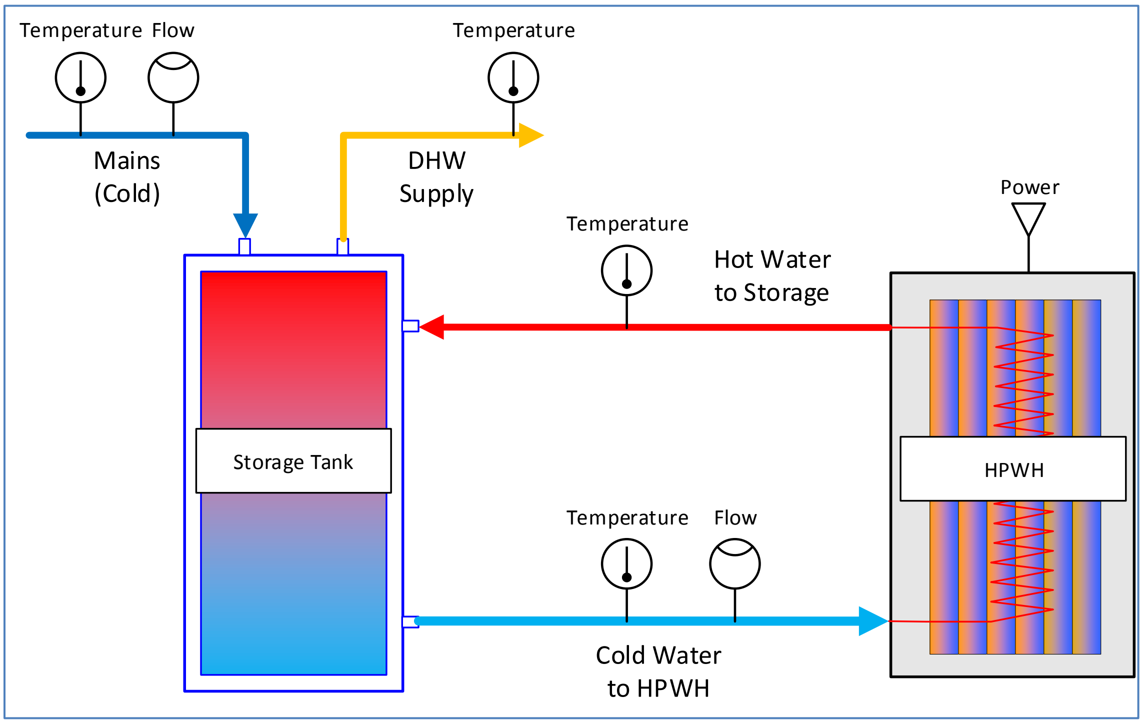
PG&E Residential Code Readiness Project: Monitoring of a Split System CO_2 Heat Pump Water Heater in an All-Electric ZNE Home

PG&E Codes and Standards 2019_1



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LEGAL NOTICE

DEFINITIONS

ACRONYM	DEFINITION
ACH50	Air Changes per Hour (at 50 Pascal pressure differential)
AFUE	Annual Fuel Utilization Efficiency
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning Engineers
AMY	Actual Meteorological Year
Btuh	British Thermal Units per Hour (rate of heat transfer)
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
GWP	Global Warming Potential
ft^2	Square feet
HPWH	Heat Pump Water Heater
kW	Kilowatt
kWh	kilowatt-hour
MADIS	Meteorological Assimilation Data Ingest System
NOAA	National Oceanic and Atmospheric Administration
PEX	Cross Linked Polyethylene
PV	Photovoltaic
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year
U-value	Overall Heat Transfer Coefficient
UEF	Uniform Energy Factor
ZNE	Zero Net Energy

FIGURES

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EXECUTIVE SUMMARY

This report documents the performance of a heat pump water heater (HPWH) utilizing carbon dioxide (CO_2) as the working refrigerant. The unit was installed in a Redding, California all-electric Zero Net Energy home and monitored in detail over the course of a year. The unit offers advantages over conventional HPWHs in that the efficiency is higher[1], the water heating capacity is higher, the heating output is stable over a much wider range of outdoor temperatures, there is no supplemental electric backup heating, and the CO_2 refrigerant has a global warming potential of 1.

The project was funded under PG&E's 2018 through 2019 Code Readiness effort. The installed water heater was one of a range of energy efficiency measures incorporated in the design of the Zero Net Energy home. A companion report of the whole house energy performance can be found at the Emerging Technology Coordinating Council website[2].

This report focuses on the detailed monitoring of the CO_2 HPWH, which included a series of flow meters, immersion temperature sensors, and a power monitor. Unlike conventional HPWHs that have gained prominence in the U.S. over the last five to ten years, the CO_2 unit is a split system configuration, whereby the storage tank is physically separated from the outdoor unit (by a pumped loop from the indoor tank). The split system configuration therefore has thermal losses associated with the storage tank (common to all storage water heaters), but additionally piping losses between the outdoor unit and storage tank that occur during system operation and between operating cycles. The advantage is that the tank can be located inside the house or other location best suited to the specific application.

The single-story 2,372 ft^2 home has four bedrooms and three full baths. It was occupied by a couple in June 2017 and detailed monitoring of the HPWH occurred from mid-July 2017 through mid-July 2018. Two sets of flow meters and immersion temperature sensors were installed to measure the flow and temperature difference between the storage tank and the outdoor unit and also from the storage tank to household domestic hot water end uses (this is termed the recovery load). A dedicated power monitor recorded total energy consumption of the unit. Energy flows were calculated on a four-second basis during all flow events to capture transient effects with a high degree of accuracy.

Average hot water loads of 23.0 gallons per day (gpd) were monitored with typical day-to-day and seasonal variation in load. The 45-gallon storage tank provided adequate capacity of this load. HPWH energy use totaled 712 kWh for the year. Annual average efficiency, expressed in terms of a non-dimensional Coefficient of Performance, was calculated at 3.04[3], with monthly performance varying from 2.24 to 3.42 COP.

The CO_2 HPWH is a high quality, high efficiency product, and as such carries a significant cost premium over competing HPWH products. Mike MacFarland, the builder of the Redding house, estimates a current first cost premium in the range of $2,000 to $2,500 over the integrated HPWHs more commonly seen in residential applications.

As part of the evaluation, a simplified economic analysis was completed based on the monitored CO_2 HPWH unit performance and the estimated performance of a conventional HPWH with an assumed annual average 2.0 COP. The evaluation was completed at both the

[1] The GS3-45HPA-US unit has a certified rating of Uniform Energy Factor (UEF) of 3.09 with a 43 gallon tank or 3.3 with an 83 gallon tank.
[2] PG&E Residential Code Readiness Project: Redding, California Site Monitoring Report Codes and Standards PGE 2018_3, www.etcc-ca.com
[3] An electric resistance water heater would generate hot water at a COP of 1.0.

observed 23 gpd loads and at a more representative 46 gpd load level. The analysis estimated 255 kWh annual savings at 23 gpd and 497 kWh at the higher 46 gpd load level. At an assumed statewide average electric rate of $.20 per kWh, annual owner cost savings would range from $51 to $100 per year based on the Redding monitored performance.

With California moving to near Zero Net Energy new construction under the 2019 Title 24, Part 6 standards, a scenario was developed whereby additional photovoltaic (PV) panels were added to offset the difference in usage between the two heat pump technologies. Assuming ~1,600 kWh/year production from one kWdc of south-facing PV in the Redding climate, an additional 0.16 to 0.31 kWdc of panel would be needed to offset the 255 to 497 kWh estimated performance penalty associated with the conventional HPWH. At current residential scale PV installed costs of $3.10 per Wdc installed, the added cost of the PV would range from $500 to $960, or roughly ¼ to ½ the incremental cost of the CO_2 unit. This analysis can certainly be refined with a more sophisticated evaluation but provides a reasonable evaluation of the near term cost challenges of the CO_2 unit. The cost premium may decline as the market for CO_2 HPWHs increases or with utility incentives.

Although costlier, the CO_2 HPWH unit offers significant efficiency and environmental benefits (low greenhouse gas refrigerant) over existing HPWH technologies. As production volumes for the product increase, retail costs should come down. Longer term reliability of both CO_2 and conventional HPWH technologies are yet to be determined and will play a role in the overall cost-effectiveness.

INTRODUCTION

Residential HPWHs have become increasingly common over the last five to ten years throughout the country both as an efficient alternative to electric resistance storage water heaters and as a lower greenhouse gas (GHG) alternative to gas water heaters. In California, natural gas-fired storage or instantaneous water heaters are the predominant residential water heater with a penetration of close to 90% of households in the state. However, strong interest in the State to decarbonize buildings (e.g., California Senate Bill 100) has led to a surge of interest in promoting all-electric, low carbon solutions for future construction. The current U.S. Department of Energy minimum UEF for residential electric storage water heaters requires heat pump technology for water heaters greater than 55 gallons, but currently allows electric resistance water heating for smaller storage volumes.

HPWHs found in the California market are typically 50 gallon or larger storage tanks integrated with a relatively small (~ 0.5 ton) compressor to drive the vapor compression process, which extracts heat from surrounding air and delivers it to the storage tank (analogous to a refrigerator operating in reverse). Since compressor capacities are relatively small relative to existing gas and electric storage water heaters, most HPWHs utilize a single 4.5 kW electric element to supplement the compressor output when the compressor is unable to keep up with the hot water load imposed on the tank. The typical configuration of these hybrid units is shown in Figure 1 below.

