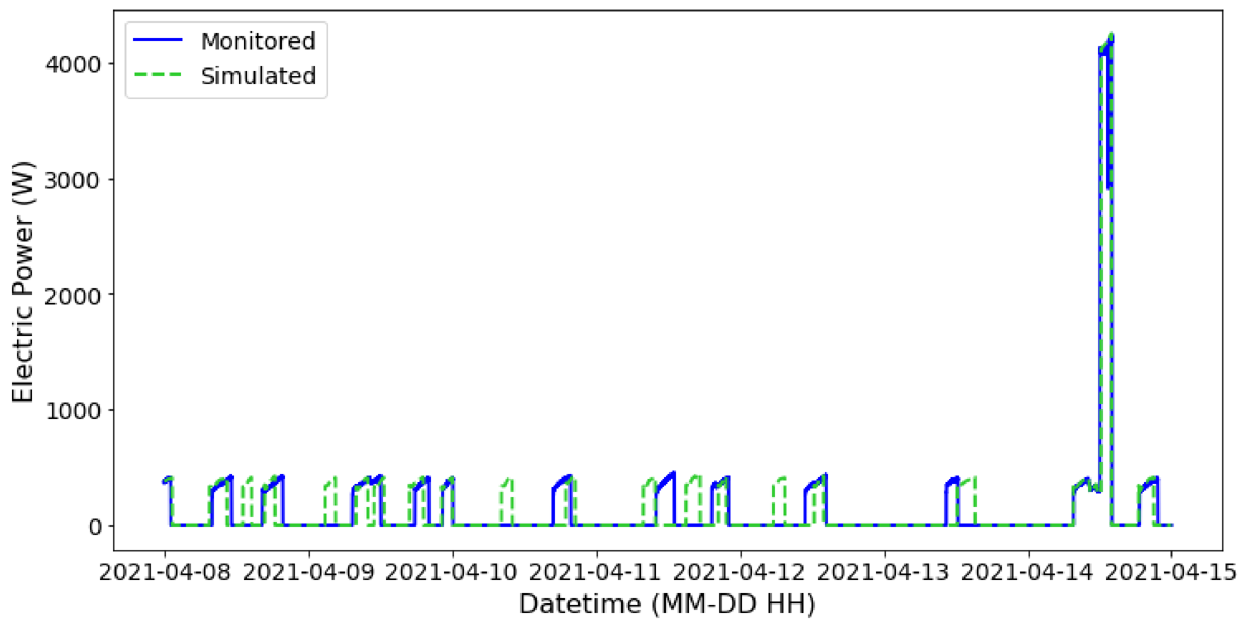


FIGURE 36: MONITORED AND SIMULATED ELECTRIC POWER FROM APRIL 8TH TO APRIL 14TH, 2021

ANNUAL PERFORMANCE VERIFICATION

To ensure that Flexi-HPWH accurately predicts the performance of the monitored HPWH on an annual basis in both typical and load-shifting operations the final validation stage identified Flexi's performance using the following five metrics:

- The annual electricity consumption,
- The annual 2nd stage electricity consumption,
- The peak period electricity consumption on days when the monitoring data used a static 125°F set temperature,
- The peak period electricity consumption when the monitoring data used a 125 to 133°F stepped load-shifting controls, and

- The reduction in peak period in electricity consumption when load-shifting.

Simulation results from Flexi-HPWH were compared to the monitored data using the Low, Medium, and High use case draw profiles.

Table 5 shows comparisons between Flexi-HPWH simulation results and the monitored data in those cases. In all cases, except the load-shifting peak period consumption, Flexi-HPWH simulation results were within 10% of the monitored data. The simulation results were especially accurate in the Medium case with annual electricity consumption error of -1.5%, annual 2nd stage electricity consumption error of -0.5%, and static peak period electricity consumption error of -7.0%. The largest sources of error arose when predicting peak period electricity consumption with load-shifting controls, with Flexi-HPWH underpredicting by 21.7% and 19.4% in the Medium and High use cases, respectively. Looking at the reduction in peak period electricity consumption shows that Flexi-HPWH is accurately predicting load-shifting performance, as evidenced by the -9.1%, -1.6%, and -8.3% errors for the Low, Medium and High use cases.

TABLE 5. ANNUAL FLEXI-HPWH VALIDATION FOR DIFFERENT HOT WATER USE CASES

PARAMETER	METRIC	LOW	MEDIUM	HIGH
Annual Electrical	Monitored kWh	1161	1650	2203
Consumption	Simulated kWh	1107	1670	2083
	Error (%)	-4.9%	1.2%	-5.4%
Annual 2nd Stage RH	2nd Stage Measured kWh	185	667	780
Electrical Consumption	2nd Stage Simulated kWh	190	709	850
	Error (%)	2.8%	6.3%	9.1%
Static 125F Peak Period	Monitored kWh	68	86	127
Electricity Consumption	Simulated kWh	58	84	111
	Error (%)	-14.5%	-3.8%	-12.4%
Load-shifting Peak Period	Monitored kWh	12	23	27
Electricity Consumption	Simulated kWh	8	19	9
	Error (%)	-33.1%	-19.7%	-14.1%
Reduction in Peak Period	Monitored kWh	56	63	100
Electricity Consumption	Simulated kWh	50	65	88
	Error (%)	-10.6%	2.2%	-11.9%

Identified Model Limitations

As demonstrated above the multi-node version of Flexi-HPWH is accurately predicting the control logic and energy consumption of the monitored Creekside HPWHs. However, the current model implementation includes some assumptions which could not be definitively verified by the monitored data and some known limitations due to uncertain observed HPWH behavior. These known issues are:

- Flexi-HPWH simplistically assumes plug flow through the hot water tank. When hot water is withdrawn from the tank, cold water refills the tank by entering the bottom node. That water then sequentially flows up through each node in the tank before being withdrawn as hot water. In reality, the water flows will cause mixing in the tank, with the inlet water directed to the bottom of the tank impacting a few of the bottom tank nodes. Flows through the tank likely cause mixing between the nodes, causing flow to progress in a less uniform fashion. These mixing effects will change the temperature profile in the tank impacting HPWH control logic and heat pump performance metrics. Collecting laboratory data measuring the water temperature at several heights in the tank during draws would enable developing a more detailed model of the water in the tank. It is possible that an improved cold water inlet location would improve tank stratification.
- The heat pump performance map was created using several separate days from the monitored data, and a single temperature measurement at the lower tank thermostat. In reality, the heat pump performance is based on the temperature of water in all nodes connected to the heat pump not only the node where the lower thermostat is located. Data indicating water temperature at several tank depths would enable creating a more accurate performance map. Similarly, performing highly controlled laboratory experiments designed for developing a heat pump performance map would provide a better dataset than the monitored data.
- The monitored HPWHs include safety control logic that deactivate the heat pump compressor, forcing it to rely solely on the resistance elements for heating. This control logic is different from the ambient air lower limit temperature cutoff. The monitoring data showed several cases where the HPWH operated in 2nd stage heating before deactivating the heat pump and using solely the resistance elements, even when the ambient temperature was as high as 54°F. At this time, the factors behind this control choice are unclear. It could be a response to reduced airflow due to the impact of the exhaust air ducting. The lower airflow causes a higher temperature drop across the coil, resulting in colder evaporator temperatures. Possibly the HPWH senses warm enough air and activates the heat pump, then the exhaust air cools below the low temperature cutoff and the HPWH deactivates the heat pump. Figure 37 shows an example of this behavior. In the plot, the monitored HPWH activates 2nd stage heating when the ambient temperature is 50.5°F, above the low temperature cutoff temperature of 37°F. It then activates in 2nd stage heating using both the heat pump and the resistance elements until 3:16 AM when the ambient temperature is 48.9°F and it deactivates the heat pump. Flexi-HPWH continues using the heat pump compressor during this 2nd stage event, thus heating the water faster and completing the heating cycle earlier than the monitored HPWH.

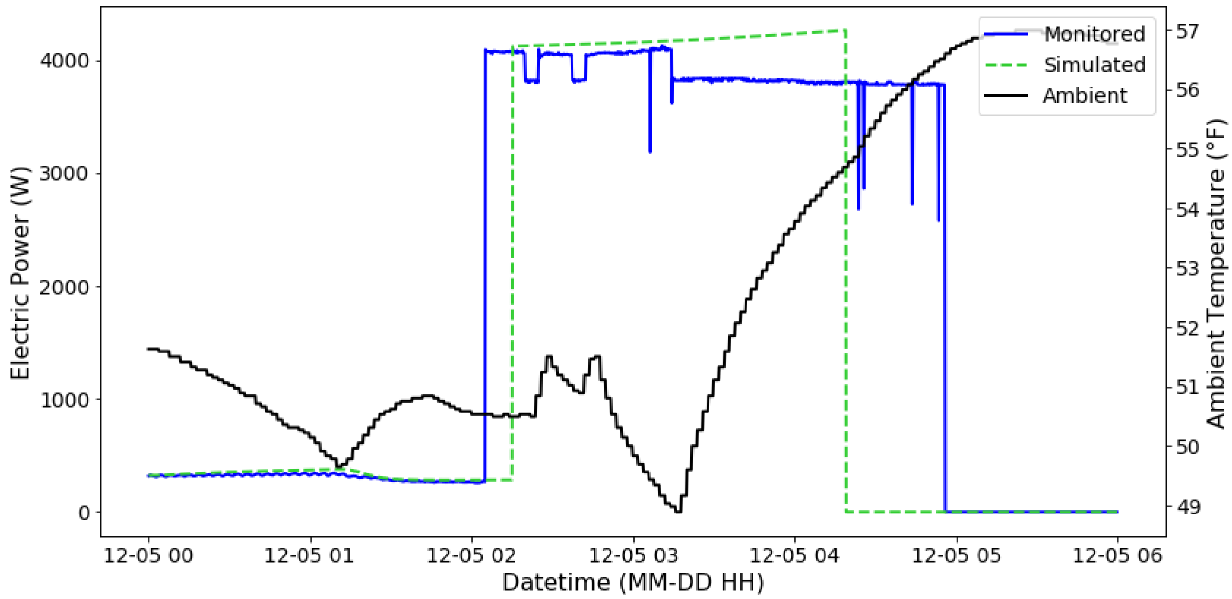


FIGURE 37: DEACTIVATED HEAT PUMP DURING 2ND STAGE HEATING

- All control logic currently modeled in Flexi-HPWH assumes that the unit is in the manufacturer's default control mode. HPWHs typically include other control modes, including one utilizing only the heat pump, which Flexi-HPWH currently cannot emulate. Since the "heat pump only" mode will provide the most efficient operation it is expected that future efforts will focus on that mode, including possibly putting the HPWH in that mode temporarily for load-shifting operation. Future lab testing projects should include identifying control logic in the other modes so Flexi-HPWH can be enhanced to model that mode.
- A patent filed by the HPWH manufacturer in 2009 states that the controller employs a lockout period. The lockout period begins when the heat pump activates, and prevents 2nd stage heating from occurring until the specified time interval has passed. This behavior was not observed during this project. Either the manufacturer no longer includes that logic in their on-board controllers, or the available data set did not provide enough evidence to determine the control logic. Future testing should include evaluating this control logic as it may be critical to identifying the timing of 2nd stage heating.
- Currently Flexi-HPWH underpredicts the occurrence and volume of water consumed during runouts. When runouts occur the temperature at the top of the tank sometimes drops more rapidly than in the Flexi-HPWH predictions, yielding unrealistically high simulated temperatures during these events. The project teams believes that this is caused by the previously described assumptions in hot water flow patterns and could be resolved by using lab testing to develop a better understanding of temperature patterns inside HPWHs during both draws and heating cycles.

ANNUAL SIMULATION RESULTS

A total of 93 simulation cases were completed as part of this study. The goal of the study was to use the model to evaluate the performance of HPWHs under a range of hot water load cases, control cases (various fixed setpoints and load-shift strategies), shared apartment configurations (either one, three, or four apartments per HPWH), alternative California climates, and also explore the impact of physical changes to the modeled HPWH to assess impacts of larger compressor size and/or larger tank volume. Clearly the range of cases to be evaluated in such a study is large, and the goal was to keep the level of reporting manageable for the reader. Subsequent modeling studies should be undertaken to provide a more detailed evaluation.

The reader should keep in mind that the findings focus on the shared configuration observed at the Creekside project with performance projections closely tied to the assumed airflow and closet thermal impacts that were experienced at the site. Since the simulations used the field monitoring data for draw profiles the findings are also tied to the hot water use behaviors of the specific residents living at Creekside.

Condensed simulation results presented here focus on energy use comparisons. On-peak energy use, and annual CO_2 projections are provided in the following tables. More detailed results from all 93 simulation runs can be found in Appendix D: Simulation Results. Appendix D shows the draw profile, load-shifting strategy, and notes describing each simulation. It also presents the electricity consumed by 1) the HPWH, 2) the compressor, and 3) the resistance elements in addition to annual COP, annual electricity costs, and carbon emissions. The COP reported in Appendix D is the simulated COP at the HPWH which differs from the COP across the mixing valve. There are three notable differences:

- The calculated COP will vary proportionally to the error in the electricity consumption. Since the error in the annual validation simulations were -4.9, 1.2, and -5.4% for the L/M/H load profiles the COP predictions are expected to typically be higher than the monitored COPs.
- Flexi-HPWH calculates delivered energy based on the hot water leaving the HPWH, while the monitored data calculated COP is based on the hot water leaving the mixing valve. Some hot water trapped in the pipes between the HPWH and the monitoring equipment was not identified in the monitoring data, reducing the monitored COP. The monitoring data showed on average 21/19/18 daily delays between draws long enough for the water in the pipes to cool for the Low/Medium/High (L/M/H, respectively) load profiles. This untracked energy causes a 5.0%/3.3%/2.4% difference between the simulated and monitored energy provided by the HPWH, and a corresponding higher model-projected COP.
- Flexi-HPWH currently underpredicts the frequency of runouts. In these situations Flexi-HPWH predicts more delivered energy to the occupants than the monitored data showed, which further increases the predicted COP when compared to the monitored COP.

These differences should be noted when comparing the COP results in Appendix D to the monitored COPs described in the Data Analysis section of the report.

The tables here are laid out to provide a flow of information evaluating various simulation cases beginning with a broader set of results for the "typical" Medium hot water usage case. The broader range of simulations for the "typical" Medium case enabled evaluation of more control strategies. Additional tabular output covers the Low and High hot water usage cases, which focus on a more refined list of higher-performing control strategies. Additional results look at other California climates and the impact of changes in HPWH storage volume and compressor size for Medium and High use cases. The Medium and High use cases were selected for these simulations to both capture the performance of a typical installation (at least from the perspective of the Creekside occupants and system configuration) and evaluate the performance degradation in abnormally high use cases. Following the tabular summaries, a series of graphs slice the data differently to display the energy and emissions impacts across the range of hot water usage levels (Low to High).

The following set of simulation output tables use an ID code to help define the simulation case presented in each row. The code contains the following information separated by dashes:

- The simulation ID number, as used in Appendix D;
- Whether or not load-shifting controls were employed. 'Std' indicates standard fixed set point control, while 'LS' indicates load-shifting;
- The draw profile used in the simulation. L, M, or H; and
- The number of dwellings served by the HPWH in the simulation.

For example, the ID '16-Std-M-4' indicates simulation number 16, which uses standard controls and the medium load draw profile with the HPWH serving 4 dwellings. All results presented in Tables 5-10 have been converted to "per apartment" results to allow for direct comparison between individual HPWH per unit and the various shared HPWH configurations.

Table 6 presents a broad range of evaluation cases for the medium hot water usage case. Shared HPWH cases at different fixed set points, and varying load-shifting approaches are presented, as well as corresponding cases for a single 50 gallon nominal tank size HPWH serving 25% of the hot water loads. Simulation projections indicate that in all but one case, the shared approach results in lower total energy consumption and annual CO_2 emissions than the individual HPWH. The one exception is the load-shifting case with non-stepped 8 AM to 4 PM increase to 140°F set point. In that case (ID 19 vs 30), the discrete jump in set point from 125 to 140°F results in a significant increase in 2nd stage RH kWh for the shared HPWH relative to the individual. The lack of a gradual, incremental step in tank set point during the pre-peak load-shifting period clearly results in a significant jump in 2nd stage RH operation and overall kWh usage.

In terms of on-peak kWh, the load-shifting strategies are effective at significantly reducing 4-9 PM usage. The other point to highlight in Table 6 is the impact of higher set points for the fixed load cases. The increase in annual kWh consumption for the shared configuration due to the 140°F set point is 18%, but for the individual HPWH case the impact is larger (35%) due to higher tank standby losses from four water heaters.

TABLE 6. FLEXI-HPWH RESULTS (MED LOAD CASE- SHARED VS INDIVIDUAL HPWH ASSESSMENT)

ID	Detailed Description	Electricity Usage (kWh/year) Total	Heat Pump	2ND Stage RH	4-9 PM Usage (kWh)	CO_2 lbs per year
16-Std-M-4	125F	368	254	114	76	206
18-Std-M-4	140F	433	320	112	90	244
19-LS-M-4	140F, 8A-4P	552	216	336	24	269
20-LS-M-4	140F, 8A-4P, Step	504	235	269	28	240
21-LS-M-4	133F, 8A-4P	419	253	167	33	228
22-LS-M-4	133F, 8A-4P, Step	414	257	157	32	220
28-Std-M-1	125F- 50 gal tank	425	411	14	87	248
29-Std-M-1	140F- 50 gal tank	572	558	14	110	334
30-LS-M-1	140F- 50 gal, 8A-4P	521	466	55	12	264
31-LS-M-1	140F- 50 gal, 8A-4P, Step	463	443	20	23	256
32-LS-M-1	133F- 50 gal, 8A-4P	527	482	45	25	238
33-LS-M-1	133F- 50 gal, 8A-4P, Step	477	455	22	22	239

Table 7 provides similar data for the low hot water usage case. Only stepped load-shifting cases are shown here, as the prior set of Medium load runs and observations during field monitoring show the benefit of gradually increasing set points for load-shifting operation. Under lower hot water load scenarios, the benefit of the shared HPWH approach is magnified as the standby losses of the four individual HPWHs become a bigger fraction of annual energy usage. This is an important finding for low load applications or hot climates where hot water loads are low.

TABLE 7. FLEXI-HPWH RESULTS (LOW LOAD CASE- SHARED VS INDIVIDUAL HPWH ASSESSMENT)

ID	Detailed Description	Electricity Usage (kWh/year) Total	Heat Pump	2ND Stage RH	4-9 PM Use (kWh)	CO_2 lbs/year
1-Std-L-4	125F	234	220	14	51	125
2-Std-L-4	140F	294	278	15	65	158
4-LS-L-4	140F, 8A-4P, Step	350	210	140	15	146
6-LS-L-4	133F, 8A-4P, Step	261	236	26	13	128
9-Std-L-1	125F- 50 gal tank	345	345	0	73	196
10-Std-L-1	140F- 50 gal tank	479	479	0	100	277
13-LS-L-1	140F- 50 gal, 8A-4P, Step	450	437	12	21	195
14-LS-M-1	133F- 50 gal, 8A-4P, Step	408	398	10	18	191

For the shared HPWH approach, the 133°F stepped load-shifting strategy performed considerably better than the 140°F strategy, as evidenced by reduced 2nd stage RH kWh and CO_2 emissions. Relative to the case ID#1 (125°F fixed) case, the ID#6 (133°F LS) case consumed 12% more annual kWh but significantly reduced on-peak kWh consumption. Annual CO_2 levels for the two cases were essentially equivalent. The shared HPWH cases performed better than the individual HPWH cases in total kWh, annual emissions, and most of the on-peak kWh cases. With the low hot water loads, the shared configuration was highly effective at eliminating virtually all on-peak usage.