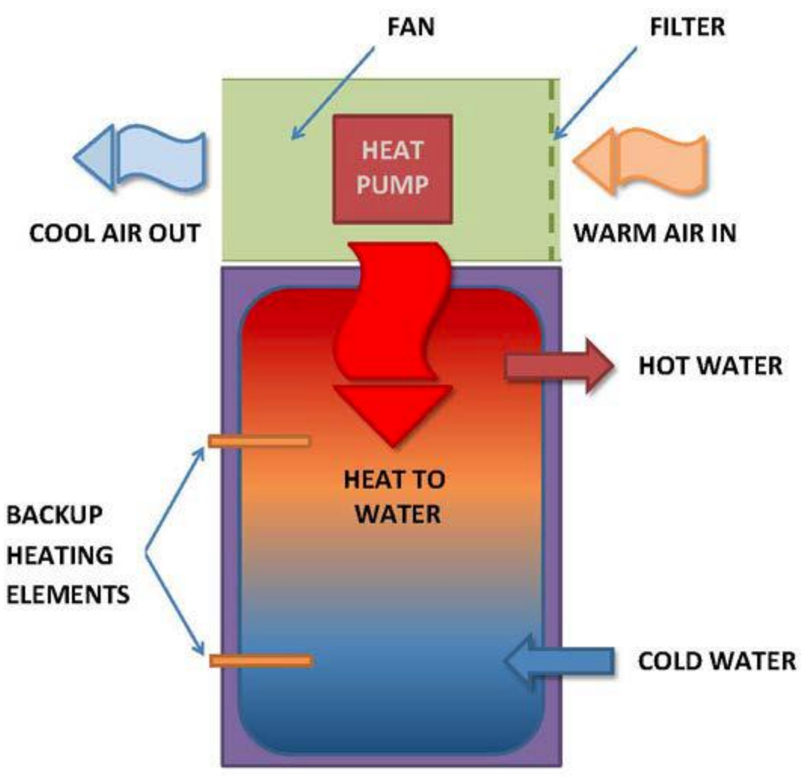

FIGURE 1. HPWH SCHEMATIC.

These conventional integrated HPWH units need to be installed in a large enough space so that the surrounding volume of air is sufficient to allow the HPWH to blow ambient air across the evaporator coil (cooling the exhausted air) without leading to overcooling of the nearby space, as this would result in diminished heating capacity as the surrounding environment space cools during long run cycles. Most manufacturers recommend a 700-1000 ft^3 minimum volume space surrounding the unit, which can be easily achieved in a garage, but not in a water heater closet or a typical interior space closet. This has led to increased interest in split system HPWHs, where the storage tank is separated from the compressor and refrigeration components, which are installed outdoors. Piping circulates water from the storage tank to the outdoor unit where heat is added and recirculated to the storage tank. In this configuration, the storage tank can be installed in a small closet, facilitating indoor installation where the tank is closer to hot water use points. Indications are that several Chinese manufacturers are starting to bring additional split system products to the U.S market.

A new product that has started to gain the attention of energy efficiency advocates in recent years is the split system CO_2 HPWH. This unit, which received Underwriters Laboratory approvals in the last two years, uses CO_2 (R-744) as the working refrigerant and has an inverter-driven compressor and a tube-in-tube gas cooler. Detailed modeling studies of the CO_2 cycle thermodynamics completed at Oak Ridge National Laboratory (Nawaz, Shen, Elatar, Baxter, & Abdelaziz, 2017) highlights the importance of thermal stratification in the water tank. The greater the thermal stratification in the tank, the higher the difference between inlet water temperature and supply water temperature for the gas cooler, which results in improved system efficiency. In fact, the ORNL study concludes that the performance of the unit is more sensitive to the temperature at the inlet of the gas cooler than to ambient air temperature entering the evaporator. The system's stable capacity at lower outdoor air temperatures and greater capacity than typical HPWHs (1.25 tons vs. 0.5 tons) allow the unit to eliminate the need for a supplemental resistance heat element in the tank. The storage tank has a sensor that measures the tank temperature (at a height about two-thirds from the bottom of the tank) which is used to control system operation, the inverter speed, and pump flow rate to the outdoor unit. When the sensed water temperature drops to 113°F, the outside unit activates (Eklund & Banks, 2015).

Key specifications of the 43 gallon CO_2 HPWH are shown in Table 1. One of the significant environmental benefits of the unit beyond its efficiency is the much lower global warming potential of CO_2 relative to conventional refrigerants,[4] which are used in other HPWHs.

TABLE 1. CO_2 HPWH SPECIFICATIONS.

PARAMETER	SPECIFICATION
Uniform Energy Factor	3.09
First Hour Rating	71 gallons
Nominal heating capacity	15,400 Btu/hr (4.5 kW)
Heating COP	5.0
Water temperature range	130-175°F
Ambient air operating temperature	-20 to 110°F
Tank heat loss rate	4.0 Btu/hr-°F

Detailed lab and field testing of the unit has been completed by Ecotope (Larson, 2013) and Washington State University (Eklund & Banks, 2015). Ecotope lab testing found that the outdoor unit (including compressor, fan, and water pump) electrical demand ranges from 0.9 to 2.4 kW depending on tank water temperature and ambient air conditions. The compressor increases speed, and therefore power draw, as the outdoor ambient temperature decreases in order to maintain heating output capacity. At 95°F, the outdoor

[4] Global Warming Potential (GWP) of CO_2 is 1 as opposed to 2,088 for R-410a and 1320 for R-134a.

unit draws 0.9 kW for most of the heating cycle. As the overall water temperature in the tank increases, the power draw increases slightly to 1.05 kW. At an outdoor temperature of 17°F, the unit was found to draw ~1.9 kW for most of the cycle, ending with an increase to 2.4 kW. WSU testing presented at the 2017 American Council for an Energy Efficient Economy Hot Water Forum found that heating capacity fell by only 13% as outdoor temperatures fell from 95°F to 17°F (Eklund K. , 2017). The input power, however, more than doubled through this range in outdoor temperatures. With an ability to deliver fairly stable heating output through a broad range of outdoor temperatures, the unit becomes an attractive high-efficiency option in more extreme climates than a standard HPWH.

OBJECTIVES

The primary objective of this work was to demonstrate the field performance of the CO_2 HPWH unit over a full year in an occupied house. PG&E's Code Readiness program gathers performance, market feasibility and compliance-related data on energy efficient technologies and practices to support advocacy in future codes and standards proceedings, as well as to inform voluntary program design.

PROJECT OVERVIEW

The monitored code readiness site is an energy-efficient custom home designed and built by Mike MacFarland, owner of EnergyDocs (a leading California high performance contracting company located in Redding). The single-story 2,372 ft^2 home has four bedrooms and three full baths. It was permitted under the 2013 Building Energy Efficiency Standards and constructed between August 2016 and May 2017. The floor plan is shown in Figure 2. The dotted outline of the conditioned second floor mechanical space centered over the middle of the house to ensure all ducting is within conditioned space. The mini-split space conditioning heat pump outdoor unit and heat pump water heater outdoor unit are both located on the left side of the floor plan.

Complete reporting of the construction details, monitoring approach, and overall energy performance over the first year of operation can be found in a separate code readiness report located at the Emerging Technologies Coordinating Council website (Haile & Hoeschele, 2018). This more focused HPWH performance report utilizes more detailed, high resolution data to assess system performance under the range of conditions that occur over the course of a year in an occupied house.

Within the attic space, the design includes a conditioned mechanical space (outline shown as dotted line on floor plan) which included the stainless steel hot water storage tank (located above and to the left of the refrigerator), a heat recovery ventilator, and the ducted mini-split heat pump. The outdoor unit was adjacent to the bathroom on the left side of the house, with 33 feet of insulated ½” PEX piping running to and from the storage tank (total length of 66 feet). Heat loss from the piping represents one of the parasitic losses for a split system HPWH as energy is lost both during the operating cycles and between operating cycles.

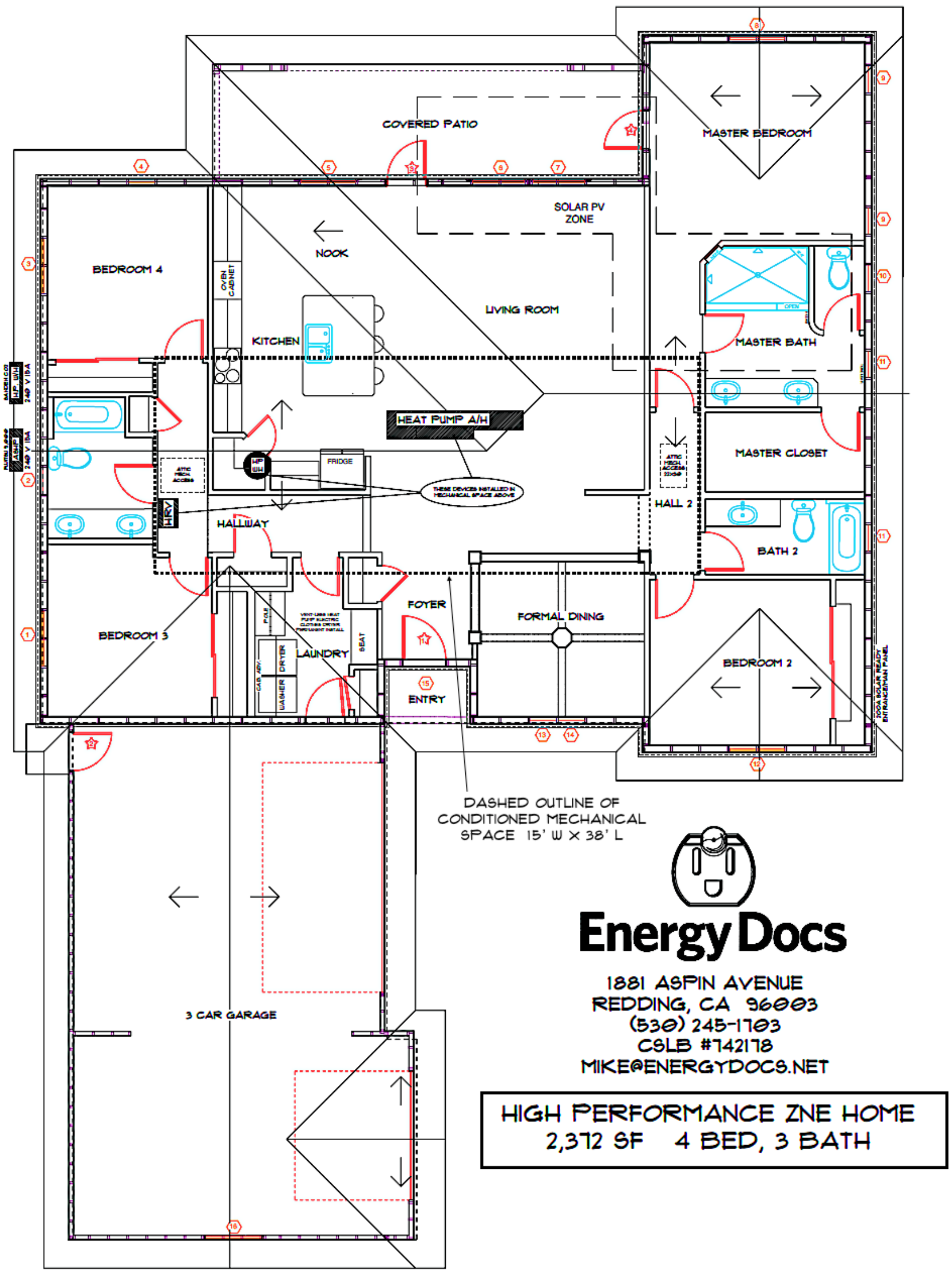

FIGURE 2. REDDING HOUSE FLOOR PLAN.