Table 8 presents a similar set of cases for the High hot water load case as shown in Table 7 for the Low load cases. Under the High load scenario, the individual HPWHs start to look a bit better relative to the Low and Medium hot water cases. For example, the 50 gallon HPWHs (ID#49 and 50) show reduced CO_2 emissions relative to the ID#45 (125°F fixed set point) individual HPWH case (267 and 286 lbs versus 291 lbs for case ID#45). This is in contrast to the shared HPWH cases (ID#40 and 42) where the combined impact of high hot water loads and load-shifting result in increases in 2nd stage RH kWh and resulting increases in emissions relative to the base ID#37 (125°F shared case). This trend shows the impact of increasing hot water loads beyond an optimal level for that size HPWH that result in increasing 2nd stage operation, reduced efficiency, and increased emissions (see Figure 20).

TABLE 8. FLEXI-HPWH RESULTS (HIGH LOAD CASE- SHARED VS INDIVIDUAL HPWH ASSESSMENT)

		Electricity Usage (kWh/year)			4-9 PM	CO_2
ID	Detailed Description	Total	Heat Pump	2nd Stage RH	Use (kWh)	lbs/year
37-Std-H-4	125F	427	334	93	80	243
38-Std-H-4	140F	512	412	100	99	292
40-LS-H-4	140F, 8A-4P, Step	637	293	344	21	321
42-LS-H-4	133F, 8A-4P, Step	505	324	181	27	277
45-Std-H-1	125F- 50 gal tank	499	481	17	110	291
46-Std-H-1	140F- 50 gal tank	656	642	13	138	383
49-LS-H-1	140F- 50 gal, 8A-4P, Step	598	550	48	23	267
50-LS-H-1	133F- 50 gal, 8A-4P, Step	557	530	27	20	286

Table 9 provides an energy use comparison for a range of shared HPWH cases based on the Medium hot water load schedule, using weather data and cold water inlet temperature assumptions included in the CBECC-Res Title 24 residential compliance software. These runs were completed to highlight expected performance differences due to climate under a uniform hot water schedule. The six climate zones shown in the table are:

- CZ3: Oakland CZ6: Los Angeles area
- CZ10: Riverside CZ12: Sacramento
- CZ15: Palmdale CZ16: Blue Canyon

Carbon emission estimates are not included for these CBECC-Res based runs.

The impact of climate on both hot water loads and HPWH performance are evident as one compares the results for the hottest climate (CZ15) to the coldest climate (CZ16). Total HPWH energy usage nearly triples for CZ16 vs. CZ15 and 2nd stage RH operation increases by a factor of nine when using a static 125 °F set point temperature in a shared HPWH. The increase in energy consumption is driven by:

- higher HPWH loads requiring more 2nd stage operation to maintain tank set point;
- more instances of the outdoor air temperature being below the heat pump low temperature lockout; and
- higher water heating energy input requirements and jacket losses.

For the shared configurations, 133°F stepped load-shifting mode increases annual kWh by only 6% in CZ16, but 10-14% in the other climates. For individual 50 gallon HPWHs, load-shifting increases annual kWh by 8% in CZ16 and 10-12% in the other climates.

TABLE 9. FLEXI-HPWH RESULTS (PERFORMANCE VARIATIONS BY CLIMATE ZONE FOR SHARED AND INDIVIDUAL HPWHS)

		Electricity Usage (kWh/year)			4-9 PM
ID	Detailed Description	Total	Heat Pump	2nd Stage RH	Use (kWh)
52-Std-M-4	125F, Shared, CZ3	459	297	162	107
56-Std-M-4	125F, Shared, CZ6	381	273	108	92
60-Std-M-4	125F, Shared, CZ10	382	264	118	83
90-Std-M-4	125F, Shared, CZ12	451	274	177	98
64-Std-M-4	125F, Shared, CZ15	288	222	66	64
68-Std-M-4	125F, Shared, CZ16	803	232	571	193
53-LS-M-4	133F, 8A-4P, Step, CZ3	505	301	204	49
57-LS-M-4	133F, 8A-4P, Step, CZ6	429	275	154	38
61-LS-M-4	133F, 8A-4P, Step, CZ10	436	262	173	35
91-LS-M-4	133F, 8A-4P, Step, CZ12	504	273	230	46
65-LS-M-4	133F, 8A-4P, Step, CZ15	327	224	102	24
69-LS-M-4	133F, 8A-4P, Step, CZ16	849	230	619	115
54-Std-M-1	125F, 50 gal, CZ3	496	485	11	109
58-Std-M-1	125F, 50 gal, CZ6	428	428	0	99
62-Std-M-1	125F, 50 gal, CZ10	427	415	12	94
92-Std-M-1	125F, 50 gal, CZ12	496	444	53	102
66-Std-M-1	125F, 50 gal, CZ15	331	331	0	71
70-Std-M-1	125F, 50 gal, CZ16	932	398	534	204
55-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ3	546	533	13	28
59-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ6	472	472	0	26
63-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ10	474	455	20	23
93-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ12	552	484	68	29
67-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ15	371	371	0	19
71-LS-M-1	133F, 50 gal, 8A-4P, Step, CZ16	1004	425	579	71

Table 10 summarizes the impact of changing the number of apartments served by each 80 gallon HPWH. This analysis was motivated by the observation during monitoring that the most highly loaded HPWH (B9AE at an average of 169 gal/day hot water usage) was clearly overloaded during the winter months and frequently struggled in meeting the loads. By reducing the load on the HPWH by reducing served apartments from 4 to 3, the HPWH would logically perform better and be more able to both meet load and effectively load-shift without relying on 2nd stage RH operation. Table 10 presents results for both the nominal 4 apartments per HPWH shared configuration, as well as for a 3 apartment case in both the 125°F fixed set point case and the preferred load-shifting strategy. The "sharing ratio" impacts performance and construction costs. HPWH performance, depending on the load, should improve as the average load is reduced. Construction costs are negatively impacted by the addition of more water heaters (added equipment first and replacement, electrical, framing costs, etc.).

TABLE 10. SUMMARY OF ANNUAL FLEXI-HPWH SIMULATION RESULTS (SHARED 3 VS 4 APARTMENTS)

		Electricity Usage (kWh/year)			4-9 PM	CO_2
ID	Detailed Description	Total	Heat Pump	2nd Stage RH	Use (kWh)	lbs/year
1-Std-L-4	125F, 4 Apts	234	220	14	51	125
72-Std-L-3	125F, 3 Apts	245	242	3	53	132
16-Std-M-4	125F, 4 Apts	368	254	114	76	206
74-Std-M-3	125F, 3 Apts	355	286	69	73	200
37-Std-H-4	125F, 4 Apts	427	334	93	80	243
76-Std-H-3	125F, 3 Apts	418	367	51	82	239
6-LS-L-4	133F, 8A-4P, Step, 4 Apts	261	236	26	13	128
73-LS-L-3	133F, 8A-4P, Step, 3 Apts	279	266	13	13	136
22-LS-M-4	133F, 8A-4P, Step, 4 Apts	414	257	157	32	220
75-LS-M-3	133F, 8A-4P, Step, 3 Apts	407	297	110	25	213
42-LS-H-4	133F, 8A-4P, Step, 4 Apts	505	324	181	27	277
77-LS-H-3	133F, 8A-4P, Step, 3 Apts	483	367	116	20	257

For the 125°F fixed case, moving from 4 to 3 apartments results in about a 5% increase in annual energy use and carbon emissions for Low load case, but for the Medium and High cases there is a 2-3% annual energy use savings projected with the 3 apartment configuration. For these higher load cases, the improved HPWH operating efficiencies more than offsets the added standby losses associated with the 3 apartment cases. One finds similar results with the load-shifting results, with a small penalty for the Low load case and small improvements with the Medium and High load cases. In terms of both 2nd stage RH kWh and on-peak energy consumption, the 3 apartment case does improve relative to the performance of the 4 apartment case.

One aspect of the 3 apartment case that cannot be adequately identified with the Flexi-HPWH model at this time is the hot water run out situation. It is safe to expect that having less connected load to each HPWH should improve run out performance to some degree.

In reviewing HPWH operation over the full 18 month monitoring period, it became clear that the performance under the actual loads and operating conditions might have been improved by some combination of increased storage capacity and larger compressor size. To evaluate this, the model was configured to evaluate a larger storage volume (100 gallon tank size) and a 12,000 Btu/hour compressor. Both of these changes would certainly impact the physical characteristics of the HPWH unit. For example, a larger compressor would require larger heat exchangers and more airflow across the evaporator coil. This would require larger ducting as well, if the unit were installed in a small closet (as at Creekside). Modeling was completed to provide a first cut evaluation of potential performance impacts of a larger storage tank (with corresponding larger UA thermal losses) and a 12,000 Btu/hour compressor with identical COP relationship as the nominal compressor.

Analysis was completed for the Medium and High load cases. Reference performance cases for the nominal 80 gallon HPWH were included in Table 11 as well (ID#16, 22, 37, and 42). Added storage volume was found to have little benefit when modeled in isolation. The larger compressor size had a much more significant impact with 11-14% reductions in annual total kWh for the fixed set point case and 16% reduction for the load-shifting cases. The reductions in energy use were largely driven by reductions in 2nd stage RH operation, which was reduced by 67 to 76% in the various cases evaluated. Carbon emissions reductions were similarly impacted with 10-13% reductions for the fixed set point case and 15-16% for the load-shifting cases. The increased impacts for the load-shifting cases point out the ability of the larger compressor to successfully build load mid-day. Combining the larger 100 gallon tank size with the larger compressor added minimal additional performance benefits.

TABLE 11. SUMMARY OF ANNUAL FLEXI-HPWH SIMULATION RESULTS (100 GAL, 1 TON)

		Electricity Usage (kWh/year)			4-9 PM	CO_2
ID	Detailed Description	Total	Heat Pump	2ND stage RH	Use (kWh)	lbs/year
16-Std-M-4	125F	368	254	114	76	206
78-Std-M-4	125F, 100 gal	363	265	98	73	203
82-Std-M-4	125F, 1 ton	317	281	35	68	180
86-Std-M-4	125F, 100 gal, 1 ton	319	289	30	68	183
22-LS-M-4	133F, 8A-4P, Step	414	257	157	32	220
79-LS-M-4	133F, 8A-4P, Step, 100 gal	416	266	150	32	215
83-LS-M-4	133F, 8A-4P, Step, 1 ton	347	296	51	21	186
87-LS-M-4	133F, 8A-4P, Step, 100gl/1ton	358	305	53	21	187
37-Std-H-4	125F	427	334	93	80	243
80-Std-H-4	125F, 100 gal	422	348	75	81	241
84-Std-H-4	125F, 1 ton	379	357	22	84	218
88-Std-H-4	125F, 100 gal, 1 ton	387	364	22	83	222
42-LS-H-4	133F, 8A-4P, Step	505	324	181	27	277
81-LS-H-4	133F, 8A-4P, Step, 100 gal	522	327	195	26	275
85-LS-H-4	133F, 8A-4P, Step, 1 ton	425	370	55	18	234
89-LS-H-4	133F, 8A-4P, Step, 100gl/1ton	435	379	56	14	234

The following series of plots highlight elements of the tabulated data to allow for visual identification of trends across the range of hot water load cases. The plots highlight key findings rather than the full set of information provided in the summary tables. Results are presented on a "per apartment" level.

Figure 38 plots the shared HPWH energy usage and annual associated CO_2 emissions across the three hot water load cases for 125 and 140°F fixed setpoints. Annual total HPWH kWh is projected to increase by 25% for the Low load case, and 18-20% for the Med and High cases. Although the percentage of on-peak kWh of total HPWH kWh is not impacted by the higher setpoint (~19-22% of total usage in all cases), the absolute change in on-peak usage increases by 27% in the Low case and 18-23% in the Med and High cases. For the Low and High case, 2nd stage RH annual kWh increases by 8-9% (1 and 7 kWh, respectively), but for the Med case it decreases by 1%). This could possibly be due to hot water load pattern differences. Annual CO_2 emissions are increased by 27% in the Low case and 19-20% in the Med and High cases.

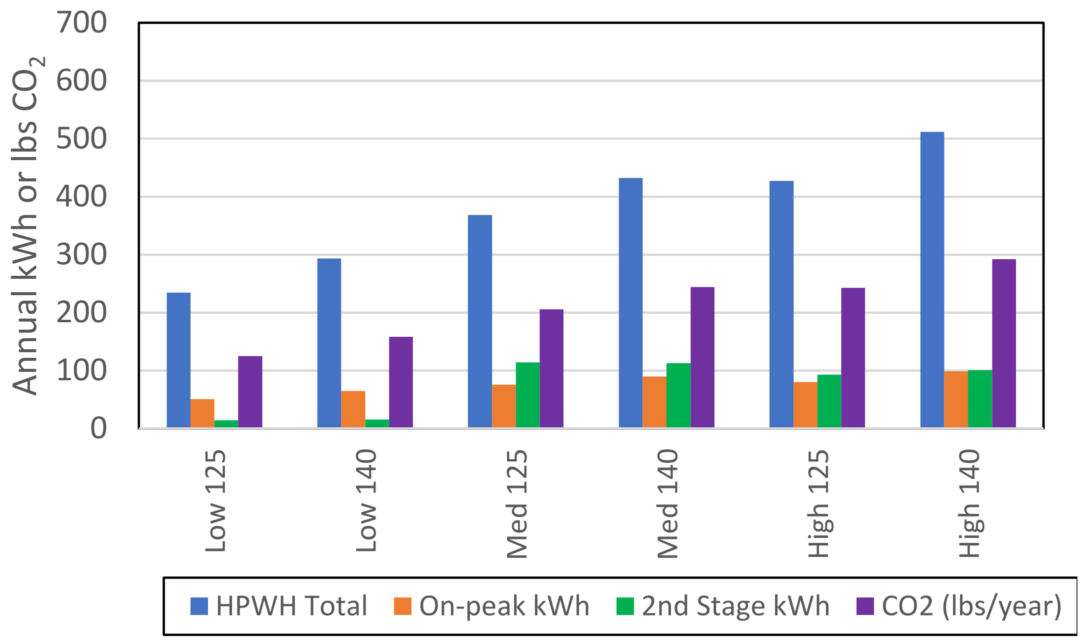


FIGURE 38: COMPARISON ACROSS LOAD CASES FOR SHARED HPWH (IMPACT OF HIGHER FIXED SET POINTS)

Figure 39 presents a comparison between four individual 50 gallon HPWHs (one per apartment) versus a shared HPWH serving the four units with both cases at fixed 125°F set point. The plotted individual HPWH data represents the summed impact of the four units combined for direct comparison to the shared case. The impacts of standby losses are amplified in the Low load case relative to the High load case as overall shared HPWH energy savings for the Low case are 32% vs. 14% at the High case and 13% for the Med case. This is due to the fact that the High load case uses significantly more hot water throughout the day, making standby losses a smaller portion of the total heating load. On-peak kWh is reduced in the shared case by 30% in the Low case, 13% in the Med, and 27% in the High case. 2nd stage RH energy consumption is significantly higher in the shared case due to the hot water loads being imposed on 80 gallons of storage for the shared case versus four 50 gallon HPWHs in the individual case. The reduced standby losses on the shared case is partially offset by increased 2nd stage consumption. In the Low load case, 2nd stage usage goes from 0 kWh/year to 14 kWh/year; for the Med and High load cases the shared case 2nd stage consumption is 5-8 times higher from 14 to 114 kWh for Med, and 17 to 93 kWh in the High case. In terms of CO_2 emissions, the reduced standby losses with the shared HPWH contribute to the much lower energy use and a resulting 36% reduction in CO_2 emissions. As the hot water loads increase, the relative impact of the standby losses diminishes, leading to reduced emission benefits of 17% for Med and 16% for High.

This shared versus individual comparison is significant as it highlights the energy and CO_2 emissions comparison of the two approaches. Additionally there are the first cost and replacement cost benefits of the shared approach. Increased hot water runouts with the more heavily loaded shared HPWH remain a concern, especially for high load cases.

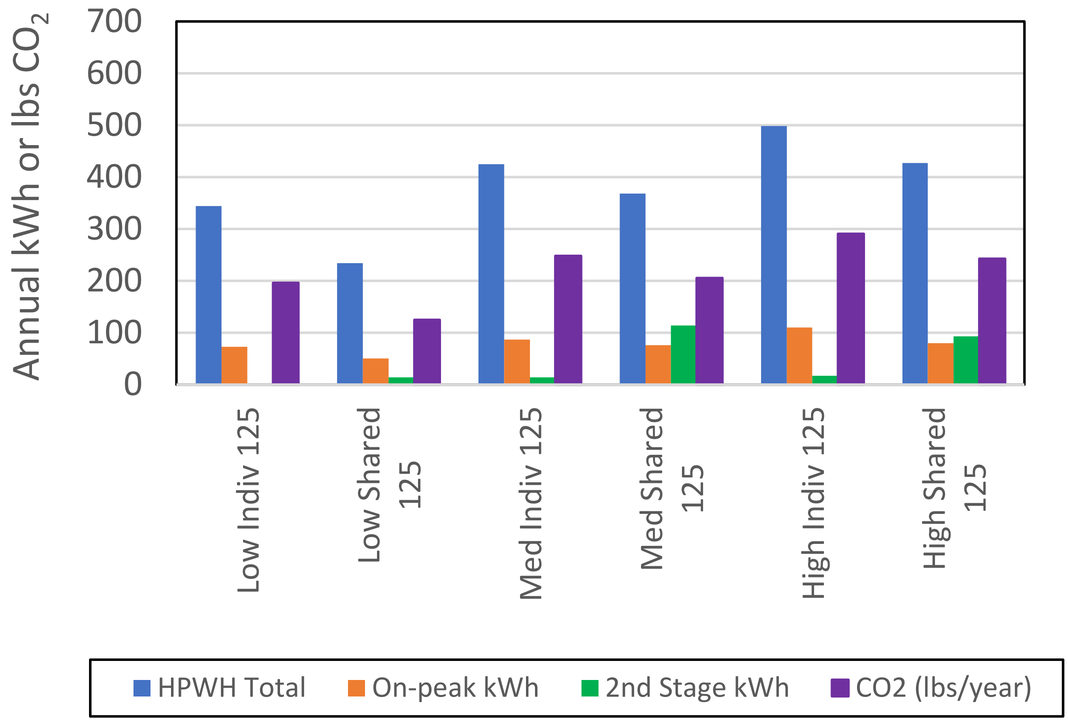


FIGURE 39: COMPARISON ACROSS LOAD CASES (INDIVIDUAL HPWHS VS SHARED AT 125F FIXED SET POINT)

Figure 40 compares the preferred shared HPWH load-shifting case (125 to 133°F, with stepped tank target set point increases) to the individual water heater case at the fixed 125°F set point. The individual plotted values are therefore identical to that shown in the prior graph. With added energy usage due to load-shifting, the benefits of the shared approach are reduced. In terms of energy savings, the shared savings range from 24% under Low loads and 2% under Med loads, but 1% increased usage is projected for the High use case. 2nd stage RH energy usage increases significantly with the shared configuration under load-shifting operation. Compared to the Shared fixed 125°F case, annual 2nd stage RH energy increases from 0 to 26 kWh for the Low case, 143 kWh (or 1023%) for the Med case, and 164 kWh (or 965%) in the High case. It becomes increasingly challenging for the HPWH to successfully complete load-shifting while high hot water loads are being imposed, especially when those high loads are imposed during the load-shifting period. This increases the likelihood of 2nd stage operation, most commonly in the winter months, as reflected in the model results and the monitoring data shown in Figure 27 through Figure 29. Overall energy usage increases with the shared 80 gallon HPWH in load-shifting operation relative to fixed set point by 11-18%, as well as CO_2 emissions by 3-14% increase. However, CO_2 emissions are still well below the levels of the individual HPWHs operated at the fixed 125°F set point at 35% lower for Low load, 11% for Med, and 5% for High.