Table 2 is included to provide additional information on the range of advanced energy efficiency measures installed in the home as compared to 2013 Title 24 standard construction practices in effect at the time the permit for the house was secured. Of particular note is the ¾ ton duct mini-split heat pump, which consistently provided a high degree of comfort in the challenging Redding climate. The 5.32 kWdc photovoltaic system installed on the house was sized to offset all electrical usage and future incorporation of an electric vehicle.

TABLE 2. COMPARISON OF TYPICAL PRACTICE AND ACTUAL INSTALLED MEASURES.

MEASURE	TYPICAL BASE SPECIFICATION	IMPLEMENTED MEASURE
Wall Construction	2x4, 16" on center construction, R-15 cavity + R-4 rigid exterior; typical 25-30% framing factor	2x6, 24" on center (low framing factor); Blown cellulose in cavity; R-13 rigid exterior insulation (~R-30 wall); 10% framing factor target using advanced framing protocols with 11.7% achieved
Attic Insulation	R-38 ceiling insulation with radiant barrier	R-60 ceiling insulation with radiant barrier; energy heel truss design
Slab edge insulation	None	2" Roxul rock wool continuous slab edge perimeter insulation (R-8 insulation level)
Air Sealing	Typical air sealing practice results in ~ 4-5 ACH50 envelope leakage level	High attention to detail with continuous plywood wall sheathing, taped & sealed air barrier, caulking/foaming, etc. Leakage target of 0.45 ACH50 with 0.53 achieved
Windows	Typical 16-20% glazing area with U = 0.32, SHGC = 0.25	10% glazing area with typical U=0.23-0.25, SHGC=0.20-0.30
Mechanical Equipment Location	Furnace/air handler located in unconditioned attic; water heater located in garage	HVAC and water heating storage tank located in attic mechanical space in the thermal boundary
Heating equipment	Typical 80% AFUE gas furnace in the 60,000 to 80,000 Btuh capacity range	¾ ton (9,000 Btuh) ducted mini-split heat pump with compact ducts located in conditioned space (sizing at 3,160 ft2/ton) Rated at 12.2 HSPF
Cooling equipment	Typical 14 SEER/ 11.7 EER with sizing at ~ 600 to 800 ft2/ton	Mini Split rated at 21.5 SEER
Mechanical Ventilation	Typically bath exhaust fans to provide airflow meeting ASHRAE 62.2-2010	Heat recovery ventilator located within conditioned space to minimize ventilation thermal loads on space
Duct location and leakage	R-8 ducts located in unconditioned space; typical duct leakage of 6%	R-8 ducts located completely in conditioned space; target duct leakage of <1% with 3% to the house interior achieved and no leakage to the outside.
Appliances	Typically gas cooking and gas dryer; appliances may or may not be EnergyStar	All-electric efficient appliances including induction cooktop and heat pump clothes dryer
Photovoltaics	Builder option	5.32 kWdc West Southwest facing; 7 in 12 roof pitch

House construction began in August 2016. Several photos taken during construction are included here to provide the reader an understanding of the HPWH installation configuration and the characteristics of the mechanical space.

Figure 3 is an image taken upwards directly below the attic mechanical space during the house framing stage. The photo shows the mechanical space vertical wall (shiny surface oriented vertically and facing attic). The 570 ft^2 conditioned mechanical space served as a return air plenum for the space conditioning system, and also accommodated the mini-split heat pump, supply ducts, heat recovery ventilator, and hot water storage tank. The mechanical space covered an area totaling 570 ft^2 and was centered over the living space as shown on the floor plan.

FIGURE 3. CONDITIONED MECHANICAL SPACE UNDER CONSTRUCTION (FROM BELOW).

Figure 4 shows the storage tank installed in the mechanical space with flow meter and immersion thermocouples shown, and Figure 5 shows the outdoor unit located adjacent to the mini split heat pump outdoor unit.

FIGURE 4. HPWH STORAGE TANK WITH FLOW METER AND THERMOCOUPLES INSTALLED.

FIGURE 5. HPWH OUTDOOR UNIT (ON LEFT).

Monitoring Methods

Detailed, high resolution monitoring was conducted on the HPWH unit to carefully characterize system thermal performance, energy consumption, and hot water loads. A logging system was installed that allowed for water temperature, water flow, and electrical energy data collection at four second intervals. This was done to capture the transients associated with water heater operation and domestic hot water draws, the latter of which are often less than a minute in duration.

Figure 6 presents a simplified schematic of the water heating system, noting the monitoring sensor configuration. Flow and immersion temperature sensors were installed between the storage tank and the house use points, as well as between the storage tank and the outdoor unit (where system power will also be monitored).

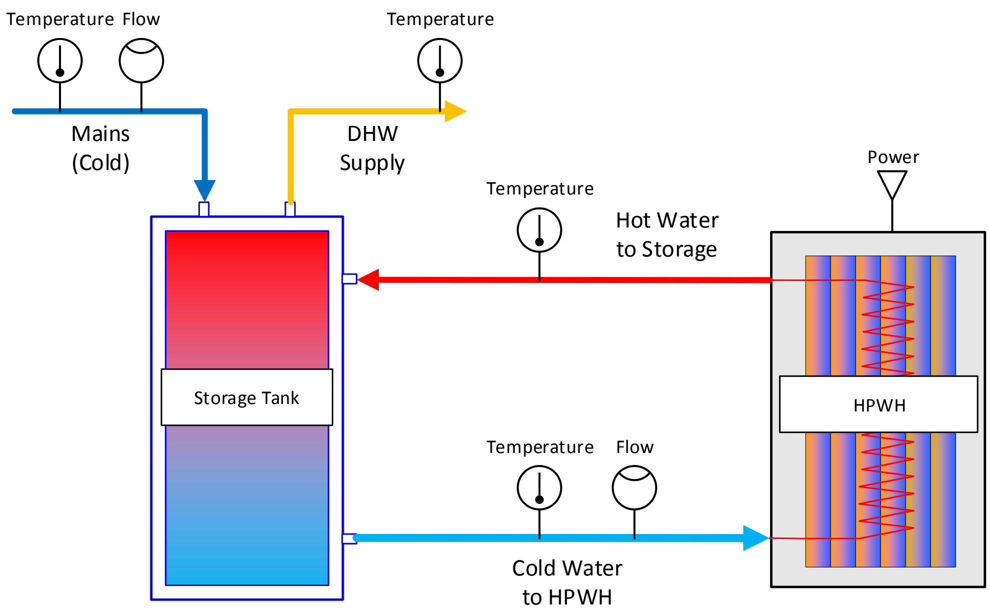

Figure 6. HPWH monitoring schematic.

By measuring flow and temperatures on each side (hot and cold), energy flows could then be calculated for each four second interval as shown in Equation 1.

Equation 1. Thermal energy content at each 4 second interval.

$$\boldsymbol{Q = 8.33 \times V \times (T_H - T_L) \times 0.001})$$

where,

Q	= Thermal energy content of water flow (kBtu)
V	= Water flow volume (gallons)
T_H	= Leaving (“high”) temperature (°F)
T_L	= Entering (“low”) temperature (°F)
8.33	= Constant representing the density and specific heat of water $\left({}^{Btu}/_{lb\cdot°F}\right)$
0.001	= Conversion from Btu to kBtu.

Equation 1 can be completed to determine the thermal energy content of the water flow from either the outdoor unit to the storage tank or the storage tank to the domestic end uses.

This study represents HPWH efficiency as the daily Coefficient of Performance (COP). Daily COP is calculated as presented in Equation 2, using daily sums of thermal energy calculated from Equation 1 and daily sums of electrical energy consumed by the HPWH.

EQUATION 2. COEFFICIENT OF PERFORMANCE (COP).

$$COP = \left(\frac{\sum Q}{\sum E}\right) \div 3.412$$

where,

COP = HPWH operating efficiency (non-dimensional)

Q = Thermal energy content of water flow (kBtu)

E = Electrical energy consumed by the water heater (kWh)

3.412 = Conversion of kWh to kBtu.

Equation 2 can be completed to determine the instantaneous COP, as well as COP at full load, by changing the interval or other conditions for the sums.

DATA ACQUISITION APPROACH

Installed monitoring equipment for the high frequency, detailed monitoring of the HPWH consisted of a Modbus gateway which continuously collected data from sensors and devices using Modbus and securely transmitted that data over the internet to the Frontier Energy Monitoring Server (FEMS). The Modbus gateway was programmed to log data from the connected devices at 4 second intervals. A list of the connected devices, detailing application and accuracy, is shown in Table 3.

TABLE 3. INSTALLED INSTRUMENTATION FOR WATER HEATING MONITORING.

TYPE	APPLICATION	MFG/MODEL	SIGNAL	ACCURACY
Electrical energy meter (1)	HPWH electrical energy consumption	Dent Powerscout 3037	Modbus	± 0.2% of reading
Ultrasonic flow meters (2)	(1) Flow to storage tank (cold inlet), and (2) to HPWH outdoor unit	Onicon F-4600	Modbus	± 1.0% of reading over 25:1 turndown
1kΩ RTDs (2)	Entering water temperatures (1) from tank to outdoor unit, and (2) from cold water main to tank	Integrated component of Onicon F-4600	Modbus	±0.32 °F
Immersion thermocouples (TCs) (2)	Leaving water temperatures (1) from outdoor unit to tank, and (2) from tank to domestic end uses	Omega Type T connected to DataTaker DT50 datalogger	mA (TCs) Modbus (DT50)	± 0.9 °F

The Modbus gateway pushes the collected data through an internet connection directly to the FEMS every hour via the Secure File Transfer Protocol.

The FEMS is a secure industrial computer system with redundant data backup and secure internet connections. The FEMS automates data collection by retrieving data, checking data for errors and common equipment issues, and automatically notifying key project team members about possible problems detected. The FEMS also tracks the internet connection status of monitoring equipment and sends weekly data summaries to key personnel.

Outside air temperature was measured at nearby weather stations[5]. Outdoor dry bulb air temperatures presented are those produced by NOAA's MADIS data quality and control analysis. The FEMS collected weather data from these weather stations through NOAA's MADIS on a quarterly basis. Data from the closest weather station was checked for gaps and filled using data from the next closest station. Relative positions of the weather stations to the site are shown in Figure 7.

FIGURE 7. RELATIVE LOCATIONS OF WEATHER STATIONS TO FIELD STUDY SITES.

A simplified diagram of the data acquisition system is shown in Figure 8.

One limitation of the field monitoring that relates to system controls is the lack of internal monitoring temperature sensor in the storage tank. The monitored CO_2 HPWH unit uses a tank sensor (located 2/3 up from the bottom of the tank) to control system operation (inverter speed and other control functions). The project team determined that installing an additional sensor in the tank would be too intrusive for an occupied home application.

[5] NOAA call signs and distance from the house: F0355 (1 mile), C5599 (2.2 miles), CI224 (2.8 miles), and KRDD (8.5 miles).

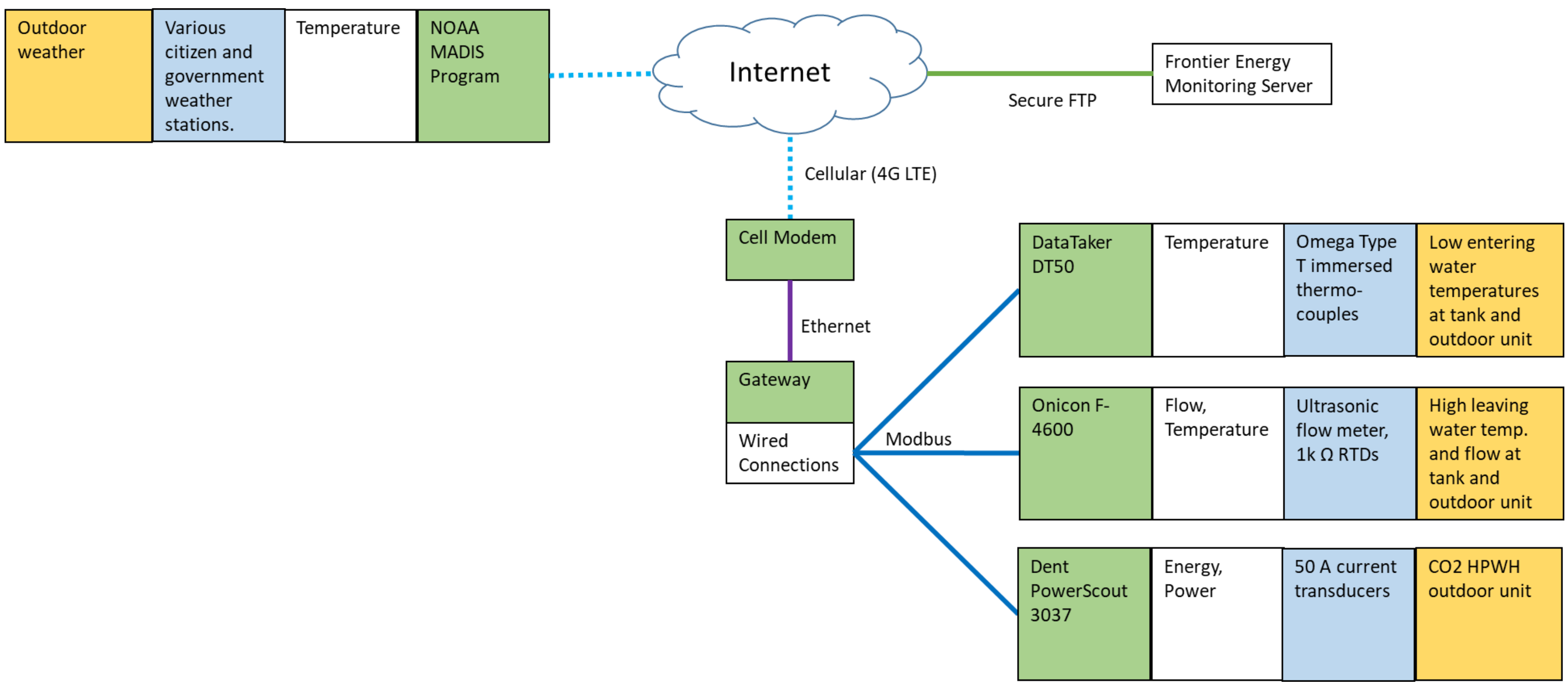

FIGURE 8. DIAGRAM OF DATA ACQUISITION SYSTEM.

RESULTS

MONITORED PERFORMANCE

Energy end use monitoring of the house documented in the previously cited ETCC Redding report occurred from July 2017 through June 2018. Difficulties in getting the HPWH monitoring system commissioned delayed the start of the water heating monitoring a few weeks. The HPWH data collection period stretched from mid-July 2017 to mid-July 2018. During that period the house was occupied by a working couple.

The bulk of the results reporting here focuses on summary performance aggregated from the high resolution data. Sample high resolution data can be found in

Appendix A:.

Table 4 provides monthly aggregation of the weather conditions, average monthly water heater cold water inlet temperature (only data during hot water draw events when water is flowing), and average daily hot water usage. For three months of the year, average outdoor maximum temperatures exceeded 100°F. Mid-winter outdoor temperatures averaged around 50°F. Cold water inlet temperatures entering the water heater during draws ranged from 63 to nearly 80°F. Average hot water usage for the two person household was found to be 23.0 gal/day with month-to-month fluctuations that are commonly observed in monitored residential sites.

TABLE 4. COMPARISON OF MONTHLY CONDITIONS AND HOT WATER LOADS.

MONTH	NUMBER OF DAYS MONITORED	AVERAGE DAILY OUTDOOR TEMPERATURE (°F)			AVG COLD WATER INLET TEMP (°F)	AVG HOT WATER USE (GPD)
		MAX	MIN	AVG		
July 2017	17	103.4	68.2	86.1	79.4	26.8
Aug	31	102.8	68.9	86.1	79.3	23.3
Sept	30	91.5	62.0	77.0	76.8	17.6
Oct	31	82.1	49.0	65.7	71.7	21.9
Nov	30	61.7	44.7	53.5	67.7	24.1
Dec	31	62.2	35.2	49.1	64.5	22.9
Jan 2018	31	58.9	41.0	50.3	63.7	22.3
Feb	28	64.4	37.9	51.4	64.1	22.0
Mar	31	63.6	41.2	52.6	64.1	21.4
Apr	30	72.2	46.7	59.7	68.2	18.9
May	31	84.4	56.9	70.9	70.3	27.4
Jun	30	95.1	63.8	79.7	73.3	19.8
July	16	100.9	68.2	84.8	75.9	31.3

Table 5 tabulates the daily average recovery load (energy leaving the water heater to serve house loads), storage tank and piping losses, and operating characteristics of the CO_2 unit in terms of run cycles per day and compressor operating time. Recovery loads vary significantly from summer to winter primarily due to changes in cold water inlet temperature. Additionally, the number of heat pump operating cycles and total unit run time per day increases from summer months to winter months. Interestingly the average cycle duration is not significantly correlated with colder weather as December data exhibited the shortest cycles and November and May the longest. Presumably the timing of hot water loads, and the system's operating speed based on sensed conditions impact this result. The average daily operating times ranging from 80-140 minutes reflects the higher capacity of the CO_2 HPWH relative to standard HPWHs which may run for two to four hours on a single operating cycle.

The Storage and Piping Loss term was calculated by subtracting the measured recovery load from the measured heat addition at the outdoor unit. Any energy delivered by the outdoor unit would be either storage tank losses or piping losses between the tank and the outdoor unit. On average, the monitored recovery load represents 66% of the energy input from the CO_2 HPWH. As with any storage water heater system, the ratio of useful energy delivered to total tank energy input increases as hot water loads increase. For example, if monitored recovery loads were double what is shown in Table 5, storage and piping losses would remain roughly the same, but the ratio of useful energy delivered to load would increase from 66% to nearly 80%.

Table 5. Monthly summary of daily energy flows and unit operation.

Month	Average daily energy flux (Btu/day) Recovery load	Storage and piping loss	Estimated storage loss*	Avg # of HP cycles per day	Avg daily HP run time (minutes)	Avg cycle length (minutes)
July 2017	11,928	5,810	4,898	1.82	90.4	49.6
Aug	10,580	6,265	5,414	1.79	88.2	49.2
Sept	8,358	6,055	5,285	1.61	83.6	52.0
Oct	11,819	6,332	5,352	1.59	112.0	70.6
Nov	14,289	5,936	4,722	1.73	131.4	75.8
Dec	14,286	6,555	4,813	2.53	137.1	54.1
Jan 2018	14,185	6,347	4,838	2.06	135.3	65.5
Feb	13,974	6,767	5,270	2.11	138.4	65.7
Mar	13,597	7,208	5,764	1.97	134.4	68.3
Apr	10,676	6,036	5,160	1.59	106.3	67.0
May	14,328	5,947	5,261	1.48	112.8	76.0
Jun	9,366	6,224	5,540	1.43	88.2	61.8
July	15,087	5,840	4,845	1.88	108.4	57.8

A calculation was completed to estimate the storage losses from the measured combined "storage + piping" losses. Given the site-measured 33 ft (each way) of ½" insulated PEX between the storage tank and outdoor unit, the number and duration of operating cycles per day, insulated PEX heat loss coefficient, and assumed temperatures (average hot water and mechanical space environment temperatures), piping losses could be reasonably approximated. On average over the full year, the Estimate Storage Loss term shown in Table 5 represents slightly over 81% of the total combined "storage and piping" losses. To assess the sensitivity of pipe heat loss on system performance, a calculation was completed assessing the impact of a two-thirds reduction in piping length (with all other conditions assumed unchanged). The nominal 66% useful energy contribution would increase to 69% under this scenario.