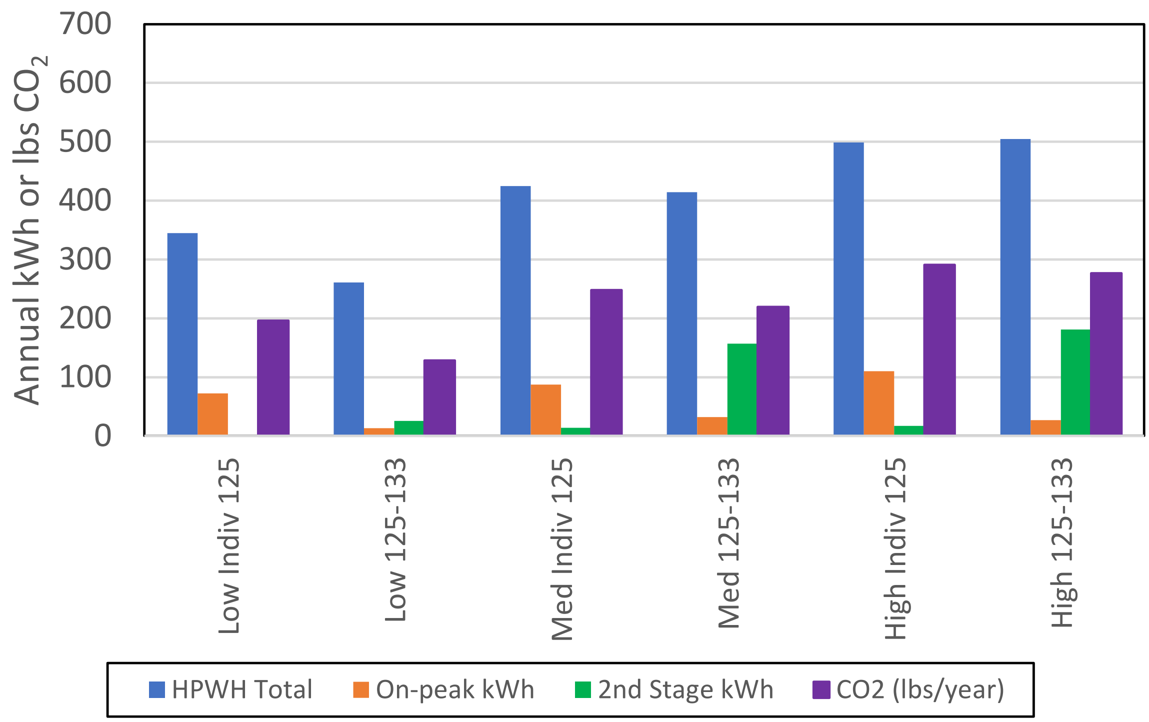


FIGURE 40: COMPARISON ACROSS LOAD CASES (INDIVIDUAL HPWHS AT 125F VS SHARED AT 125-133F LOAD SHIFT)

The prior two graphs highlight how the shared configuration compares against individual HPWHs. One conclusion from Figure 40 is that as the hot water loads increase, the installed 80 gallon HPWH struggles to both effectively overheat the storage and avoid using inefficient 2nd stage heating. One obvious solution is to increase the capacity of the compressor. Although this would impact the design and physical configuration of the unit, it seems to be a logical scenario to evaluate for future product development activities. Figure 41 presents the results of modeling a 1 ton capacity compressor on the Med and High load cases. With the larger capacity compressor, the HPWH should perform better and demonstrate reduced 2nd stage operation. It is important to recognize that as the compressor size increases, the required evaporator airflow must also increase meaning larger ducts will be needed. Figure 41 shows that with fixed 125°F set point, annual energy use is projected to decrease by 11-14% for the High and Med cases, primarily due to a 69-76% reduction in 2nd stage RH usage. On-peak energy consumption with the larger compressor shows a 10% reduction for the Med case, but a 5% increase for the High use case. CO_2 emissions are improved for both cases by 10-13% with the larger compressor as it can both more consistently bias operation closer to when the hot water loads occur and reduce total electricity consumption.

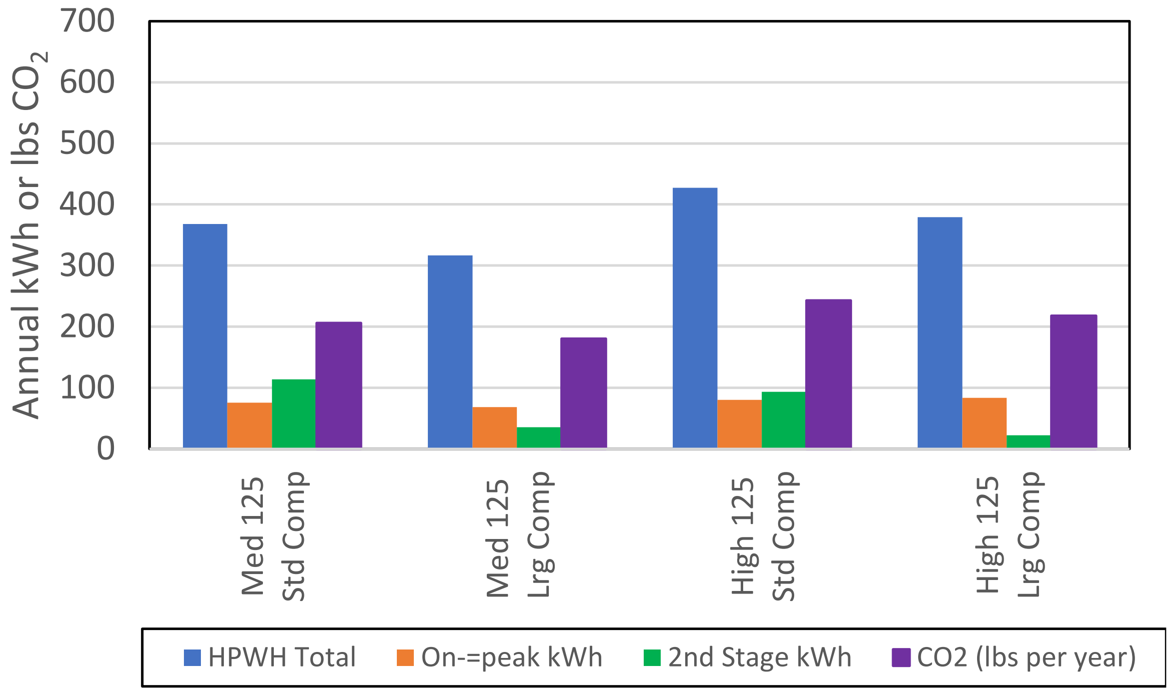


FIGURE 41: COMPARISON ACROSS LOAD CASES (SHARED VS. SHARED WITH 1 TON COMPRESSOR AT 125 FIXED SET POINT)

Figure 42 plots similar data as Figure 41 but operating under the preferred 125-133 stepped load-shift scenario. The larger 1 ton compressor shows a 16% reduction in energy usage, a 33% reduction in on-peak kWh, a 69% reduction in 2nd stage RH usage, and a 15% reduction in CO_2 emissions for both the Med and High load profiles. The larger compressor therefore provides enhanced benefits in load-shifting operation relative to the nominal compressor size.

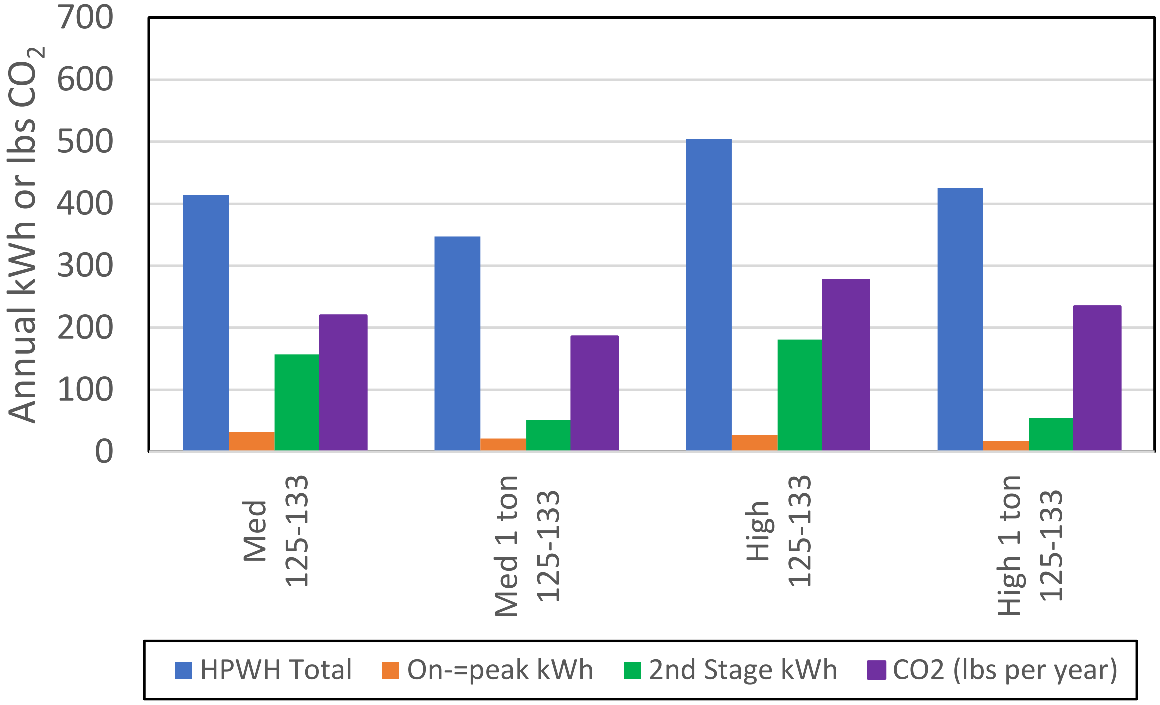


FIGURE 42: COMPARISON ACROSS LOAD CASES (SHARED VS SHARED & 1 TON COMPRESSOR AT 125 -133 LOAD SHIFT)

UTILITY COST COMPARISON

As previously discussed, representation of annual utility costs is not easy since any shared configuration would have multiple HPWHs, as well as potentially other non-apartment electrical loads (i.e. outdoor lighting) connected to a single meter. This makes calculation of utility costs challenging in terms of applicable utility rates and baseline quantity effects. Although Appendix D contains annual water heating utility cost estimates for all cases simulated, only the individual HPWH cases can be compared with a high degree of confidence.

Table 12 presents annual costs for the Low, Med, and High hot water usage profiles for three cases: 1) 125°F fixed setpoint, 2) 140°F fixed setpoint, and 3) the preferred 8 AM – 4 PM 125-133°F stepped load-shifting strategy. Annual water heating costs are shown for each case for both the current PG&E TOU-C rate and the hypothetical TOU rate with the more dramatic on- to off-peak rate differentials, presented in the table with the format (PG&E Cost / Hypothetical Cost). The projected costs show the 125°F fixed case to consistently have the lowest annual cost and the 140°F fixed case to have the highest cost. The load-shifting case is closer to the 125°F costs, especially when applying the hypothetical TOU rates. The general conclusion is that under existing PG&E TOU rates, load-shifting with the observed Creekside HPWH controls performance will likely result in higher operating costs[27]. Judging by the clear energy savings benefit of the shared configuration (at least for the Low and Medium load profiles), adding the shared configuration on top of the load-shifting should improve the annual cost comparison. Improvement in the TOU rate structure for load-shifting is an area that warrants attention since there is ever increasing value to the grid to absorb mid-day excess generation rather than curtail that generation. The magnitude of the curtailed generation will only continue to increase from year to year as the renewable content on the grid expands, as highlighted in Figure 2.

TABLE 12. PROJECTED ANNUAL PER APARTMENT UTILITY COSTS (INDIVIDUAL HPWH CONFIGURATION)

	Annual Utility Cost		
Detailed Description	Low	Medium	High
50 gal unit, 125°F fixed	\$93 / \$83	\$115 / \$103	\$136 / \$123
50 gal unit, 140°F fixed	\$129 / \$115	\$154 / \$137	\$179 / \$161
50 gal unit, 125-133°F Load-shift	\$108 / \$91	\$127 / \$106	\$149 / \$124

EVALUATIONS

OVERVIEW OF FIELD PERFORMANCE

The shared configuration demonstrated at the Creekside project offers value and should be further evaluated. In the installed configuration, three of the four HPWHs that would have been installed in an individual "per apartment" HPWH configuration have been eliminated, reducing construction costs by ~ \$1,850 per apartment, the compact hot water distribution system avoids the need for recirculation pumps, as well as reducing the embodied energy of the installed equipment. There were negative performance impacts observed for some of the heaviest loaded HPWHs as average annual COPs were lower, due to excessive use of inefficient 2nd stage heating, and greater frequency of hot water run outs. Clearly more work is needed to fully assess this approach to determine the right balance of optimal performance, costs, and resource requirements.

Communications using the manufacturer's API proved challenging at times. Improvements are necessary to make the API more reliable and secure in the future.

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[27] Developing and/or testing other communication and control strategies which are less likely to trigger 2nd stage heating would also reduce load shifting costs, perhaps below the costs of 125 °F fixed operation.

The project chose to use the manufacturer's API because of two limitations in CTA-2045 at the start of the project. First, it was not widely adopted and the installed HPWHs did not communicate via that protocol. Second, CTA-2045 had no ability to increase water temperatures above the user-specified set temperature, limiting the ability to shift load. Recently the CTA-2045 communications protocol has both become widely adopted and added an 'Advanced Load Up' signal. The 'Advanced Load Up' command both increases the set temperature to perform load-shifting, and enables stating a preference for using the heat pump. This approach works more directly with the on-board controller and gives more ability to exclusively use the heat pump for load-shifting operation. Future projects should evaluate the potential to use 'Advanced Load Up' to perform load-shifting with reduced 2nd stage heating.

Observed hot water loads during the monitoring period were highly variable among the ten HPWHs which resulted in highly varied performance impacts. Average load per HPWH was found to be 92 gal/day, but varied from 53 to 169 gal/day. The usage of the highest loaded unit is difficult to comprehend, but may be due to the unique hot water needs of the specific occupants. Satisfying this range of consumption clearly poses a challenge and ways to better balance the loading, or provide supplemental heating to challenged units would improve overall performance.

There was a strong seasonality to hot water loads in the Davis climate with summer loads averaging around 75 gal/day and winter loads averaging 110 gal/day. The variation is primarily due to a range of cold water inlet temperatures at the site from 55°F in mid-winter to 85°F in mid-summer. Other California climates will have different ranges in temperatures dependent on climate and water source (well or surface water), with resulting impacts on performance.

Annual HPWH COPs averaged 1.96, and ranged from 1.58 to 2.17. The HPWH subjected to the 169 gal/day loads logged the lowest COP, due to nearly 67% of the energy consumption occurring when 2nd stage operation was triggered. The lowest loaded HPWH only had 11% of annual operation in 2nd stage mode. The units with highest loading were unable to handle the imposed loads. Achieving optimal efficiency for a HPWH involves matching expected hot water loads with operating environment and tank (and compressor) size.

HPWH control logic algorithms are necessarily complex as the triggering of 2nd stage operation is important in, first and foremost providing adequate hot water, while also achieving optimal performance. High resolution data collection during the course of the project clearly indicated cases where backup heating shouldn't have been triggered, as well as cases where it should have been. Manufacturers are continually evaluating their control algorithms, and future improvements should focus on optimizing backup heating operation.

The load-shifting performance observed in this project was mixed. The highest loaded units struggled to effectively load-shift and consumed more 2nd stage RH in trying to achieve higher target temperatures, especially in winter conditions. Less heavily loaded units performed much better at shifting load to off-peak periods. For the Davis climate, effective spring/summer/fall load-shifting can generally be completed. More work appears to be needed to achieve effective load-shifting with minimal 2nd stage operation, especially in winter months. Incorporating a communication signal that collaborates with the on-board controller to simultaneously increase set temperature and bias towards heat pump operation whenever feasible would help resolve this issue.

SIMULATION DISCUSSION

The modeling results highlight one challenge of implementing load-shifting by directly changing the set temperature of the HPWH. Since this approach does not collaborate with the HPWH's on-board controller it is quite possible to create conditions that trigger the resistance elements, which is not the intended or ideal result. Avoiding this outcome requires careful implementation of controls, and/or collaboration with manufacturers to create control modes designed for load-shifting.

As demonstrated in this project, gradually increasing the set temperature over the load-shifting period reduces the incidence of 2nd stage heating. This is because the heat pump is able to keep up with the gradual increase in set temperature more frequently than a sudden increase in set temperature, preventing the upper thermostat from falling far below the set temperature as often.

Switching the HPWH from Energy Saver mode to Heat Pump Only mode may reduce the frequency of 2^{nd} stage operation, but will likely also increase the frequency of runouts, especially in higher load situations. At this time adequate data to determine the control choices of the tested HPWHs in Heat Pump Only mode is not available preventing simulations studying this option. High use load cases, and high use days, would be more likely to fail to maintain set temperature in this control modes.

Increasing the number of dwellings sharing a HPWH increases the hot water loads and likelihood of runouts and 2^{nd} stage heating, but reduces construction costs and the combined tank standby losses. Since the shared configuration experiences an increase in runouts and 2^{nd} stage heating in higher load profiles, the most efficient configuration depends on the occupants. Low load cases showed more energy use with fewer dwellings sharing a HPWH. The high load case showed the most energy with one dwelling per HPWH, second most with four dwellings per HPWH, and least with three HPWHs per dwelling. Selecting the best configuration given hot water load variability is challenging, and requires a clear understanding of common load profiles to enable more accurate analysis.

Inlet water temperatures and ambient air/evaporator inlet air temperatures also impact HPWH performance. Colder inlet water temperatures create higher load on the HPWH, both making use of 2^{nd} stage heating more common and decreasing the likelihood of successfully avoiding peak period electricity consumption. Lower ambient temperatures increase jacket losses, decrease heat pump COP, and increase the time when the HPWH uses resistance only mode as a result of the low temperature cutout. The simulations in different climate zones indicate that this approach should work well in all of the highly populated climate zones in California, with climate zone 3 showing slightly higher energy use than the monitoring site in climate zone 12 and all other densely populated climate zones using less energy. Climate zone 16, with significantly colder temperatures than elsewhere in California, showed dramatically higher energy use than elsewhere. This approach may not be successful in that climate.

Simulations predicted the performance of a theoretical HPWH with a 1 ton compressor. This theoretical HPWH was assumed to be identical to the monitored HPWH in every way except the compressor size (e.g. scaling of evaporator and condenser heat exchangers). Increasing the compressor to 1 ton showed significant reductions in electricity consumption, caused by decreases in 2^{nd} stage heating, along with decreases in peak period consumption and carbon emissions. This finding makes sense as the larger compressor is more able to maintain the set temperature and perform load-shifting operation without engaging 2^{nd} stage heating.