The annual Estimated Storage Loss from Table 5 was compared to the manufacturers reported value in Table 1 and found to be within 3% based on the observed 52.5°F average annual temperature difference between the storage tank and the approximated mechanical space temperature[6].

Table 6 summarizes average daily energy consumption and operating COP for each month, with the COP being defined as energy contribution to the storage tank. On an annual basis, the CO_2 HPWH unit consumed 712 kWh in satisfying the daily average hot water load of 23.0 gal/day. Daily energy use ranged from 1.35 kWh/day in September to a high of 2.72 kWh/day in December. Annual average COP ranged from 2.24 in December to 3.42 in May.

Table 6. Monthly summary of daily energy use and operating efficiencies.

Month	Avg energy use (kWh/day)	Avg kWh/gal delivered	Avg daily COP
July 2017	1.55	17.3	3.35

[6] The mechanical space temperature was assumed to be within a few degrees of the interior house temperature since the mechanical space was extremely well insulated and also closely coupled thermally to conditioned space.

Aug	1.46	16.0	3.38
Sept	1.35	13.1	3.14
Oct	1.87	11.7	2.85
Nov	2.21	10.9	2.68
Dec	2.72	8.4	2.24
Jan 2018	2.41	9.2	2.49
Feb	2.56	8.6	2.37
Mar	2.38	9.0	2.56
Apr	1.72	11.0	2.84
May	1.74	15.8	3.42
Jun	1.43	13.8	3.20
July	1.85	16.9	3.31

Using average monthly hot water consumption per day and HPWH energy use (kWh/day), the metric of kWh per gallon of hot water is presented which incorporates both the seasonally changing system efficiency as well as the reduced amount of thermal energy needed to heat a gallon of water in the summer relative to mid-winter. This metric shows a roughly 2 to 1 variation throughout the year, ranging from 8.4 to 17.3 gallons per kWh. In higher load households, where daily hot water usage can easily be 50 gallons/day or more, the observed gallons per kWh value would further increase as the recovery load energy becomes a larger fraction of the CO_2 unit's thermal output.

A more detailed look at seasonal performance impacts associated with the monitored site can be found in the following Figures. Figure 9 plots averaged monitored recovery load (represented in terms of Btu's extracted to meet the house load) for winter, summer, and spring/fall time periods. (Winter includes the months of December through February, summer is June through September, and spring/fall is March, April, and November). The monitored data shows the distinctive dual humped hot water usage pattern commonly seen in most households, although often the morning peak is higher than the evening peak[7]. The seasonal variability is evident as summer loads are considerably reduced relative to winter and spring/fall, from 14,100 Btu/day during winter down to 10,400 Btu/day in summer.

The variability in recovery load is a function of both inlet water temperature to the water heater (which determines how much heat must be added), gallons of hot water consumed, and any seasonal changes in occupant behavior (e.g. cooler showers in the summer, tub use only in winter, or reduced hot water use at lavatories in the summer). The city of Redding has both surface water and groundwater as part of its municipal water service. The Sacramento River (fed by upstream Lake Shasta) and nearby Whiskeytown Lake provide 74% of the Redding municipal water supply, while the remaining 26% is groundwater that comes from 16 city wells. Both of the surface water sources provide relatively cold water supplies generated largely from snowmelt from the neighboring mountain watershed. Prior monitoring of HPWHs at two residential sites in Redding (Hoeschele & Seitzler, 2017) found that in mid-summer, the deviation in the water supply could result in a 15°F difference in cold water temperatures entering the water heater[8]. Other factors observed at one of the sites include the house supply water line from the city mains running under the driveway leading to up to nearly ten degree increase in cold water temperature during the course of a mid-summer day (from sunrise to early evening) as solar gain transmitted through the driveway contributes to measurable heating of the water. These type of site-specific effects

[7] See http://www.bwilcox.com/BEES/reference.html and California Residential Domestic Hot Water Draw Profiles link for a summary of California monitored hot water usage data.
[8] https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/64082.pdf

that occur in real world monitoring projects often contributed to unexpected performance variations.

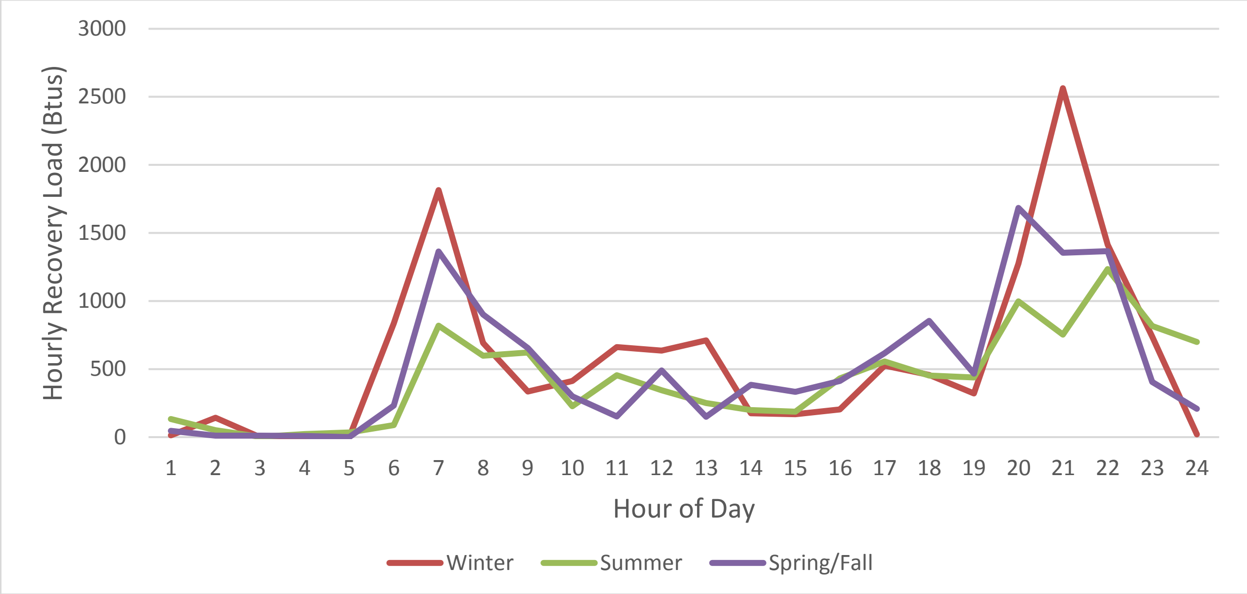

FIGURE 9. SEASONAL HOURLY RECOVERY LOAD PROFILE BY TIME OF DAY

Figure 10 plots the observed average daily cold water inlet temperature based on the four second interval data at times during which hot water demand occurred so that the temperature measurement represents flowing water rather than water that has been tempering in the ambient environment. Note the significant day-to-day variability present. This can be attributed to the magnitude of the draw volume for the day (low volumes are more impacted by the thermal effects associated with draw startup and the immediate volume and temperature of water adjacent to the water heater) and the ratio of high volumetric draw events to overall daily draw volume (fewer high volume draws in a day would pull water that is more closely coupled to ground temperature than shorter draws). The plot also shows a 30-day moving average trend line.

Figure 11 plots the CO_2 HPWH average electrical demand over the same time periods as shown in Figure 9. As one might expect, the shape of the demand profiles is very similar to the hot water recovery load, although shifted later by an hour or so. Average summer demand never exceeds 0.13 kW, roughly 1/3 of the peak winter demand. The relatively high capacity of the unit coupled with its lack of supplemental resistance heat make it a potentially attractive piece of equipment for load shifting implementation.