The simulation results indicate that this style of load-shifting control typically increases the carbon emissions of the HPWH, when comparing to HPWHs in fixed set point to HPWHs in load-shifting mode. However, it is important to note that the reduced jacket losses in the 4 apartment shared configuration vs. individual HPWHs, reduces annual CO_2 emission projections by 5-35%, with the highest benefit achieved in the low hot water load case[28]. Shifting the HPWH operation earlier in the day decreases the marginal carbon emissions per kWh, but the increase in energy consumption caused by the strategy leads to higher carbon emissions under current grid carbon content profiles. However each year the grid renewable content increases, which will change this conclusion fairly soon. Improving the HPWH control strategy to reduce energy consumption in load-shifting mode would also reduce carbon emissions.

Finally, it is worth commenting on the impact of hot water use profiles on the projected HPWH performance presented in this report. The Low, Med, and High profiles selected represent a range of hot water usage. Embedded in the gal/day usage metric are different patterns of loading and load intensity. For example, the Low and High usage profiles both have slightly less than average amount of high volume flow events (see Figure 15), while the Med profile has approximately twice as many high volume flow events. This has implications for triggering 2nd stage operation, extended operating cycles that impact load-shifting potential, and hot water run outs. The authors surmise that these differences contribute to some of the results for Med and High use cases, which don't quite fit preconceived expectations. A much broader simulation evaluation would need to be completed, looking at the other seven use profiles and possibly other sources of draw profiles such as CBECC-Res or the Building America Draw Profile Generator, to get a more thorough understanding of performance variability in different modes of operation.

RECOMMENDATIONS

Shared HPWHs and load-shifting are both new technologies that are not well understood by industry. A design guide providing sizing and control recommendations by climate and number of dwellings would support industry adoption. Additionally, further study is needed to better understand current industry practices for multi-family building types.

Flexi-HPWH is a flexible, publicly available[29] simulation model for HPWHs. Improving identified limitations or expanding Flexi-HPWH's capabilities would yield more accurate results across a wider variety of simulation cases. Specifically testing could provide data sets to:

- Verify or improve the in-tank heat transfer and COP calculations;
- Better understand the currently ambiguous control logic elements and update Flexi-HPWH accordingly;

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[28] Low hot water use cases expend a greater fraction of total energy used in maintaining the tank temperature.

[29] https://github.com/PeterGrant/Flexi-HPWH

- Collect performance and control data on HPWHs from other manufacturers and add them to Flexi-HPWH's library.

Laboratory testing can expand the findings from this project by evaluating performance in a controlled environment. Laboratory testing should evaluate:

- The impacts of various closet ventilation solutions;
- The performance of products from multiple manufacturers including developing performance maps, understanding water flows inside the tank, and emulating the logic of their on-board controllers;
- CTA-2045's Advanced Load-Up feature and the impacts of using that communication strategy to implement load-shifting;
- Shared vs. individual HPWHs in a controlled setting; and
- Determine the benefits of using either a drain water heat recovery device, solar thermal, or supplemental water heater (per apartment building) to pre-heat water and reduce the heating load on all, or only the heavily loaded HPWHs.

Simulation results indicate that the shared configuration offers significant benefits relative to individual HPWHs in a multi-family application. The capability to model this shared configuration should be added within the Title 24 compliance models. System design and installation requirements supporting high-performance operation should be included when adding this system to Title 24 compliance models.

Other recommendations include:

- Establish OEM API functionality requirements to optimize performance of all HPWHs installed in California. Include requirements for controls that optimize load modifying operation that minimizes resistance electric use. Perform testing evaluating existing industry protocols and either create requirements for those protocols or propose new protocols as appropriate.
- Develop and field verify protocols for manufacturer's API that are robust, provide secure communications, and provide push notifications if communications do not work. If an existing protocol meets the criteria, require that installations use either that protocol or another protocol with demonstrated equivalent capabilities.
- Evaluate ducted exhaust airflow performance for different units and develop a minimum required airflow level that must be achieved (i.e X% of nominal). Provide prescriptive design approaches that meet these airflow requirements.
- Complete additional research to inform HPWH sizing procedures, as well as developing an improved understanding of distribution system performance for shared and central system configurations. This work would lead to a design guide supporting high performance system installations.
- Develop field verification protocols to ensure proper installation, controls setup, and communication.
- Develop education materials for maintenance personnel or building owners.

APPENDICES

APPENDIX A: PROJECT START UP OBSERVATIONS

May 27, 2020

As of early May 2020, all ten HPWHs at the Creekside Affordable multi-family project in Davis, CA are operational and fully monitored for water heating performance evaluations which will include both standard operating modes, as well as load-shifting which will bias operation to mid-day periods when excess solar generated electricity is more likely to be available. Utilizing this mid-day photovoltaic generation is beneficial for the grid as it allows the energy to be used to heat domestic hot water 10 to 15°F above setpoint, serving as a low cost thermal battery. Unused mid-day photovoltaic generated electricity to overheat storage for later use is desirable since on many days that energy is curtailed.

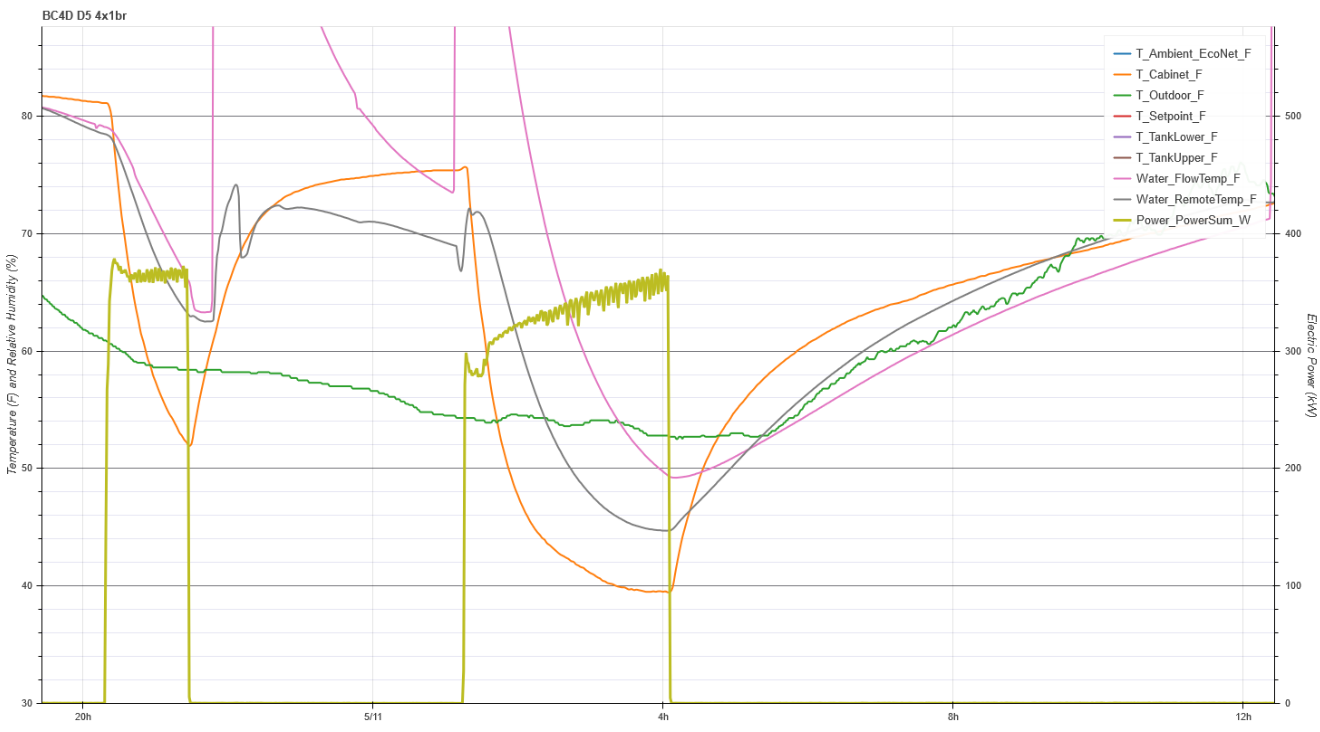
The installed 80 gallon unitary HPWHs at the Creekside project each serve four adjacent apartments. The vast majority of the apartments are single person units. Several of the ten monitored HPWH units have one two bedroom apartments. With the current Covid-19 situation, occupancy at the project is going much slower than anticipated. Indications are that it may take three to four months to fully occupy the project.

The HPWHs are installed in fairly small closets external to the apartments. Louvered doors, as per manufacturer's specifications, are intended to provide sufficient ventilation to outside to avoid a situation where the cold exhaust air from the HPWH contributes to an unfavorable operating environment. At ambient temperatures of ~37°F, the HPWH will disable the compressor and operate with inefficient electric resistance elements at about half the efficiency of the HPWH compressor.

Figure 1 below shows initial hot water operation that occurred on May 10th and 11th. Prior to May 10th, the HPWH was operating daily only to offset storage tank losses. (Note: before the HPWH operating cycle – shown as olive green line power demand -- the (orange) closet temperature is about 15-20°F warmer than the (green) outdoor air sensor. This is largely due to piping in the closet being uninsulated.[30])

[30] Note: At the time of this initial report, hot water piping was uninsulated, indicating non-compliance with a Title 24 requirement. This was brought to the plumber's attention and subsequently addressed.

Figure 1: Initial HPWH Sample Monitoring Data



Just prior to the HPWH cycle starting around 8 PM on May 10th, the orange closet temperature is found to be about 20F warmer than green outdoor temperature. At the end of the 8 PM cycle, closet temp has dropped from about 82F to 52F, or about six degrees cooler than outdoors. On May 11th, hot water loads are first observed during the early AM hours, which triggers the next HPWH cycle around 1 AM. At 1 AM, the closet temperature is about 76F, or ~20F warmer than outdoors. Since this HPWH operating cycle is triggered by hot water usage, more energy is needed to recharge the storage tank and the operating cycle is correspondingly longer. The three-hour long cycle shows an even more dramatic drop in the closet temperature as it starts at 76F and falls to 40F at the end of the draw (about 13F below the outdoor air temperature). Although the temperature did not drop sufficiently to disable the compressor, a similar situation during the colder part of the year would likely result in frequent and excessive backup electric heating usage.

To remedy the situation, Frontier Energy proposed several potential solutions to the project developer and architect.

- Option 1: Replace the louvered door with a more open door to facilitate the exhausting of air to outside (240 in^2 of net free area was recommended by the manufacturer).
- Option 2: Install rigid sheet metal elbows off of the HPWH exhaust port to direct air to the back of the louvered door. A gasketed rectangular register boot could be positioned to provide solid contact with the back of the door allowing air to exhaust from the closet, which would induce (fresh) air from outside to be sucked into the closet.

- Option 3: Install a duct termination port above or through the door which would involve cutting through the door, but would ensure all air is getting exhausted from the closet.
- Option 4: Install an exhaust fan with airflow directed above the closet door and the fan controlled to operate only when the HPWH compressor is operating.

Discussions with the architect and developer resulted in the decision to follow an incremental approach to determine what level of fix would be appropriate. Option 2 was selected and the Frontier field engineer procured parts to complete the retrofit on one of the ten closets. Total cost of parts was on the order of $70 for the one closet. The work was completed on May 22nd.

The two photos below document the fix. Figure 2 shows rigid sheet metal elbows installed to direct evaporator exhaust air to a floor register boot that was gasketed and positioned to be flush with the louver door when the door was shut.

Figure 2: Gasketed Floor Register Position Relative to Open Door

Figure 3 shows the louvered panels of one quadrant of the door taped over to prevent air from deflecting back into the closet.

Figure 3: Louvered Door Interior Panel Taped to Prevent Exhaust Air Backflow

Figures 4 and 5 plot subsequent data showing the impact of the duct on closet temperatures during times when the HPWH is operating. Figure 4 shows an unmodified closet during an approximate 2 hour HPWH cycle with the cabinet temperature dropping from 80 to 56°F during the duration. Figure 5 shows the modified closet (with the ducting) temperatures during a similar 2 hour long cycle. Closet temperatures fall from 81 to 74°F.

Figure 4: Unmodified Closet Temperature During Two Hour HPWH Cycle

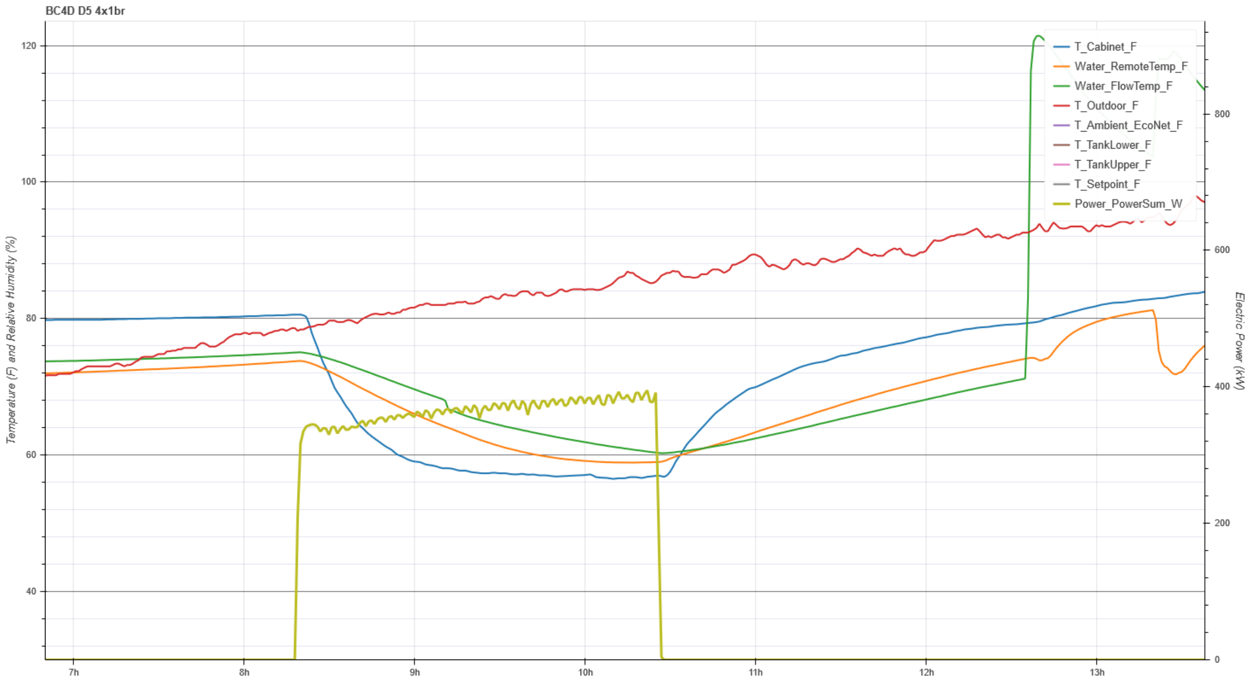


Figure 5: Ducted Exhaust Closet Temperature During Two Hour HPWH Cycle

Next Steps

The information will be shared with the developer and performance will be observed over the coming weeks. Temperature drops in basements and garages of a few degrees are commonly seen with HPWHs, so the seven degree observed drop does not appear to be excessive[31]. The low cost of the retrofit makes it an attractive solution. Frontier will communicate with the developer and determine if they are in a position to move forward with a fix on the remaining 22 HPWHs at the project. PG&E may be in a position to contribute to the remediation effort.

In terms of ongoing monitoring plans for the ten HPWHs, Frontier plans to slowly deploy preliminary load-shifting strategies to verify the controls and operation of the EcoNet app which allows scheduling of setpoints.

At the same time, occupancy at the project will increase and the plumbing contractor is also scheduled to return to insulate closet hot and cold water piping to reduce additional loads on the HPWHs.

[31] Other cycles on different days show an 8-9 °F drop.

APPENDIX B: DUCTING IMPACT STUDY

Initial Evaluation of Ducted vs. Non-Ducted Small Closet HPWH Performance

Marc Hoeschele, Frontier Energy

Peter Grant, Beyond Efficiency

December 7, 2021 revision

Overview

This evaluation provides a preliminary assessment of the performance impact of ducting residential unitary heat pump water heaters (HPWHs) that are installed in cramped closets with limited ventilation. It relies on performance data collected at the Davis, CA Creekside multifamily affordable project, where Frontier Energy is conducting load-shifting HPWH monitoring activities for PG&E. This effort is a first step in assessing whether additional field testing and/or more detailed lab testing is warranted to better understand a broader range of ducting impacts on airflow and performance. A NEEA-sponsored lab project currently underway (led by Larson Energy Research and Cascade Engineering) will provide additional information on the performance of closet located HPWHs, as well as how manufacturer-prescribed ducting configurations impact performance.

This initial evaluation is based on field data specific to the Creekside configuration, which may influence the findings to a degree. However, it is the best available data at this time and Creekside field data were used to drive the Flexi-HPWH python-based simulation tool (developed by Peter Grant). The Flexi-HPWH model is specifically designed to:

- Be flexible enough to simulate a variety of HPWH installation configurations,
- Utilize monitoring data to drive the simulation, and
- Accurately evaluate the performance of grid-friendly flexible control strategies such as load shifting[32]

The goal of this evaluation was to utilize the Flexi-HPWH tool to assess the performance of the 80 gallon HPWHs installed at the Creekside project in multiple configurations:

- Unducted in a confined closet,
- Ducted in a confined closet,
- Unducted in an idealized open air environment,
- Unducted in an open outdoor setting,

[32] Load-shifting HPWH operation is the primary research goal for the Creekside project.

- Ducted in a confined closet with ducts connected to/from a standard attic,
- Ducted in a confined closet with ducts connected to/from a high performance attic[33],
- Unducted with HPWH located in a standard attic, and
- Unducted with HPWH located in a high performance attic.

The model is driven by actual hot water loads and weather conditions observed at the project. At the start of the Creekside field monitoring in April 2020, the HPWHs operated for roughly two months without the benefit of ducting, allowing the project team to observe performance in that configuration[34]. Unducted HPWH operation was found to significantly decrease closet air temperatures during compressor operation (due to air recycling) raising concerns that this would lead to efficiency reductions and there would be significant issues with winter operation. To mitigate those issues, in later June 2020 the project helped support retrofitting ducting to all of the HPWHs at the project. Water heater performance with the ducting has been monitored continually since that time, allowing the team to make before/after treatment comparisons. In July 2021 the team collected additional airflow data on the ducted system performance to aid in this evaluation.

Approach

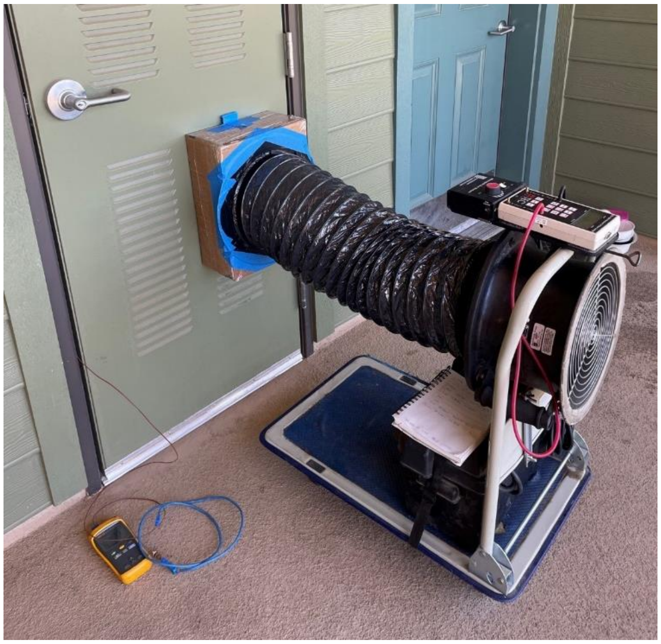
Frontier field staff measured evaporator airflow at ten ducted HPWHs and the unducted HPWH in the facility's common area in late July 2021. Airflow was measured using a pressure balancing approach. The photograph below shows the basic setup with the Duct Blaster connected to the air exhaust from the HPWH. All exhaust airflow passes through the ducted portion of the louvered door, and the rest of the louver remains open to provide supply air to the closet.