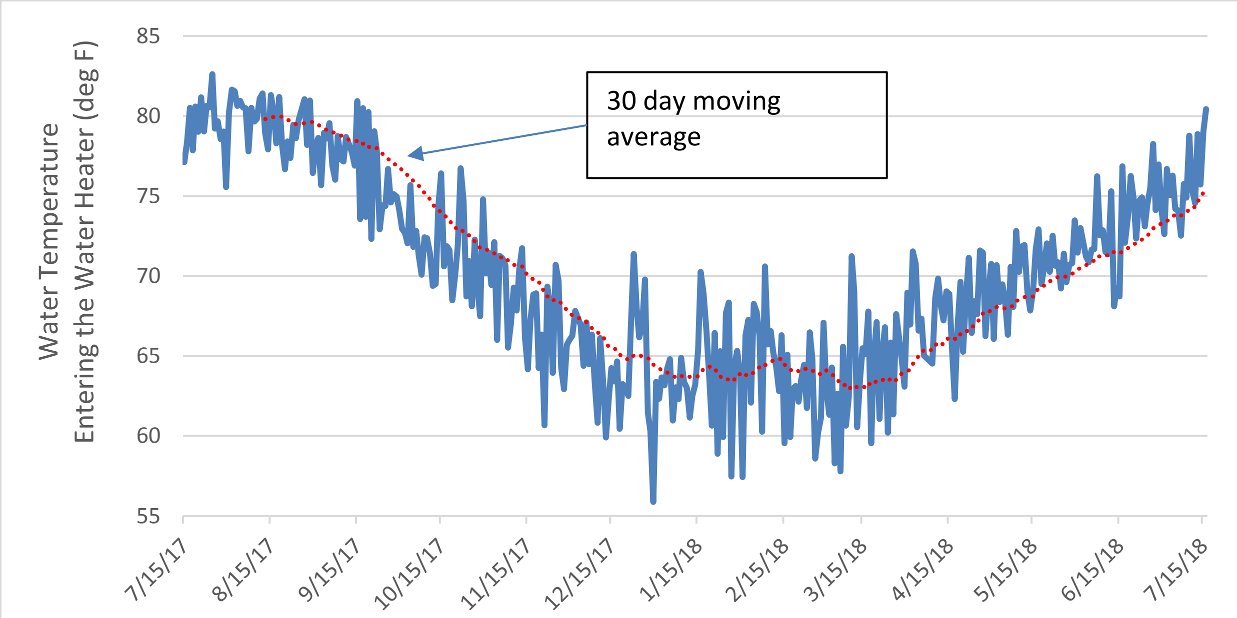

FIGURE 10. SEASONAL VARIATION IN WATER HEATER COLD WATER INLET TEMPERATURE

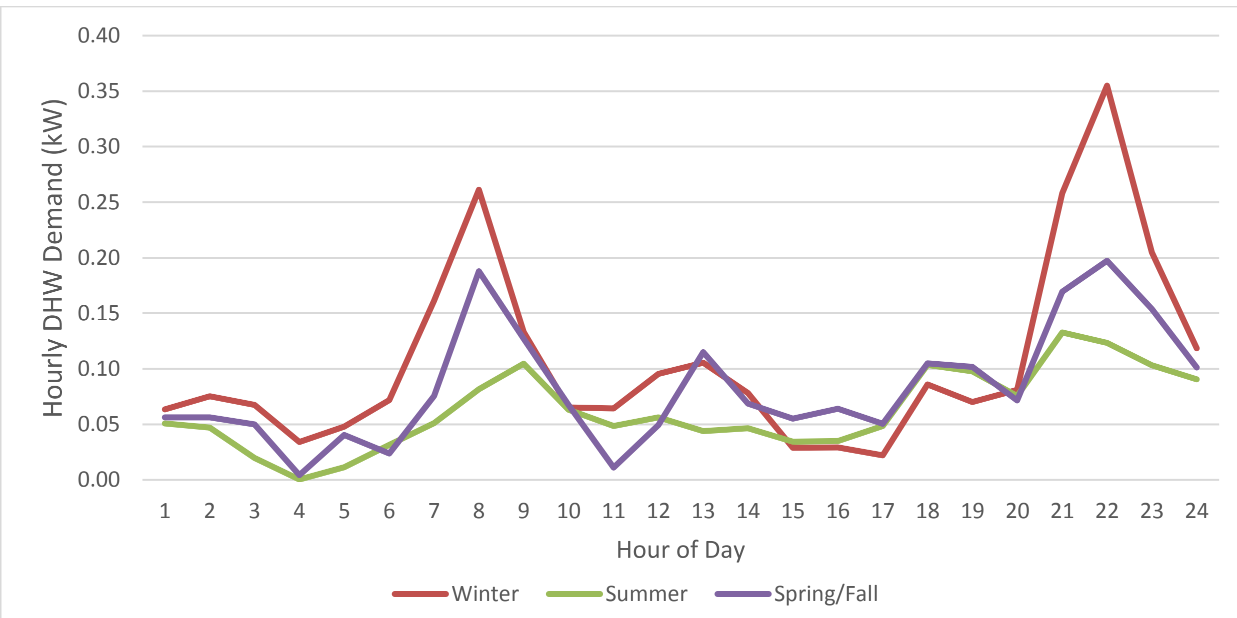

FIGURE 11. SEASONAL CO_2 HPWH ENERGY USE PROFILE BY TIME OF DAY

ECONOMIC ASSESSMENT

As a highly efficient emerging technology, the CO_2 HPWH represents a potential component of the forward-thinking approaches needed to optimize efficiency and environmental benefits for California's future. From this perspective, the authors completed a first cut assessment of technology cost effectiveness in comparison to conventional mainstream integrated HPWHs. Although this is purely an economic assessment, it does provide a viewpoint from which the technology is currently assessed. Since PV is now an essential component of efficient construction practices, this cost effectiveness evaluation estimated whether a conventional HPWH coupled with additional PV (to offset the added kWh relative to the efficient CO_2 unit) would be a more cost-effective investment.

PV costs were estimated based on a published Energy Commission cost estimate of $3.10 per Watt[9] used in the 2019 Title 24, Part 6 code development activities. Annual kWh production estimates for a one kW south-facing PV array in the Redding climate total 1,600 kWh per year. Table 7 summarizes the relative annual energy and first cost impacts of the CO_2 HPWH relative to a conventional HPWH with added PV to offset the incremental energy use (detailed tabulations of the projected energy performance can be found in Appendix B).

The current incremental cost of the CO_2 unit over competing conventional HPWH products is in the $2,000 to $2,500 range, based on information from Mike MacFarland (the general contractor at the Redding house). With expected savings in the range of 255 to 497 kWh per year (for the two load cases identified in Table 7), and typical residential electric rates for the California investor owned utilities of ~$.20 per kWh, CO_2 HPWH operating cost savings of $51 to $100 per year translate to simple paybacks well over 15 years.

PV incremental sizing due to the added 255 kWh/year (23 gpd load level) and 497 kWh/year amounts to 0.16 and 0.31 kWdc, with an added PV first cost impact of $500 to $960. This amounts to 22% to 43% of the average estimated incremental cost of $2,250. From a strictly cost effectiveness perspective, cost reduction is necessary for the CO_2 HPWH product to achieve significant market share.

TABLE 7: PRELIMINARY COST AND PERFORMANCE COMPARSION OF CO_2 VS. CONVENTIONAL HPWH WITH PV

DHW LOAD	CO2 HPWH KWH/YR	STD HPWH KWH/YR	HPWH ADDED PV	ADDED PV COST	% OF CO2 UNIT COST*
23 gpd	716	971	0.16 kWdc	$500	22%
46 gpd	1,207	1,704	0.31 kWdc	$960	43%

* at an incremental cost of $2,250

[9] https://www.energy.ca.gov/title24/2019standards/documents/Title24_2019_Standards_detailed_faq.pdf

CONCLUSIONS

The CO_2 HPWH is a very efficient all-electric water heating device which offers four main performance benefits over conventional HPWH products:

- very low GHG refrigerant,
- enhanced water heating capacity,
- elimination of any supplemental electric resistance heating, and
- ability to maintain heating output at low outdoor temperatures.

In applications where minimizing energy use is the goal, the unit represents a viable solution. For the low load application monitored at the Redding site, the water heating savings will be lower than for higher load cases. As loads increase, the relative performance benefit of the CO_2 HPWH will increase since the efficiency remains high and there is no supplemental heating, which tends to degrade conventional HPWH performance under high load situations where the smaller compressor capacity often cannot keep up with the loads.

Estimated energy savings of the monitored CO_2 unit (based on observed performance and estimated base case HPWH performance) indicate savings in the 25-30% range for the Redding climate. At typical California electric rates of $.20 per kWh, expected savings are in the $51-$100 a year range (255 to 497 kWh per year savings). Current incremental costs of the unit of about $2,250 more than a conventional HPWH suggest a long simple payback. A preliminary economic calculation suggests that adding PV to the conventional HPWH, to offset the 255 to 497 kWh added consumption, is a more cost effective approach.

Title 24 compliance economics under the 2019 Title 24, Part 6 code (where PV is required) paints a more favorable picture as the builder must first achieve a certain efficiency performance level before PV is applied to the building to demonstrate overall building compliance. As builders are increasingly challenged to meet the required level of building energy efficiency under the 2019 code, alternative competing measures must be compared to determine which measure gives the most benefit per dollar of added cost. Under this compliance environment, the CO_2 HPWH may prove to be a better choice than other measures in many situations.

From a policy point of view, the CO_2 technology is a valuable component in the movement to increase the use of natural refrigerants. The unit is "grid friendly" since it does not have resistance electric second stage heating which can activate during peak electricity demand times.

RECOMMENDATIONS

The monitored CO_2 HPWH represents a high-efficiency water heating solution that is just gaining traction in this country. High costs relative to other water heating technologies make it a challenging proposition for the production home and mainstream replacement market although there are certainly niches in the custom home and replacement market (early adopters).

Potential future activities for further validation and assessment of this technology could include:

Investigate product durability: Sponsor a project where multiple installations occur at a subdivision or apartment complex. The project could track operation, efficiency, maintenance, and equipment lifetime to generate data for life cycle cost estimation.

Investigate combined space and water heating applications for the CO_2 technology: The unit's very stable heat output at a wide range of outdoor temperatures, lack of resistance heat, and high efficiency make it an ideal application for applications with higher loads where energy savings and cost effectiveness will be improved. Two potential variants of this approach include:

- Single family applications: hydronic technologies for space conditioning will likely gain more interest in the coming years as lower space conditioning load all-electric buildings become more common. Using hydronic heating would support radiant panels and/or distributed fan coils for space conditioning delivery.
- Multifamily water heating configurations with shared water heaters: Modular multifamily water heating designs where a water heater serves two to four apartments is a strategy that may be ideal for the higher capacity CO_2 HPWH unit. With higher heating capacity and no supplemental heat, the unit can likely serve more units than a conventional HPWH.