Evaporator airflow measurements were completed both with the door closed and the door open, to evaluate whether the louvered door adds an additional restriction to airflow[35]. Due to differences in the orientation of each HPWH evaporator exhaust relative to the closet sidewall there is some degree of variation in amount of constriction in the flex duct to the louvered door.

[33] High performance attics are an attic configuration seen in California where insulation is applied at both the roof deck and the ceiling plane.

[34] Hot water loads were very low at the start of the project due to low occupancy rates as the spread of Covid advanced delaying tenants from moving in.

[35] Gary Klein had suggested that in one project, the measured evaporator airflow was distinctly different with open and closed doors due to the airflow restriction associated with the closed louvered door.

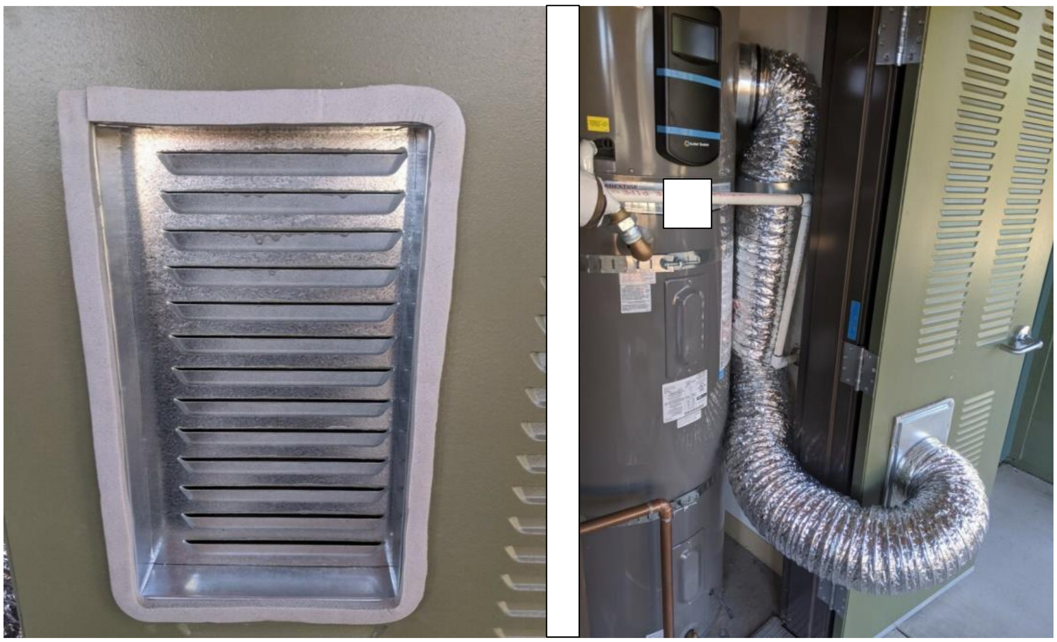


On average, the "closed door" closets averaged 72.8 cfm (range of 64 to 77 cfm) and the "open door" averaged 74.0 cfm (range of 65 to 78 cfm). In contrast, the unducted HPWH in the common area was measured at 133 cfm. Therefore, on average, the ducted HPWH airflow is 55% to 56% of the airflow of the unducted unit. The results with open and closed doors were very similar, indicating that the airflow reduction is primarily caused by the ducting, not the louvered door. As airflow across the evaporator falls the air's heat capacity air decreases, resulting in a corresponding increase in the temperature difference from evaporator inlet to outlet (since there is less air moving across the evaporator, the decline in temperature for the diminished air mass is that much greater). If the HPWH heating capacity is unchanged, a halving of the airflow would result in a doubling of the temperature difference.

Simultaneous evaporator inlet and outlet temperatures were completed at the ten HPWHs serving apartments and the common area HPWH using a Type T thermocouple measurement device. As anticipated, these measurements corroborated the impact of the reduced airflow. For the common area (unducted) HPWH unit located in conditioned space, the temperature difference across the evaporator coil was measured at 16.2°F. On average the temperature difference for the ten ducted HPWHs was 31.0°F (ranging from 28.3° F to 33.1°F. The temperature difference across the unducted evaporator coil was 58% of the temperature difference across the unducted coils, closely matching the 55-56% change in airflow between the two cases.

With this larger temperature difference with the ducted HPWHs, the actual performance benefit of these ducted units is diminished because the average evaporator temperature is reduced by the lower airflow. The reduced average evaporator air temperature both reduces the coefficient of performance (COP) of the heat pump and increases the likelihood that the HPWH will switch to resistance heating. To represent this in Flexi-HPWH, a 7.5°F ({31.0-16.2} divided by two) reduction in inlet air temperature was used to model ducted performance[36].

In addition to the airflow across the evaporator coil, the ducted configuration has a beneficial impact on the HPWH closet temperatures. In the ducted configuration exhaust air is directed out through the louvered door and therefore does not cool the closet to the same degree[37] as the unducted configuration does. The photos below show the sheet metal duct boot can connected to the outer louver of the door. This ensured that virtually all of the air was exhausted, although the outer door panel louvers do exert back pressure.



Cooler closet (or environment) temperatures both increase tank jacket losses, reduce operating efficiency, and increase the likelihood that the HPWH will switch to resistance heating to avoid freezing the evaporator coil (a.k.a. low-temperature compressor cutout). During the study the team observed a few cases of more extreme Central Valley winter conditions which did not require low-temperature cutout operation in the ducted case but would have in the unducted case.

Monitoring data shown in Figure 1 plots the relationship between HPWH closet and outdoor ambient temperature during times of HPWH operation, by time of day and time of year (seasonal plots are

[36] Flexi-HPWH, as currently configured, assumes nominal airflow at all times. By reducing the inlet air temperature, we are approximating the observed impact of the reduced airflow.

[37] Heat transfer from the uninsulated flex duct does provide some cooling to the closet.

shown, rather than monthly, for visual clarity). For the vast majority of the time, the closet is warmer than ambient. This is most pronounced in the morning hours and late in the day, presumably since the HPWH tends to run less during those hours, and the heat losses from the tank, solar gains on the closet wall, and thermal mass effects of the building keep closet temperatures above ambient.

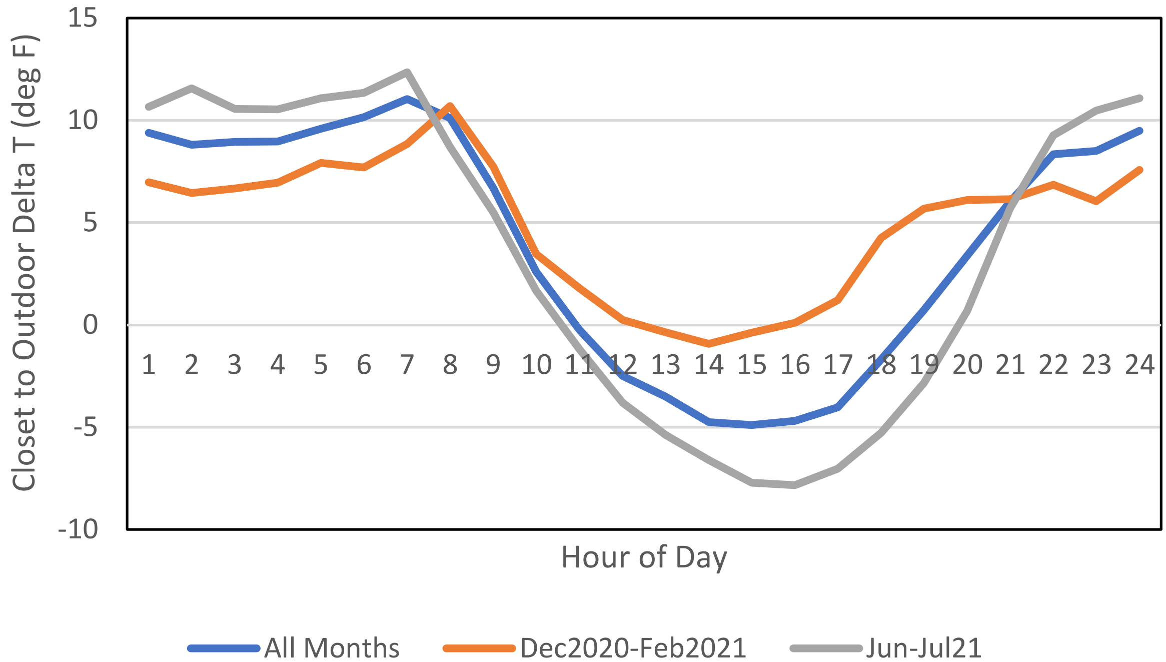


Figure 1: The average temperature difference between the closet and outdoor temperatures during 1) All months, 2) Winter months, and 3) Summer months while HPWH operating

An algorithm was added to Flexi-HPWH to account for these observed temperature differences using relationships that vary monthly, rather than the seasonal relationships shown in Figure 1. The algorithm estimates the temperature inside the closet during HPWH operation by adding the observed hourly temperature adjustment to the outdoor temperature. This adjustment process is necessary since model-predicted HPWH operation will not align perfectly with monitored HPWH operation, rendering the measured inlet air temperatures meaningless at times when the HPWH operation does not align. The data analysis and algorithm consist of the following steps:

1. Split the data set into months,
2. Identify the average difference between outdoor and closet air temperatures during HPWH operation for each hour of each month,
3. Add the average temperature difference to the monitored outdoor air temperature for each month/hour combination to estimate the closet air temperature.

A similar adjustment was made to simulate the relationship between the unducted closet conditions and outdoor ambient temperature. Field data collected before the June 2020 closet ducting retrofit was used to characterize unducted performance with Figure 2 presenting data for both configurations. On average, the unducted case resulted in closet air temperatures 11°F cooler than the ducted case during HPWH operation. The lack of any unducted data other than the limited June 2020 dataset may result in some seasonal inaccuracies.

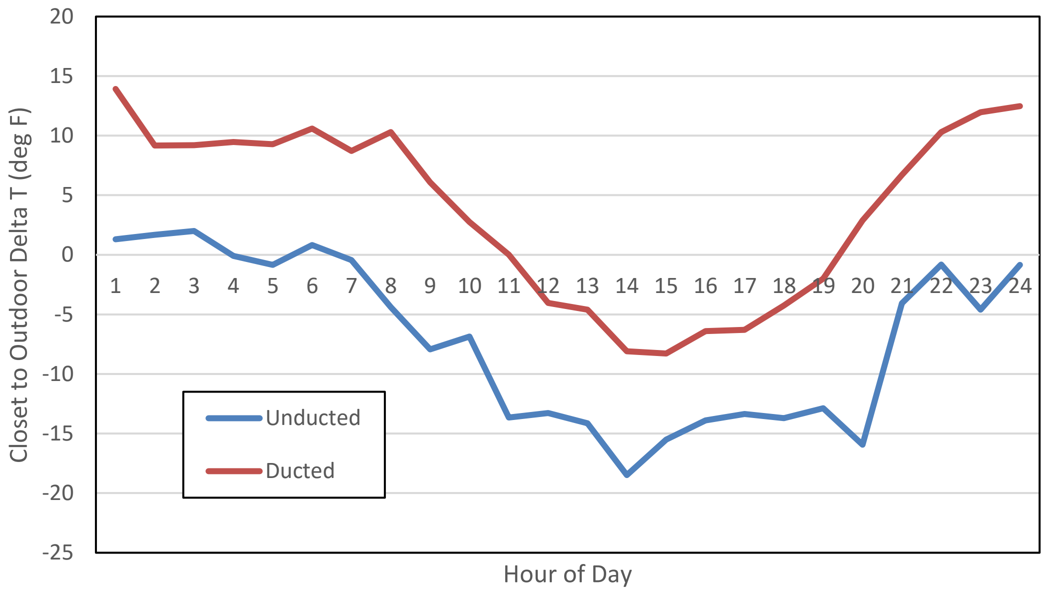


Figure 43: The average temperature difference between the closet and outdoor temperatures with a ducted or unducted HPWH during operation

Flexi-HPWH was modified with these adjustments and the cases were simulated using a 90 gallon/day hot water usage dataset of observations from one of the HPWHs at the Creekside project. The 90 gallon/day case was selected because 1) It is a medium-use dataset from the Creekside project, and 2) Occupancy and hot water use patterns for that water heater remained stable through the entire monitoring period. The simulation was completed for a twelve-month period with data spanning October 1, 2020 to September 30, 2021. Inlet water and ambient air temperatures during that period were also used to drive the model. The following cases were simulated to evaluate impacts:

Closet, Unducted: Assumes that the HPWH is in a confined closet that benefits from tank storage losses, but is impacted by exhaust air being recirculated (11.0°F below ambient plus time of day adjustment). The jacket losses and COP are both calculated using the reduced closet temperatures.

Outdoor Location: Assumes the HPWH is totally unaffected by exhaust air recirculation and that storage losses and evaporator inlet air condition is defined by the outdoor ambient temperature.

Closet, Ducted: Assumes the HPWH is in a confined closet that benefits from tank storage losses, but the heat pump performance is impacted by reduced airflow (7.5°F reduction in evaporator air inlet temperature). The jacket losses are calculated using the increased closet temperatures, and the COP is calculated using the 7.5 °F reduction. The closet temperature is also impacted by cooling from the uninsulated flex duct to the closet.

Idealized: This case assumes the warmer closet temperatures of the ducted case, but without any evaporator airflow degradation due to ducting restrictions. This case is intended to roughly approximate the effects of a HPWH installed in a garage, which will benefit from solar gains and thermal mass similarly to the closet but have enough air volume to avoid cooling the space or installing ducting.

Closet, Ducted Standard (Std) Attic: This case represents the effect of ducting air from a standard attic (attic with insulation exclusively at the ceiling level) into the HPWH evaporator inlet and ducting the exhaust air back into the attic. The jacket losses are calculated using the air temperature in the closet, benefitting from storage tank losses like the Closet, Ducted configuration, and the COP is calculated using the air temperature for a standard attic[38]. Since the ducted evaporator air reduces the airflow, this case uses the 7.5 °F evaporator air inlet temperature reduction to represent the reduced airflow.

Closet, Ducted High Performance (Perf) Attic: This case is the same as Closet, Ducted Std Attic except it uses the air temperatures for a high performance attic (attic insulation at both ceiling level and roof deck). The high performance attic results in more moderate winter and summer attic temperatures than a standard attic, with improved winter temperatures having presumably more significant benefits on HPWH performance.

Standard (Std) Attic, Unducted: This case assumes that the HPWH is installed directly in a standard attic. It uses the same air temperatures as Closet, Ducted Std Attic but does not use a 7.5 °F evaporator air inlet temperature reduction because there is no ducting assumed.

High Performance (Perf) Attic, Unducted: This case assumes that the HPWH is installed directly in a high performance attic. It uses the same air temperatures as Closet, Ducted, High Perf attic but does not use a 7.5 °F evaporator air inlet temperature reduction because there is no ducting assumed.

Modeling Results

Figure 3 presents simulation results for the 80 gallon HPWH over the full year simulation period, operating at a fixed 125°F setpoint. The data labels in the graph compare total HPWH annual energy consumption relative to the Closet, Unducted case. As expected, the Idealized configuration shows the lowest energy consumption over the twelve-month period and the Closet, Unducted the highest (with Idealized consuming 22% less electricity than Closet, Unducted).

[38] Representative hourly attic temperatures were obtained from CBECC-Res simulations. CBECC results were taken from simulations from CZ12 runs with both standard attic and high performance attics to assess whether the roof deck insulation impact (i.e. more tempered attic air) has appreciable impact on HPWH performance.

The increased energy consumption relative to the Idealized case is a direct result of lower ambient and evaporator air inlet temperatures in all cases. The Idealized case showed the highest average ambient temperature, leading to reduced jacket losses and increased heat pump compressor coefficient of performance (COP). The Outdoor case had a lower average ambient temperature, leading to higher jacket losses and lower heat pump COP, as well as times when the ambient temperature was below the heat pump cutoff temperature, leading to electric resistance element use instead of heat pump operation. The main impact of the Closet, Ducted case was a constant reduction of heat pump COP caused by the reduced airflow across the evaporator coil, resulting in a reduced average evaporator temperature. The cooling effect of the recycled exhaust air in the Closet, Unducted case resulted in the lowest average ambient temperature leading to several instances where the ambient temperature was below the compressor cutoff temperature.[39]

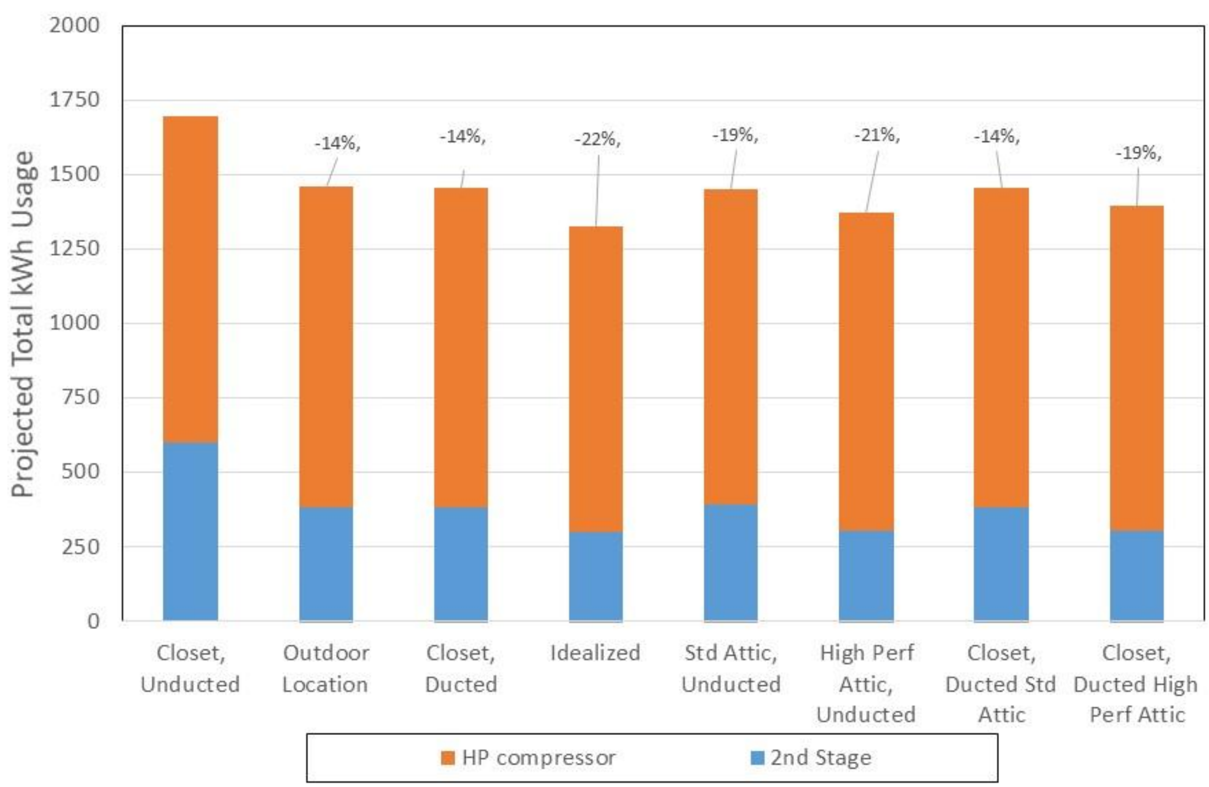


Figure 3: Projected annual energy consumption for different HPWH ducting/location configurations

[39] This would have greater consequences in climates colder than the Davis, CA location.