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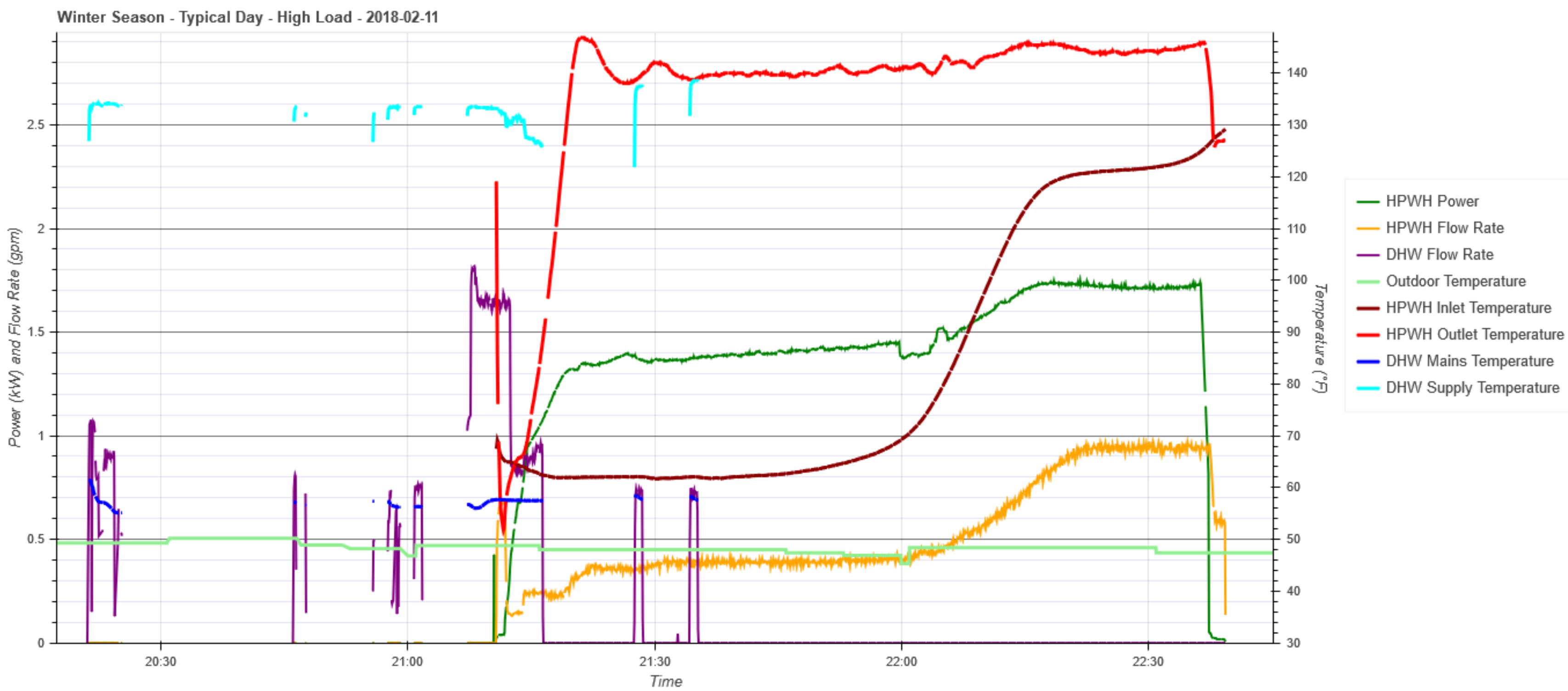
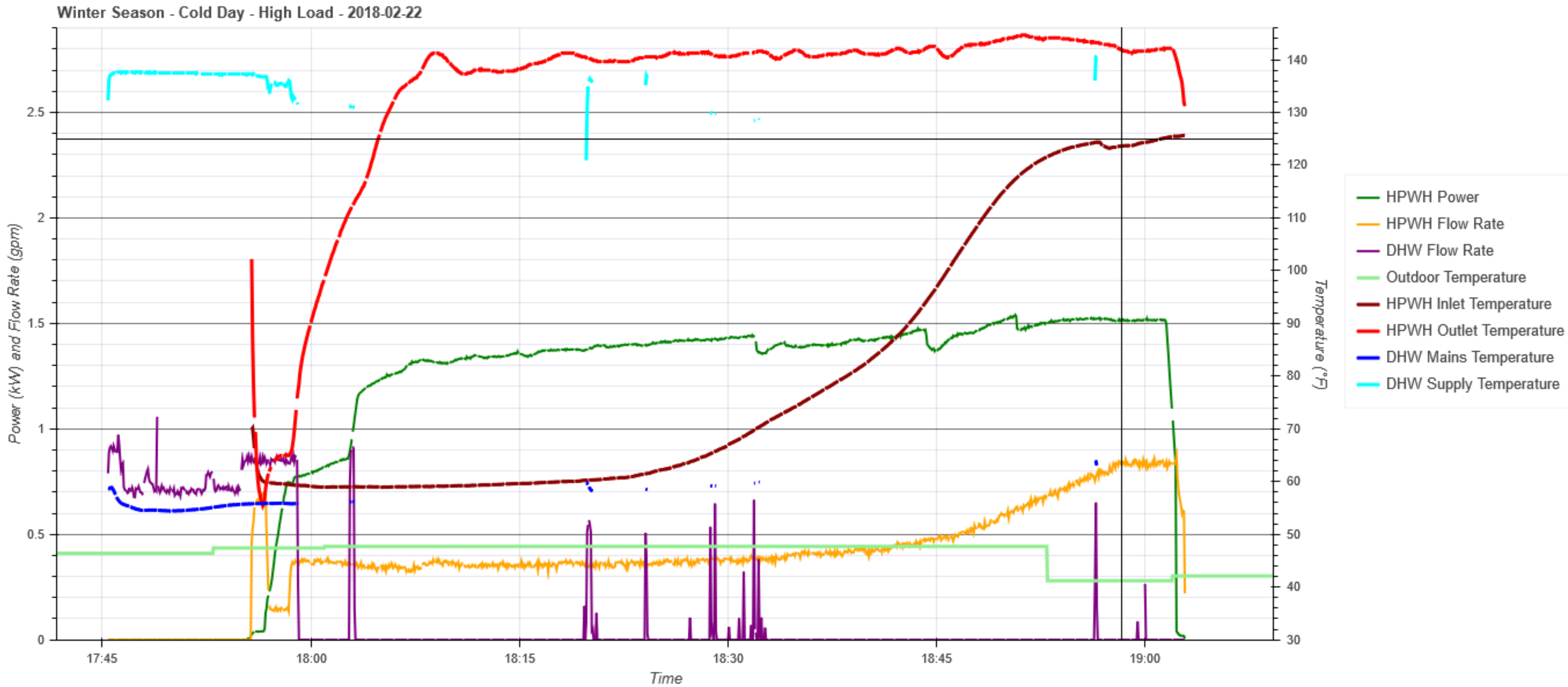
APPENDIX A:
HIGH RESOLUTION DATA PLOTS FOR OPERATING PERIODS ON KEY DAYS

The following series of graphs depict some of the high resolution data collected from the Redding monitoring site. The selected plots are from a range of days throughout the year with weather conditions and hot water loads varying considerably. The plots represent a portion of the day and include all the high resolution data. Specific data plotted includes:

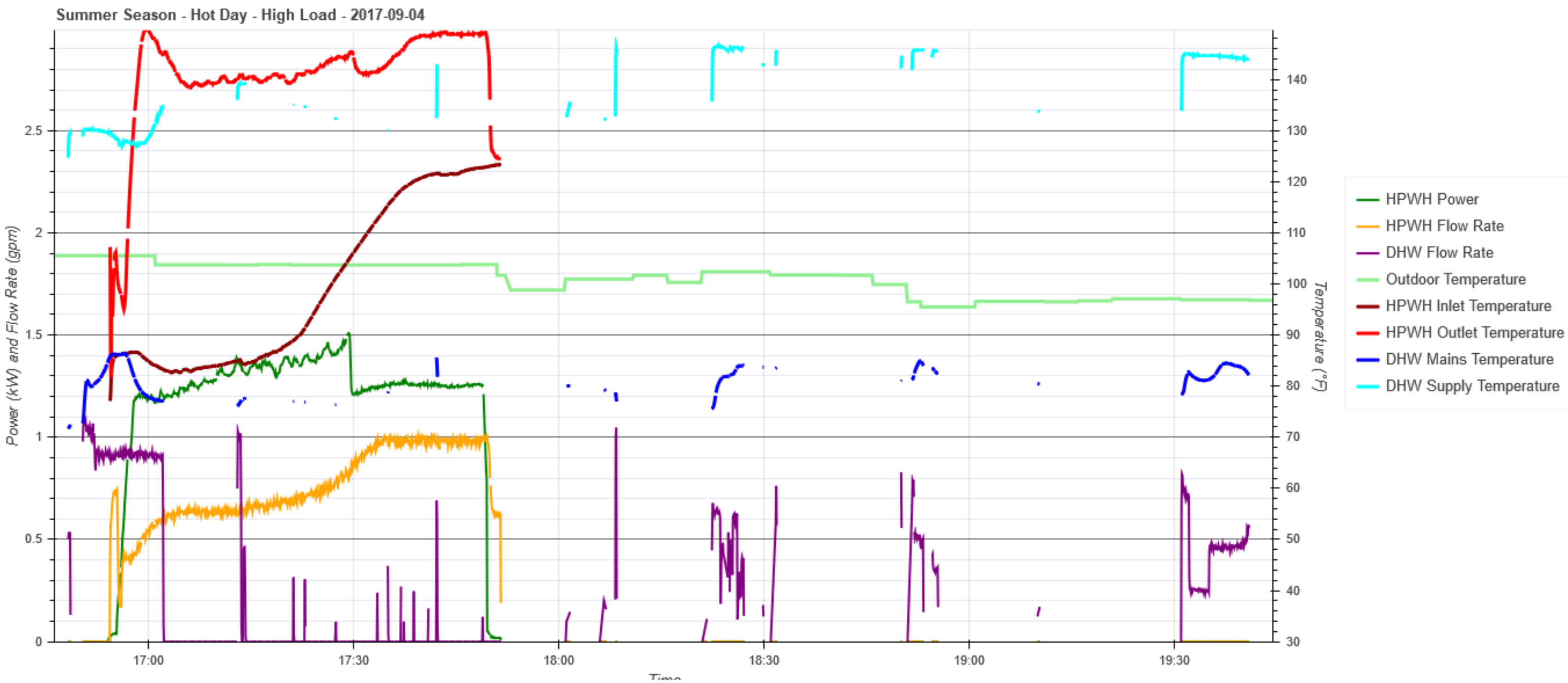
- CO_2 HPWH kW
- HPWH and DHW flow rate (the former is to the outdoor unit, the latter is the flow to the house hot water use points)
- Outdoor temperature
- Heat pump inlet and outlet temperatures (to and from the outdoor unit)
- DHW mains and supply temperatures (cold water entering the indoor storage from the city line and hot water leaving the storage tank)