Figure 4 plots projected annual jacket losses from the tank as a percentage of the total energy input to the HPWH. The jacket losses range from 13.4% to 17.0% of the total energy with the Closet, Std Attic, Unducted and High Perf Attic, Unducted performing equivalent to the idealized case. The Closet, Unducted case shows a significantly higher jacket loss percentage as the recycled air reduces the average closet temperature.

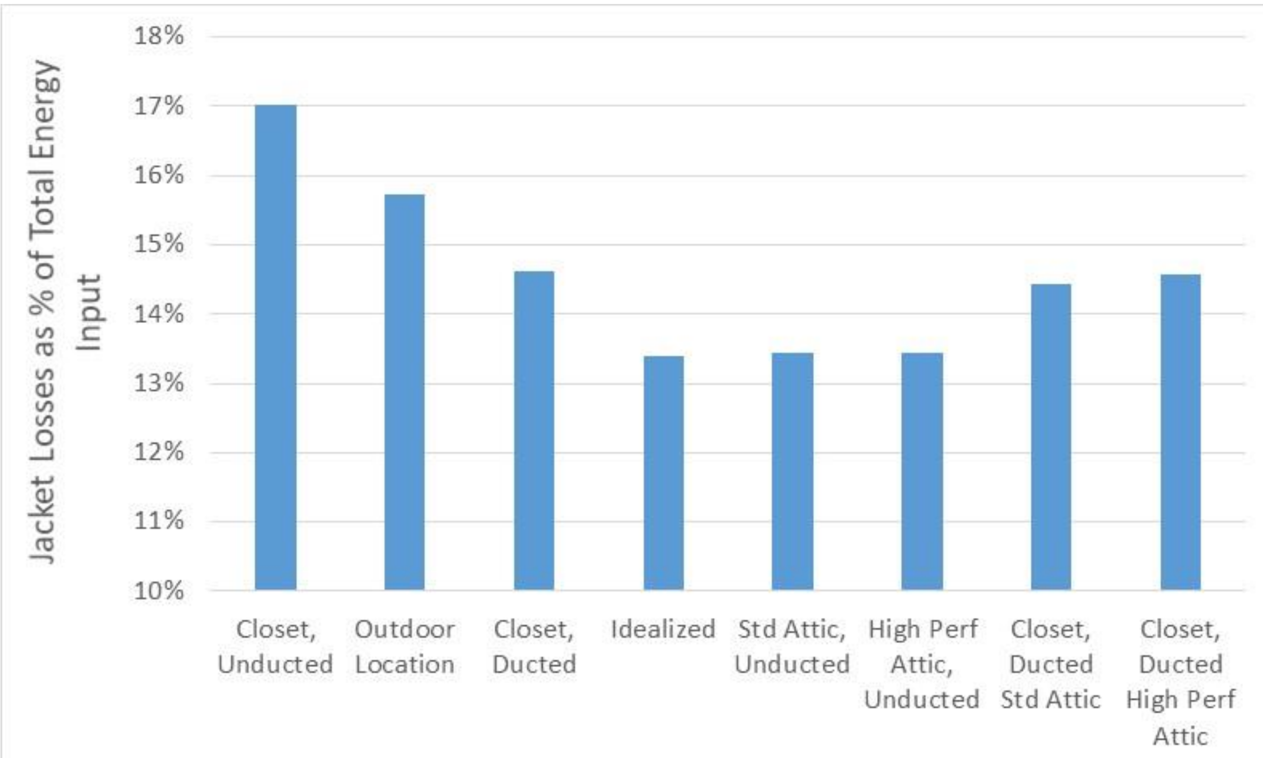


Figure 4: Projected annual jacket losses as a % of total energy added to the water

Table 13 shows the complete set of results for the 125 °F simulation set. The Idealized case consumed a total of 1326 kWh over the 12-month simulation period, lower than the other cases (which ranged from 1338 to 1694 kWh), though the HPWH located in the High Performance Attic was a very close second. Most of the difference in energy consumption is explained by the average and minimum ambient temperature columns. The Idealized case had the highest average ambient temperature, causing both the lowest jacket losses and the highest average heat pump compressor COP. The High Performance Attic case had a slightly lower average ambient temperature increasing the jacket losses.

The Closet, Ducted case had a slightly lower average ambient temperature relative to the Idealized case, leading to minor increases in jacket losses and reduction in average heat pump COP. The biggest performance difference between the Ducted Closet and Idealized cases arose from the 7.5 °F reduction in evaporator air inlet temperature, resulting in a decrease in average heat pump COP for the modeled ambient conditions.

The Closet, Unducted case consumed the most energy of all cases, caused by the average 11 °F reduction in closet air temperature. That reduction increased jacket losses, decreased heat pump COP, and contributed to more operation below the ambient temperature cutoff threshold, causing the HPWH to switch from heat pump operation to resistance element operation.

The two cases exploring the effects of ducting attic air into the closet (Closet, Ducted Standard (Std) Attic and Closet, Ducted High Performance (Perf) Attic) both showed increased total energy consumption relative to the Idealized case and decreased consumption relative to the Closet, Ducted case. The increased performance relative to the Closet, Ducted case is the result of warmer air from the attic being supplied to the HPWH, which simultaneously increased average heat pump COP and reduced the times when the evaporator air inlet temperature was below the ambient temperature cutoff threshold. The Closet, Ducted High Perf Attic performed nearly as well as the Idealized case, with the reduction primarily coming from the airflow restriction caused by the ducting reducing the COP of the heat pump. The Closet, Ducted Std Attic case performed worse due to the lower minimum evaporator air inlet temperature and the ducting further reducing the evaporator inlet air temperature, resulting in more resistance heating operation.

The case where the HPWH is located in a Standard Attic performed better than the Ducted, Standard Attic case. This reflects the impact of the ducting on the evaporator air inlet temperature and the resulting use of electric resistance elements. Since the Standard Attic used no ducting there were fewer instances of the air temperature being too cold, and the HPWH was able to use the heat pump compressor more and the resistance elements less.

Table 13: Complete Results for 125 °F Simulations

Installation Configuration	Electricity Consumed (kWh)	Electricity Consumed Heat Pump (kWh)	Electricity Consumed Backup (kWh)	Jacket Loss % of Energy Input	Average Ambient Temperature (deg F)	Minimum Ambient Temperature (deg F)	HP only COP
Closet, Unducted	1694	1092	602	17.0%	56.2	28.4	3.9
Outdoor Location	1458	1075	384	15.7%	63.1	30.8	4.0
Closet, Ducted	1453	1072	381	14.6%	67.2	39.4	4.0
Idealized	1326	1026	300	13.4%	72.1	44.3	4.2
Std Attic, Unducted	1365	1027	338	13.4%	71.5	31.7	4.2
High Perf Attic, Unducted	1338	1035	303	13.4%	71.5	44.6	4.2
Closet, Ducted Std Attic	1451	1059	392	14.4%	67.2	39.4	4.1
Closet, Ducted High Perf Attic	1371	1067	304	14.6%	67.2	39.4	4.1

Conclusions and Next Steps

Precisely modeling HPWH operating transitions from first to second stage is a critical aspect of identify HPWH performance and is very challenging without direct knowledge of the control schemes and precise representation of tank temperatures at the two heights where the HPWH unit is sensing tank temperature. This is an area where the Flexi-HPWH tool (and other HPWH models) are most challenged to accurately reflect performance. Small changes in the control assumptions likely have a moderate to significant impact on energy usage. Preliminary investigations into the control logic of the HPWHs installed at Creekside show that the standard deviation of "Tank setpoint – lower thermostat temperature" at the time of second stage activation is 16 °F, strongly implying that the control logic is driven by something in addition to temperature. Manufacturer control logic patents generally discuss different electric resistance activation control strategies, including a pre-heat mode for times when the water in the tank is too cold to safely operate the heat pump. Future work efforts should include identifying the employed control strategies and using lab testing to better determine their parameters so they can be accurately replicated in HPWH models.

This preliminary investigation into the impacts of ducting on HPWH performance suggests that ducting is beneficial to the performance of HPWHs in cramped closets, despite the reduction in airflow across the evaporator. In addition, units located in the attics or in closets with ducting to/from the attic, all performed better than the Closet, Ducted case. The latter finding has practicality for single family applications but is not generally a viable configuration for multi-family applications. These findings represent a preliminary assessment due to the loads assumptions used here, but the expected 14-22% energy penalty represented in Figure 3 should be reasonably robust as a first cut impact assessment. Findings from the current NEEA-sponsored work will help bolster this work.

This initial work effort has fostered additional research questions in this area including:

- Does the observed Creekside ducting airflow impact reasonably represent most ducted applications[40]?
- For a closet configuration such as Creekside, would an alternative ducting configuration provide better results[41]? Testing in a lab environment would be beneficial to assess airflow impacts of various designs and the impact of various louvered door types (impact on net free area) and other closet ventilation options (i.e less airflow restrictive door thresholds). NEEA is currently working with Larson Energy Research and Cascade Engineering to complete laboratory testing of HPWH performance in different sized closets and also looking at performance using

[40] Communications with Ben Larson suggest that from his early days of testing HPWHs for Ecotope/NEEA, that a 20% reduction in airflow did not have an appreciable impact on performance. This is his recollection and may not be representative of current models but does provide some context for assessing airflow impacts.

[41] The HVAC contractor that completed a work felt that the rigid sheet metal short duct configuration proposed by Frontier was not as durable as the accordion style flex duct approach favored by the contractor.

manufacturer prescribed acceptable ducting strategies. These findings will further help inform this research topic. The work is expected to begin in December 2021.

- Is it possible to design an efficient closeted HPWH system that does not require ducts? Some of these questions will be answered in the NEEA testing. Alternative approaches, such as a controlled exhaust fan in the closet would increase "uncontaminated" airflow to the HPWH but would the fan energy use be lower than the reduced HPWH energy consumption caused by increased COP?
- Are there opportunities to take advantage of the free cooling provided by the HPWH, by directing the air into conditioned space?
- How can we most accurately simulate the effects of a HPWH on a closet space, and the effects of ducting on HPWH performance? This preliminary study used average values for closet temperature reductions and evaporator inlet air reductions. A more sophisticated first principles model would likely provide improved results.
- Finally, unitary HPWHs in closets have applications for both single family (older homes with indoor water heaters that will be retrofitted to HPWHs) and multifamily projects. For the latter, elimination of central water heating distribution losses (estimated to be in the +/- 30% range) is a significant benefit that must be carefully evaluated on a systems level.

APPENDIX C: HIGH RESOLUTION HPWH PLOTS

The following set of plots present a full day of data for various HPWHs under different loads and operating modes and seasons. The data are presented to provide the reader more detailed data on operational characteristics of the units under varying conditions and modes of operation. Raw data collected was largely on 15 second intervals, but for the plots shown here the data has been rolled up into one minute data. The data is a combination of data read from the HPWH on-board controller (upper tank temperature, lower tank temperature, set point) and also from the installed datalogging system (HPWH power, closet air temperature, hot water flow, and HPWH outlet supply temperature (downstream of the mixing valve).

The first plot was collected during the very early days of the monitoring (May 4, 2020), prior to finalizing the communications link allowing for direct data access from the HPWH. The data is also prior to installing ducting to exhaust air out of the closet (which occurred mid-June 2020). This plot shows HPWH 3CFA in standby operation mode, as there was no occupancy in the apartments and therefore no hot water loads. The key information to be gleaned from this plot is the impact of HPWH operation on the closet temperature and the amount of energy consumed to keep the storage tank hot. During the 80 minute HPWH cycle, the unit consumed 0.49 kWh to maintain the tank temperature. (Although small, this usage is reflective of what standby usage would be for multiple individual HPWHs (vs. shared) during a mild part of the year.) During this preoccupancy period, these cycles occurred daily.

Figure 1:

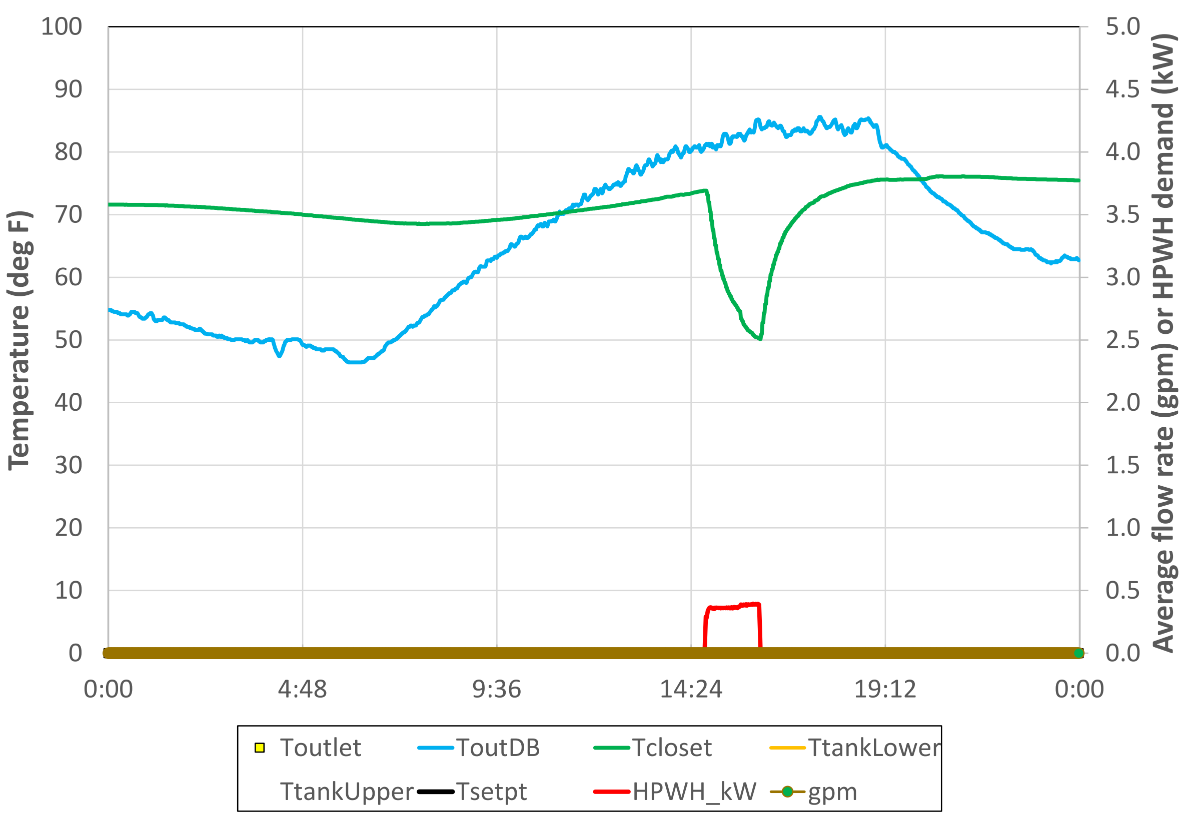


Figure 2 shows HPWH 3DDD operating in standard fixed setpoint mode (130°F) during the winter (December 4th, 2020). Hot water usage for this day totaled 113 gallons. The closet temperature was generally 10-15°F warmer than outdoor temperature during nighttime hours. The impact of HPWH operation is evident as the closet temperature falls below outdoor temperature with the start of the first HPWH operating cycle. Hot water loads are moderate until about 2 PM, at which point they increase from about 2:30 to 9 PM. The HPWH operates most of the day with the compressor, but at around 11 PM 2nd stage operation ensues. It is not entirely clear why 2nd stage was energized at that time since the upper tank temperature had fallen more than 15°F below set point for several hours. There is possibly a delay timer at work which prevented 2nd stage operation for a period of time or possibly a lower limit temperature cut out. The yellow markers show outlet supply water temperature. For very short draws on the order of seconds, the one minute average plots indicate lower average temperatures since there are other data points in the average without flow. Periods of consistent hot water flow are more representative of the outlet condition.

Figure 2:

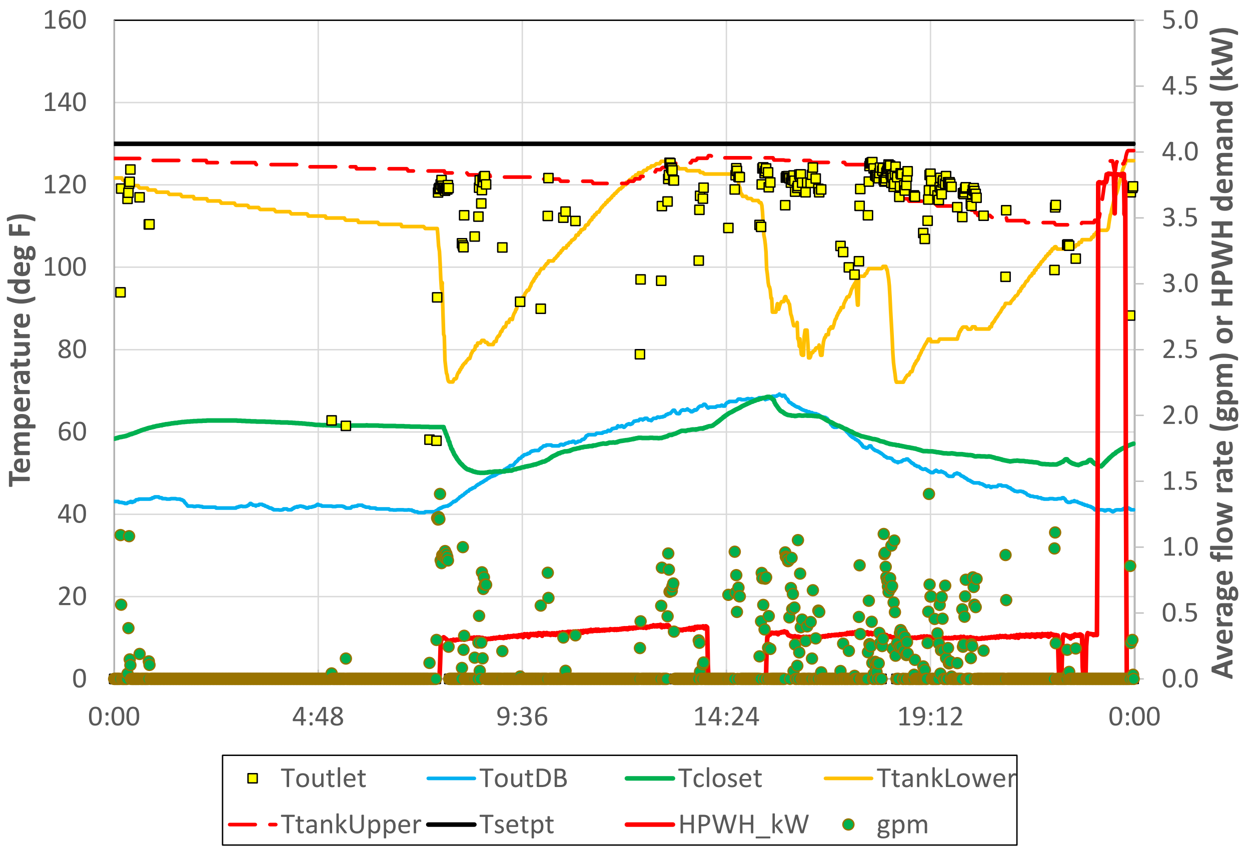


Figure 3 shows the operation of HPWH 3E82 on March 26, 2021 on a very low hot water draw day (21 total gallons drawn for the tank). The unit is controlled to perform load-shifting on this day with four steps in temperature up from the nominal 125°F set point. The HPWH responds to the first step at 8 AM, but apparently the 10 AM increase in set point is insufficient to trigger operation. The noon increase also results in a heating cycle, but similarly the 2 PM increase does not trigger operation. Entering the peak period, the upper tank temperature is below the 133°F target and small hot water loads during the 4-9 PM peak period are enough to trigger an operating cycle beginning at 8:15 PM. This pattern of operation is of interest for a low hot water load scenario. Under higher loads, especially in the late AM/early PM hours, the HPWH would not only be working against a higher set point, but also greater energy extraction from the storage tank. This would likely result in continuous operation leading up to the peak and hopefully a fully charged tank at the 4 PM start of peak. It's also interesting to note that the HPWH did not respond to the increased set temperatures at 10 AM and 2 PM. Since the HPWH does not always respond to changing set temperatures, load-shifting controls based on changed set temperature such as in this project would need to be finely tuned to trigger the desired response.

Figure 3:

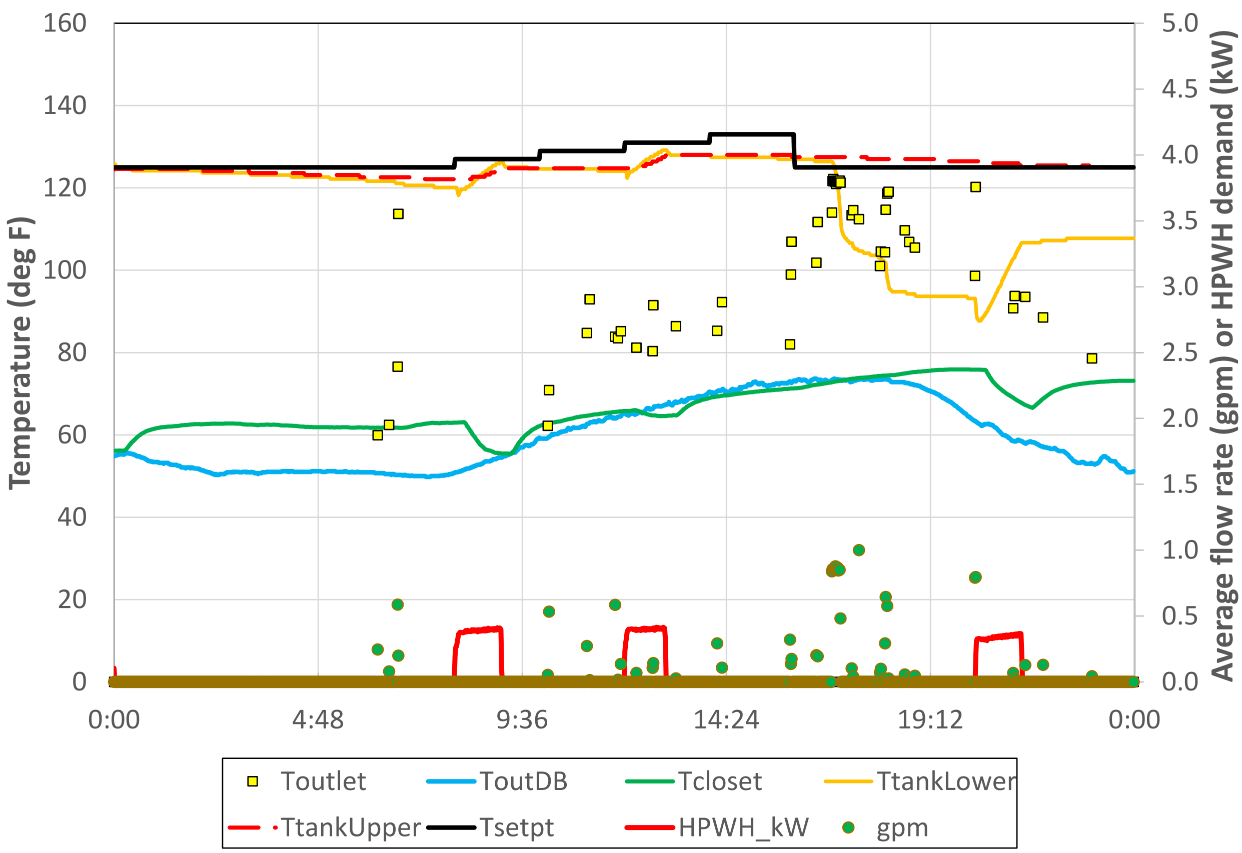


Figure 4 shows a similar type of situation, but under a higher load (80 gallon hot water demand) day. The May 1, 2021 operation for HPWH 3D8C shows the upper tank temperature starting the day above the 125°F set point, due to the prior days load-shifting and apparently small post peak period hot water loads. In this load-shifting case, the HPWH is working to get up to 140°F by 4 PM. The HPWH does not begin to operate until noon and runs continuously until 4 PM. However, hot water loads are building during the early PM and eliminate the unit's ability to achieve the 140°F target. As the peak begins and hot water loads continue, the HPWH is quickly forced to operate to maintain the new 125°F target. The timing of the hot water loads played a big part in this day's less than ideal load-shifting performance. This example speaks to the potential of a larger capacity compressor which would be more effective in boosting storage tank temperatures prior to the peak.

Figure 4:

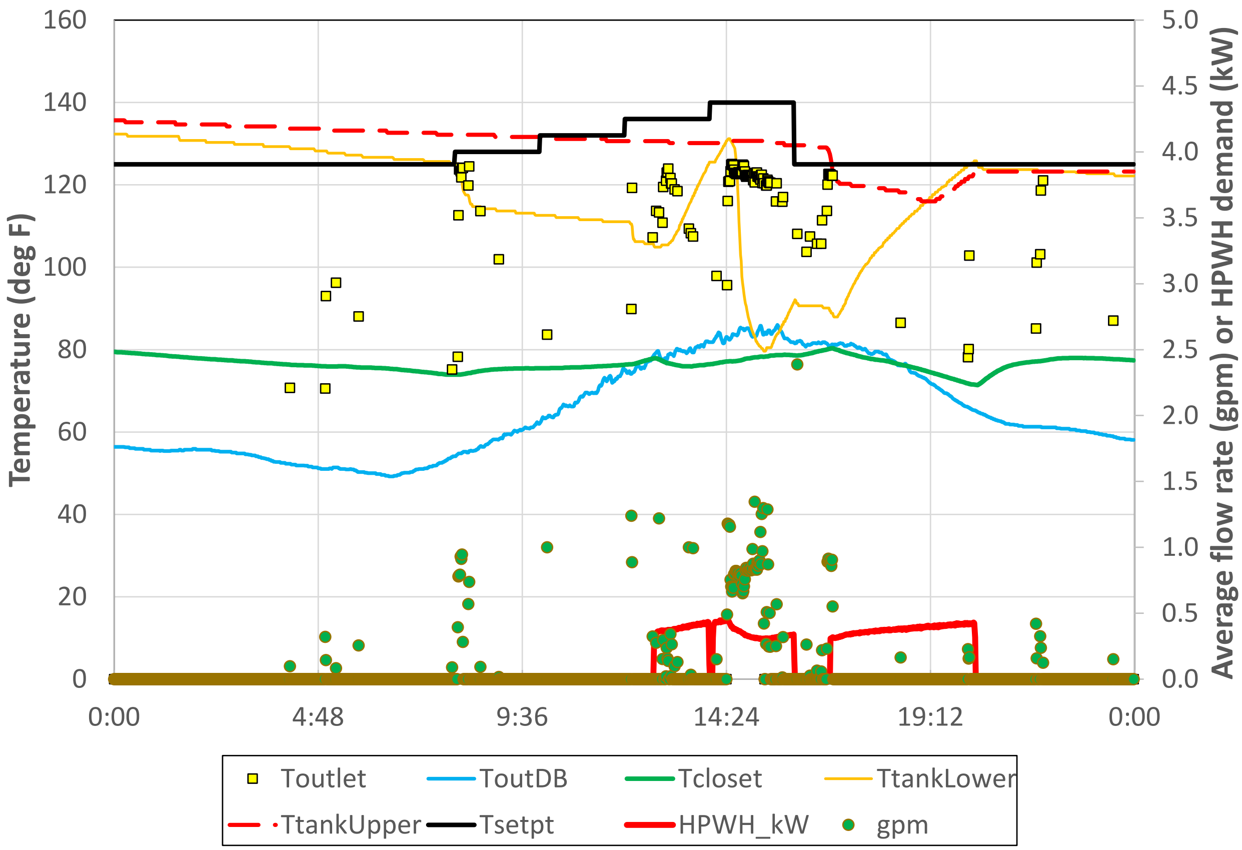


Figure 5 for HPWH BA3A on July 29, 2021 demonstrates a highly successful load-shift under a high hot water usage day (156 gallons). Load-shifting is more easily attainable in mid-summer when hot water loads are reduced due to warmer cold water inlet temperatures and favorable evaporator inlet air conditions. On this day, the HPWH runs in compressor only mode from about 3 AM to 4 PM, in response to both hot water loads early in the morning and the set point increases prior to the peak. At 4 PM, the upper and lower tank temperatures are both up to the 140°F target ensuring maximum energy storage. The HPWH can then handle all the hot water demands through the peak period and continue to coast through the end of the day.

It is also worth noting that the HPWH did not begin heating until the upper thermostat temperature fell below the set temperature, despite the lower thermostat temperature being steady at 80 °F. This operation has been commonly observed in the monitored HPWHs. At this time it is believed that the HPWH on-board controllers include a heating lockout when the upper thermostat is above the set temperature. This example shows a case of the lockout delaying load-shifting operation. While this did not impede successful load-shifting performance on July 29, 2021 in BA3A it could do so in other cases.

Figure 5:

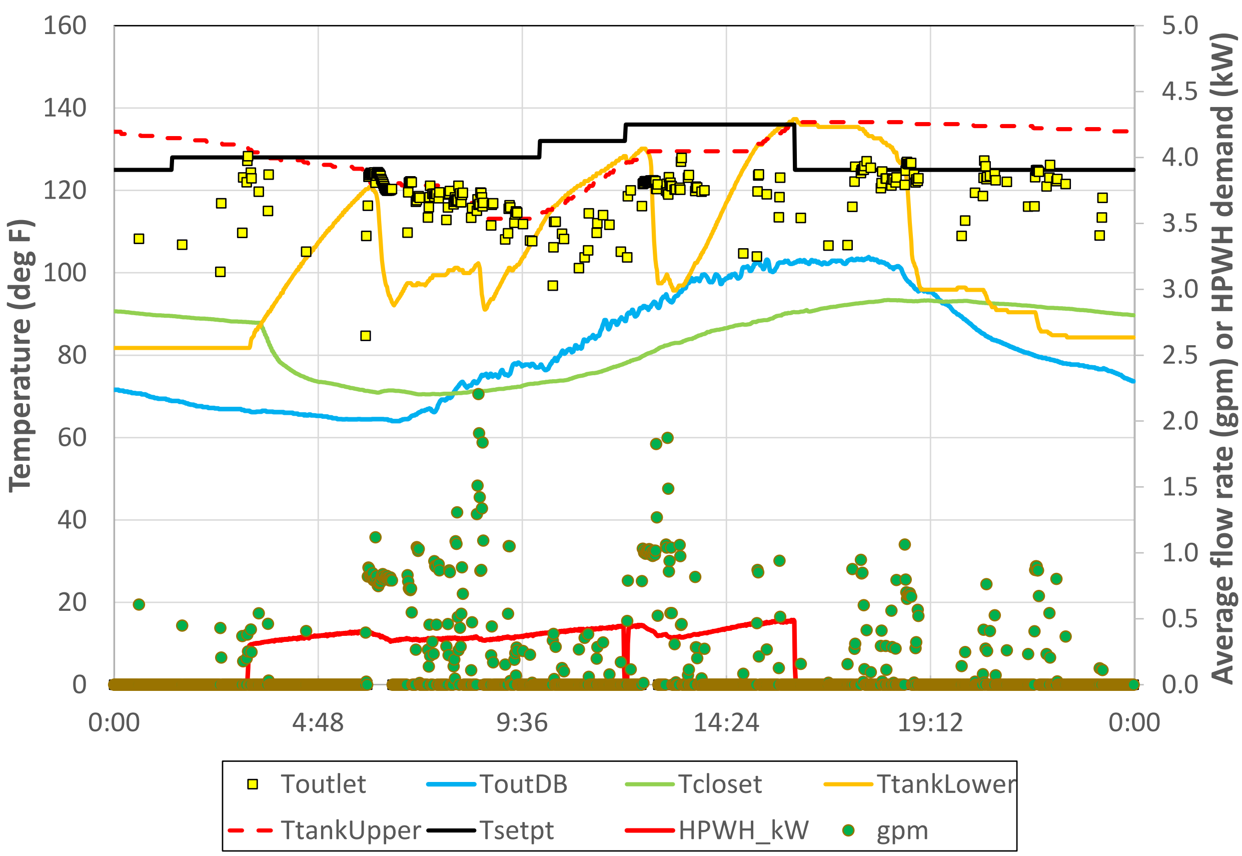
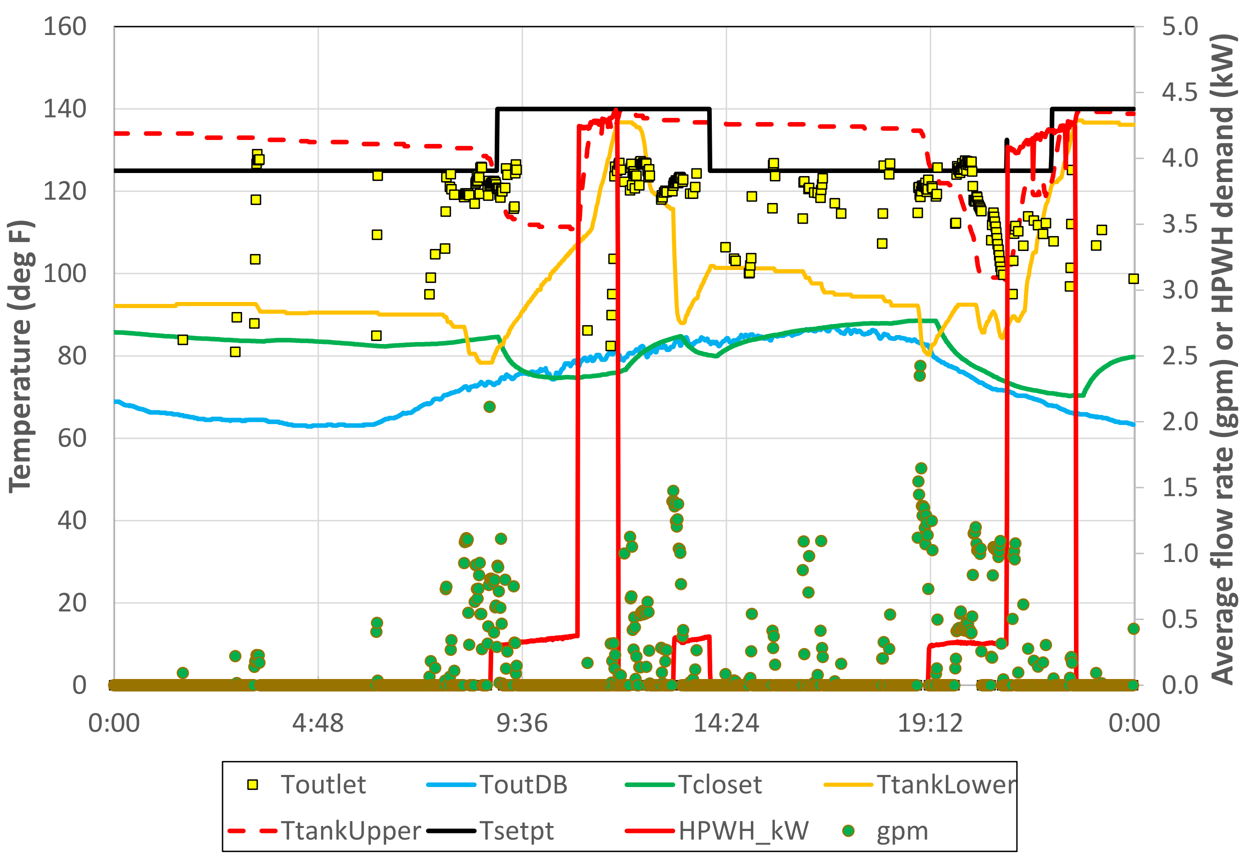


Figure 6 and Figure 7 provide summer data for HPWH B9AE (the highest loaded unit of the ten monitored). Figure 6 shows operation in load-shifting mode under a 154 gallon hot water demand on June 14, 2021. The load-shift at 8 AM provided a single 15°F jump in set point which triggered immediate compressor operation. After two hours, the control logic determined that 2nd stage was needed, even though there hadn't been any hot water draws in nearly an hour. 2nd stage operation brought the tank temperature up to 140°F quickly. Continuing draws prior to the 2 PM peak[42] triggered an additional short cycle until 2 PM. During the 2-9 PM peak, continuing hot water draws slowly pulled down the tank temperature and at ~ 7 PM another steady draw triggered a compressor cycle, which again transitioned into 2nd stage operation.

Figure 6:



[42] Some testing was done with a 2-9 PM peak.

Figure 7 shows B9AE operation on June 28, 2021 with nearly identical total hot water loads as in Figure 6 (153 gallons). Here the loads are much more concentrated in the early AM hours. HPWH operation is triggered around 3:30 AM and high loads continue to draw the tank down, nearly 30°F below the set point at 8 AM. For some reason 2nd stage operation isn't triggered until 9 AM when the 15°F jump in set point activates 2nd stage. It may have occurred at this time due to the increased set temperature, without the upper thermostat temperature increasing to catch up, surpassing the allowable difference between the setpoint and upper thermostat temperature. The tank is satisfied and makes it through the peak period without any on-peak HPWH operation.

Figure 7:

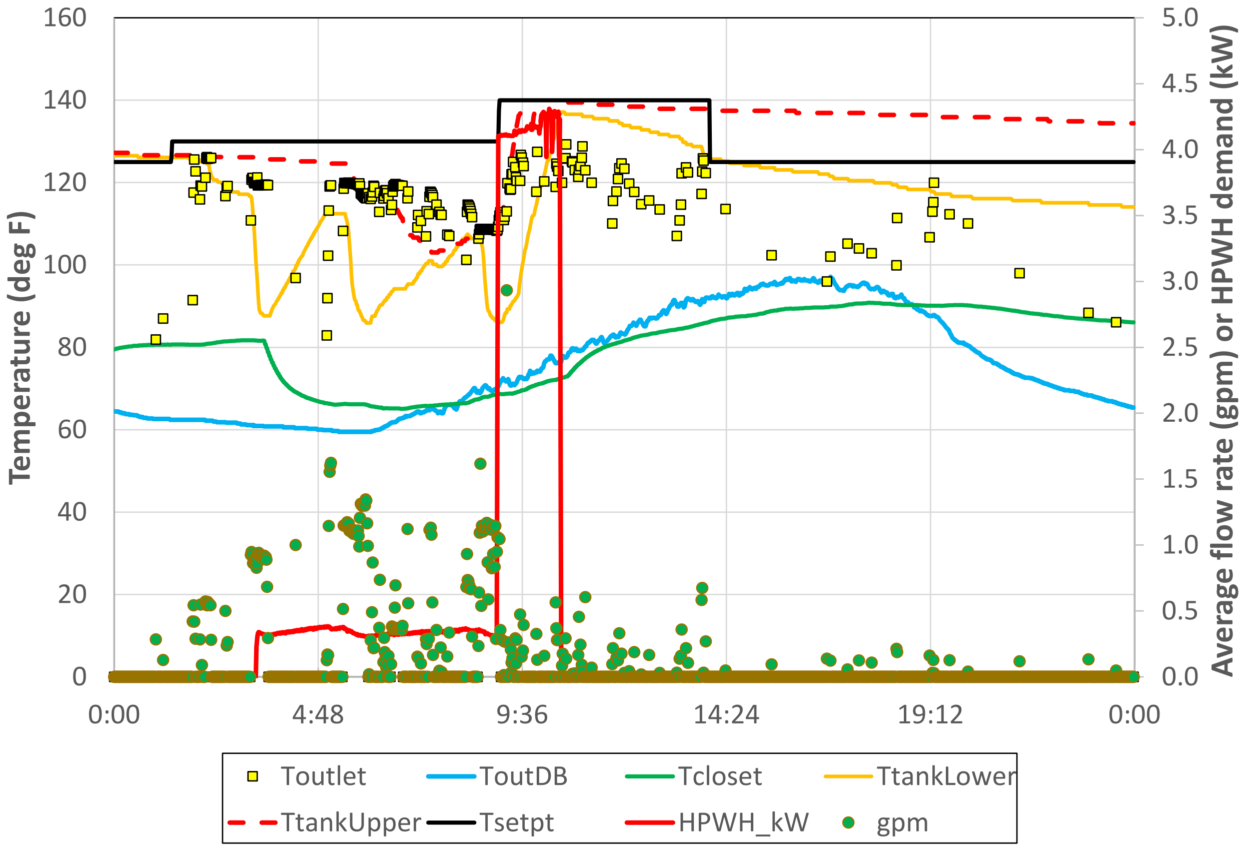
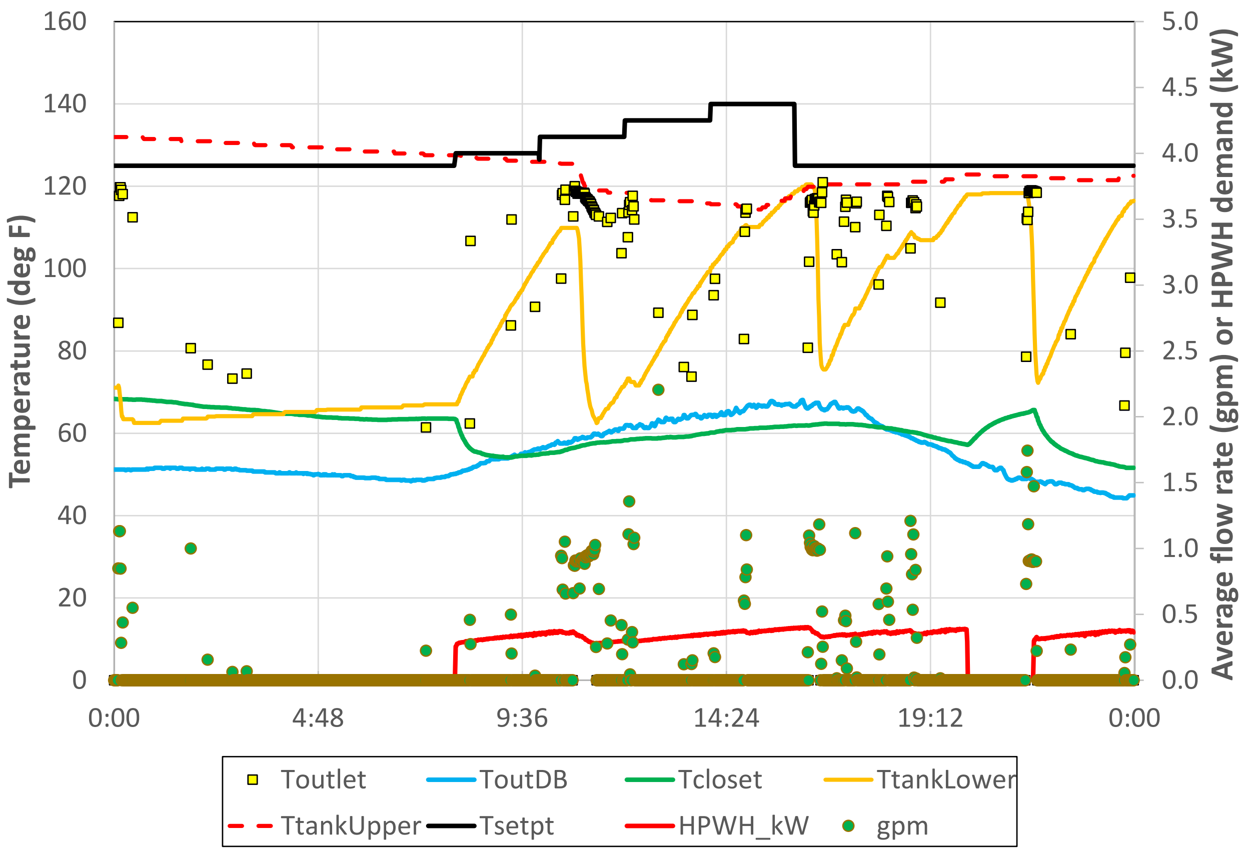


Figure 8 shows HPWH BD13 operating on February 28, 2021 a day with 101 gallon hot water loads. HPWH compressor operation ensues at 8 AM with the first increase in set point temperature. The HPWH continues to operate in compressor only mode until the 4 PM peak, despite the fact that the upper tank temperature is nearly 30°F below the setpoint (from 2-4 PM). In prior situations with similar temperature conditions 2nd stage operation has been triggered, but not under these circumstances. Relying solely on the compressor prior to the 4 PM start of peak results in the unit needing to run continuously for most of the peak. Some 2nd stage operation prior to the peak could have eliminated the on-peak operation. This highlights the complexities in fully deciphering system operation with monitoring data alone.

Figure 8:



Appendix D: Simulation Results

Notes: Results for all 93 simulation cases reported here. Results assume a shared configuration with 4 apartments per 80 gallon HPWH, unless noted differently in NOTES. Both 50 gallon individual HPWHs (per apartment) and a Shared 3 apartments per HPWH are highlighted. Resulting energy use, operating cost (TOU-C and hypothetical TOU rate—HYPO), and $C0_2$ data is for the configuration shown and may represent one, three, or 4 apartments. $C0_2$ data not shown for CZ runs where the weather data does not align with CAISO data.

				Electricity Usage (kWh/year)					Electricity Cost ($/yr)		CO_2
ID #	Draw Profile	Set Temperature Schedule	Notes	Total	Heat Pump	2nd Stage RH	4-9 PM	COP	PG&E TOU-C	HYPO TOU	lbs /yr
1	Low	Hr 0-24: 125 deg F		937	881	56	203	3.2	$253	$227	499
2	Low	Hr 0-24: 140 deg F		1175	1113	61	258	2.6	$317	$285	633
3	Low	Hr 8-16: 140 deg F All others:125 deg F		1457	828	629	24	2.1	$382	$315	656
4	Low	Hr 8-16: 140 deg F All others:125 deg F	Stepped loadshift	1399	840	559	58	2.2	$369	$308	582
5	Low	Hr 8-16: 133 deg F All others:125 deg F		1045	930	116	36	2.9	$276	$230	540
6	Low	Hr 8-16: 133 deg F All others:125 deg F	Stepped load shift	1045	942	103	54	2.9	$277	$232	513
7	Low	Hr 8-16: 140 deg F All others:125 deg F	ER activate at T_Out < 105	1196	909	287	40	2.5	$315	$262	527
8	Low	Hr 1-5: 133 deg F All others:125 deg F		1132	847	286	423	2.7	$308	$293	710

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	Hypo TOU	CO_2 lbs/yr
9	Low	Hr 0-24: 125 deg F	50 gal tank	345	345	0	73	2.2	$93	$83	196
10	Low	Hr 0-24: 140 deg F	50 gal tank	479	479	0	100	1.6	$129	$115	277
11	Low	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank	446	407	40	7	1.7	$118	$97	223
12	Low	Hr 8-16: 133 deg F All others:125 deg F	50 gal tank	389	378	9	24	2.0	$103	$86	209
13	Low	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank Stepped load shift	450	437	12	21	1.7	$120	$100	195
14	Low	Hr 8-16: 133 deg F All others: 125 deg F	50 gal tank Stepped load shift	408	398	10	18	1.9	$108	$91	191
15	Low	Hr 8-16: 140 deg F All others:125 deg F		429	414	14	6	1.8	$113	$93	214
16	Medium	Hr 0-24: 125 deg F		1472	1017	455	303	2.7	$396	$355	823
17	Medium	Hr 0-24: 130 deg F		1567	1094	473	324	2.6	$422	$378	876
18	Medium	Hr 0-24: 140 deg F		1730	1281	449	358	2.4	$465	$417	976
19	Medium	Hr 8-16: 140 deg F All others:125 deg F		2207	865	1342	95	1.8	$587	$490	1076
20	Medium	Hr 8-16: 140 deg F All others:125 deg F	Stepped load shift	2014	939	1075	113	2.0	$535	$450	959
21	Medium	Hr 8-16: 133 deg F All others:125 deg F		1678	1011	667	133	2.4	$446	$378	911

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	Hypo TOU	CO_2 lbs /yr
22	Medium	Hr 8-16: 133 deg F All others:125 deg F	Stepped load shift	1657	1028	629	129	2.4	$440	$373	879
23	Medium	Hr 8-16: 140 deg F All others:125 deg F	ER activate at T_Out < 105	1856	977	879	108	2.1	$490	$412	922
24	Medium	Hr 8-14: 133 deg F All others:125 deg F		1647	1008	639	155	2.4	$437	$373	924
25	Medium	Hr 8-14: 133 deg F All others:125 deg F	Stepped load shift	1634	1022	613	131	2.5	$433	$368	899
26	Medium	Hr 1-5: 133 deg F All others:125 deg F		1731	951	780	499	2.3	$468	$433	1035
27	Medium	Hr 1-5: 133 deg F Hr 8-16: 133 deg F All others:125 deg F	Stepped load shift	1711	1036	676	135	2.4	$454	$385	938
28	Medium	Hr 0-24: 125 deg F	50 gal tank	425	411	14	87	2.4	$115	$103	248
29	Medium	Hr 0-24: 140 deg F	50 gal tank	572	558	14	110	1.8	$154	$137	334
30	Medium	Hr 8-16: 140 deg F All others:125 deg f	50 gal tank	521	466	55	12	2.0	$138	$114	264
31	Medium	Hr 8-16: 133 deg F All others:125 deg F	50 gal tank	463	443	20	23	2.2	$123	$103	256
32	Medium	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank	527	482	45	25	2.0	$140	$117	238

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	Hypo TOU	CO_2 lbs /yr
33	Medium	Hr 8-16: 133 deg F All others: 125 deg F	50 gal tank, Stepped load shift	477	455	22	22	2.2	$127	$106	239
34	Medium	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank ER activate at T_Out < 105	521	466	55	12	2.0	$138	$114	264
35	Medium	Hr 8-14: 133 deg F All others:125 deg F	50 gal tank	471	450	22	1	2.2	$124	$102	247
36	Medium	Hr 1-5: 133 deg F Hr 8-16: 133 deg F All others:125 deg F	Stepped load shift	501	474	27	22	2.1	$133	$111	277
37	High	Hr 0-24: 125 deg F		1709	1337	372	321	3.1	$468	$415	972
38	High	Hr 0-24: 140 deg F		2048	1646	402	395	2.6	$561	$499	1169
39	High	Hr 8-16: 140 deg F All others:125 deg F		2828	1062	1766	72	1.9	$761	$627	1450
40	High	Hr 8-16: 140 deg F All others:125 deg F	Stepped load shift	2548	1171	1378	84	2.1	$686	$567	1283
41	High	Hr 8-16: 133 deg F All others:125 deg F		2044	1276	768	102	2.6	$552	$460	1140
42	High	Hr 8-16: 133 deg F All others:125 deg F	Stepped load shift	2018	1294	724	106	2.6	$545	$455	1107
43	High	Hr 8-16: 140 deg F	ER activate	2294	1230	1065	76	2.3	$617	$510	1201

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	Hypo TOU	CO_2 lbs /yr
		All others:125 deg F	at T_Out < 105								
44	High	Hr 1-5: 133 deg F All others:125 deg F		2076	1218	858	650	2.5	$576	$538	1243
45	High	Hr 0-24: 125 deg F	50 gal tank	499	481	17	110	2.7	$136	$123	291
46	High	Hr 0-24: 140 deg F	50 gal tank	656	642	13	138	2.0	$179	$161	383
47	High	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank	600	526	74	13	2.2	$160	$132	302
48	High	Hr 8-16: 133 deg F All others:125 deg F	50 gal tank	544	510	34	30	2.5	$146	$122	304
49	High	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank, Stepped load shift	598	550	48	23	2.2	$160	$133	267
50	High	Hr 8-16: 133 deg F All others:125 deg F	50 gal tank, Stepped load shift	557	531	57	20	2.4	$149	$124	286
51	High	Hr 8-16: 140 deg F All others:125 deg F	50 gal tank ER activate at T_Out < 105	600	526	74	13	2.2	$160	$132	302
52	Medium	Hr 0-24: 125 deg F	CZ 3	1836	1189	647	430	2.7	$503	$456	
53	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 3, Stepped load shift	2021	1204	817	194	2.5	$545	$466	
54	Medium	Hr 0-24: 125 deg F	CZ 3	496	485	11	109	2.6	$136	$122	

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	HYPO TOU	CO_2 lbs/yr
55	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 3, Stepped load shift	546	533	13	28	2.3	$147	$123	
56	Medium	Hr 0-24: 125 deg F	CZ 6	1525	1092	433	368	2.9	$418	$380	
57	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 6, Stepped load shift	1716	1101	616	150	2.6	$463	$393	
58	Medium	Hr 0-24: 125 deg F	CZ 6	428	428	0	99	2.7	$117	$106	
59	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 6, Stepped load shift	472	472	0	26	2.4	$127	$106	
60	Medium	Hr 0-24: 125 deg F	CZ 10	1526	1056	471	334	2.9	$414	$373	
61	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 10, Stepped load shift	1742	1050	692	142	2.5	$465	$395	
62	Medium	Hr 0-24: 125 deg F	CZ 10	427	415	12	94	2.6	$116	$104	
63	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 10, Stepped load shift	474	455	20	23	2.4	$127	$106	
64	Medium	Hr 0-24: 125 deg F	CZ 15	1154	889	264	257	3.1	$311	$281	
65	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 15, Stepped load shift	1306	898	408	95	2.7	$348	$294	
66	Medium	Hr 0-24: 125 deg F	CZ 15	331	331	0	71	2.7	$89	$80	
67	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 15, Stepped load shift	371	371	0	19	2.4	$99	$83	
68	Medium	Hr 0-24: 125 deg F	CZ 16	3212	929	2284	773	1.7	$891	$814	

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year)				COP	Electricity Cost ($/yr)		CO_2
				Total	Heat Pump	2nd Stage RH	4-9 PM		PG&E TOU-C	Hypo TOU	lbs /yr
69	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 16, Stepped load shift	3396	921	2475	459	1.6	$937	$821	
70	Medium	Hr 0-24: 125 deg F	CZ 16	932	398	534	204	1.5	$247	$223	
71	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 16, Stepped load shift	1004	425	579	71	1.4	$262	$222	
72	Low	Hr 0-24: 125 deg F	3 apt	735	725	10	160	3.1	$198	$179	395
73	Low	Hr 8-16: 133 deg F All others:125 deg F	3 apt, Stepped load shift	837	798	40	40	2.7	$222	$186	407
74	Medium	Hr 0-24: 125 deg F	3 apt	1066	859	207	219	2.9	$287	$257	600
75	Medium	Hr 8-16: 133 deg F All others:125 deg F	3 apt, Stepped load shift	1221	891	330	75	2.5	$323	$272	638
76	High	Hr 0-24: 125 deg F	3 apt	1253	1102	152	246	3.2	$344	$306	718
77	High	Hr 8-16: 133 deg F All others:125 deg F	3 apt, Stepped load shift	1449	1101	348	61	2.7	$390	$324	770
78	Medium	Hr 0-24: 125 deg F	100 gal tank	1453	1061	392	292	2.8	$390	$349	811
79	Medium	Hr 8-16: 133 deg F All others:125 deg F	100 gal tank, Stepped load shift	1666	1065	601	127	2.4	$441	$374	861
80	High	Hr 0-24: 125 deg F	100 gal tank	1689	1390	299	325	3.1	$463	$412	962
81	High	Hr 8-16: 133 deg F All others:125 deg F	100 gal tank, Stepped load shift	2088	1308	780	104	2.5	$564	$469	1100

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	HYPO TOU	CO_2 lbs/yr
82	Medium	Hr 0-24: 125 deg F	1 ton compressor	1266	1126	141	273	3.2	$342	$307	720
83	Medium	Hr 8-16: 133 deg F All others:125 deg F	1 ton compressor, Stepped load shift	1389	1185	204	86	2.9	$369	$311	742
84	High	Hr 0-24: 125 deg F	1 ton compressor	1516	1427	89	335	3.5	$416	$374	872
85	High	Hr 8-16: 133 deg F All others:125 deg F	1 ton compressor, Stepped load shift	1699	1481	218	70	3.1	$457	$380	935
86	Medium	Hr 0-24: 125 deg F	100 gal tank 1 ton compressor	1276	1158	118	270	3.2	$345	$309	732
87	Medium	Hr 8-16: 133 deg F All others:125 deg F	100 gal tank 1 ton compressor, Stepped load shift	1432	1219	214	84	2.9	$380	$320	749
88	High	Hr 0-24: 125 deg F	100 gal tank 1 ton compressor	1546	1457	90	331	3.5	$424	$381	888
89	High	Hr 8-16: 133 deg F All others:125 deg F	100 gal tank 1 ton compressor, Stepped load shift	1738	1516	222	57	3.1	$468	$387	935
90	Medium	Hr 0-24: 125 deg F	CZ 12	1803	1095	708	392	2.6	$487	$439	

ID #	Draw Profile	Set Temperature Schedule	Notes	Electricity Usage (kWh/year) Total	Heat Pump	2nd Stage RH	4-9 PM	COP	Electricity Cost ($/yr) PG&E TOU-C	Hypo TOU	CO_2 lbs/yr
91	Medium	Hr 8-16: 133 deg F All others:125 deg F	CZ 12, Stepped load shift	2015	1093	922	185	2.3	$540	$461	
92	Medium	Hr 0-24: 125 deg F	CZ 12	497	444	53	102	2.4	$134	$120	
93	Medium	Hr 8-16: 133 deg F All others 125 deg F	CZ 12, Stepped load shift	552	484	68	29	2.2	$147	$123	

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