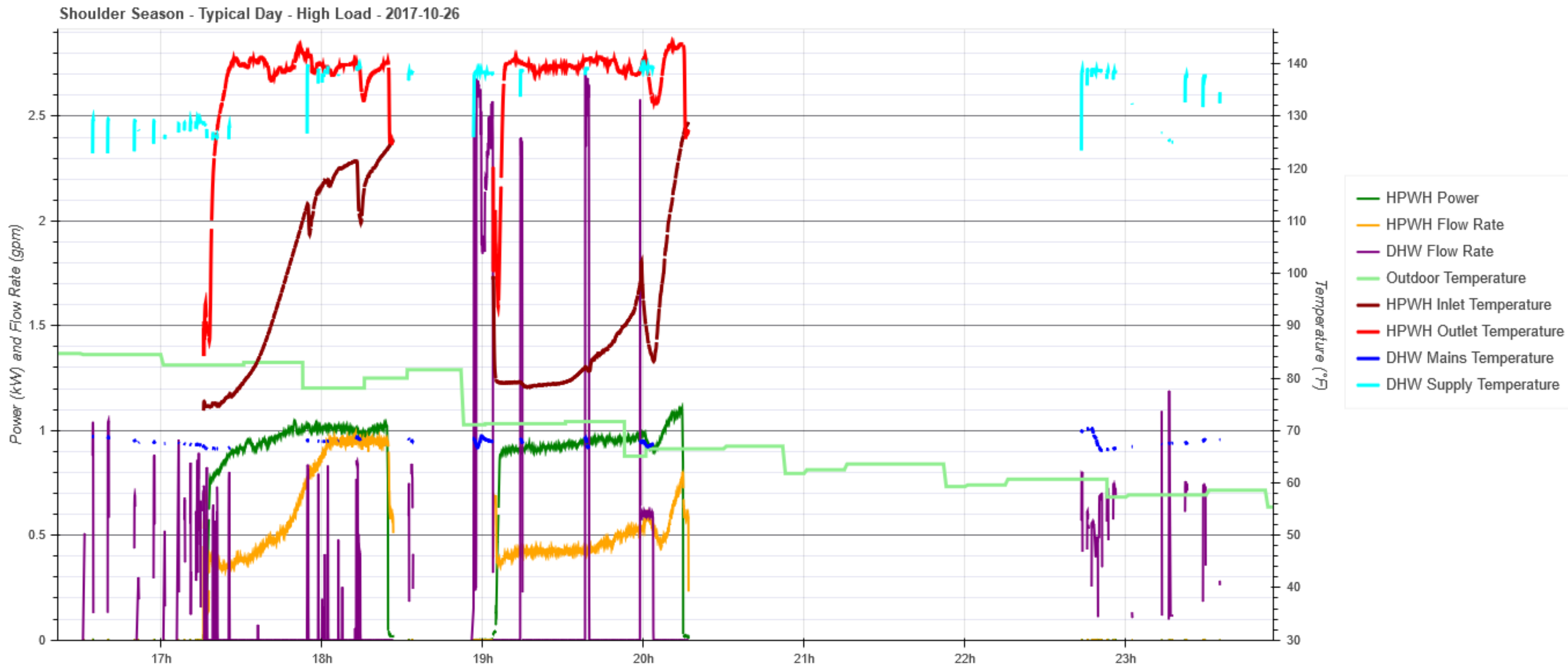
DHW flow and temperature data is sporadic as it only corresponds with flow events which can be a few seconds or minutes long. Startup conditions may show temperatures that are affected by the surrounding environment. DHW mains temperature, especially in the summer shows the influence of different environments, depending upon on the duration of the draw.


Winter Season - Typical Day - High Load - 2018-02-11
Power (kW) and Flow Rate (gpm)
Temperature (°F)
Time
20:30
21:00
21:30
22:00
22:30
HPWH Power
HPWH Flow Rate
DHW Flow Rate
Outdoor Temperature
HPWH Inlet Temperature
HPWH Outlet Temperature
DHW Mains Temperature
DHW Supply Temperature



Winter Season - Cold Day - High Load - 2018-02-22
Power (kW) and Flow Rate (gpm)
Temperature (°F)
Time
17:45
18:00
18:15
18:30
18:45
19:00
0
0.5
1
1.5
2
2.5
30
40
50
60
70
80
90
100
110
120
130
140
HPWH Power
HPWH Flow Rate
DHW Flow Rate
Outdoor Temperature
HPWH Inlet Temperature
HPWH Outlet Temperature
DHW Mains Temperature
DHW Supply Temperature


Summer Season - Hot Day - High Load - 2017-09-04
Power (kW) and Flow Rate (gpm)
Temperature (°F)
Time
17:00
17:30
18:00
18:30
19:00
19:30
HPWH Power
HPWH Flow Rate
DHW Flow Rate
Outdoor Temperature
HPWH Inlet Temperature
HPWH Outlet Temperature
DHW Mains Temperature
DHW Supply Temperature



Shoulder Season - Typical Day - High Load - 2017-10-26
Power (kW) and Flow Rate (gpm)
Temperature (°F)
0
0.5
1
1.5
2
2.5
30
40
50
60
70
80
90
100
110
120
130
140
17h
18h
19h
20h
21h
22h
23h
HPWH Power
HPWH Flow Rate
DHW Flow Rate
Outdoor Temperature
HPWH Inlet Temperature
HPWH Outlet Temperature
DHW Mains Temperature
DHW Supply Temperature

APPENDIX B
CO_2 AND CONVENTIONAL HPWH COMPARATIVE PERFORMANCE ANALYSIS

The spreadsheet snapshot below outlines a preliminary performance comparison of the CO_2 HPWH and a generic conventional HPWH (with performance estimated). This is not intended as a definitive performance characterization, but only as a first cut look at energy use and cost effectiveness. Conventional HPWH performance has been shown in numerous studies to be relatively sensitive to weather effects (both air temperatures entering the evaporator coil) and cold water inlet temperatures), hot water total load and usage pattern, and the model and control configuration (i.e. hybrid mode, economy mode) of the installed HPWH. Since these units can quickly transition from standard compressor heating to backup electric resistance heating with a very small change in sensed tank temperature, the variability in performance between units can be significant. With this backdrop, the authors assumed an annual average operating COP of 2.0 for a default HPWH installed in the Redding climate under an imposed load of 23 gpd (as monitored at the Redding site). The monthly variability in COP was assumed to mirror the relative variability as observed in the monitored unit.

Since the 23 gpd load level was observed at a two person household, the authors decided to also evaluate a higher load level (46 gpd) which would be more representative of a larger household.

Several comments about the evaluation results shown below:

- The CO_2 HPWH unit was assumed to perform at the same average monthly efficiency for the 23 and 46 gpd load levels. Since there is no resistance heat, this is a reasonable assumption.
- The CO_2 unit was assumed to have to meet slightly higher loads than the conventional HPWH since it must also offset the piping losses to the outdoor unit. This amounts to about a 6-7% higher load for the CO_2 HPWH unit.
- The conventional HPWH was assumed to operate at a 5% lower annual average COP for the 46 gpd load level as additional backup resistance heat was assumed due to higher hot water loads. The resulting 2.0 COP at 23 gpd was therefore reduced to a 1.9 COP average.

The results below show monthly energy consumption for each of the two cases. Under the assumptions of this analysis the CO_2 unit was assumed to save 26% (971 vs. 716 kWh/year) at the 23 gpd load level and 29% (1,207 vs. 1,704 kWh/year) at the 46 gpd load level.

Projected CO2 and Default HPWH Energy Use at Monitored 23 gpd Recovery Load

Month	# of days in Month	Daily Recovery Load (Btu/day)	Daily Storage Losses (Btu/day)	Daily Piping Losses (Btu/day)	CO2 HPWH Unit Monitored COP	CO2 Thermal Load (Btu/day)	Std HPWH Thermal Load (Btu/day)	Std HPWH Estimated COP	CO2 Monthly Energy (kWh)	HPWH Monthly Energy (kWh)
Jul 2017	15	11,928	4,898	912	3.35	17,738	16,826	2.32	23	32
Aug	31	10,580	5,414	851	3.38	16,845	15,994	2.34	45	62
Sept	30	8,358	5,285	770	3.14	14,413	13,643	2.18	40	55
Oct	31	11,819	5,352	980	2.85	18,151	17,171	1.97	58	79
Nov	30	14,289	4,722	1,214	2.68	20,225	19,011	1.86	66	90
Dec	31	14,286	4,813	1,742	2.24	20,841	19,099	1.55	85	112
Jan 2018	31	14,185	4,838	1,509	2.49	20,532	19,023	1.73	75	100
Feb	28	13,974	5,270	1,497	2.37	20,741	19,244	1.64	72	96
Mar	31	13,597	5,764	1,444	2.56	20,805	19,361	1.77	74	99
Apr	30	10,676	5,160	876	2.84	16,712	15,836	1.97	52	71
May	31	14,328	5,261	686	3.42	20,275	19,589	2.37	54	75
Jun	30	9,366	5,540	684	3.20	15,590	14,906	2.22	43	59
Jul	16	15,087	4,845	995	3.31	20,927	19,932	2.29	30	41
							Annual		**716**	**971**
							Savings/yr			**255**

Projected CO2 and Default HPWH Energy Use at 46 gpd Recovery Load

	# of days in Month	Daily Recovery Load (Btu/day)	Daily Storage Losses (Btu/day)	Daily Piping Losses (Btu/day)	CO2 HPWH Unit Monitored COP	CO2 Thermal Load (Btu/day)	Std HPWH Thermal Load (Btu/day)	Std HPWH Estimated COP	CO2 Monthly Energy (kWh)	HPWH Monthly Energy (kWh)
Jul 2017	15	23,856	4,898	1,824	3.35	30,578	28,754	2.21	36	51
Aug	31	21,160	5,414	1,702	3.38	28,276	26,574	2.22	67	95
Sept	30	16,716	5,285	1,540	3.14	23,541	22,001	2.07	97	138
Oct	31	23,638	5,352	1,960	2.85	30,950	28,990	1.88	119	168
Nov	30	28,578	4,722	2,428	2.68	35,728	33,300	1.76	147	202
Dec	31	28,572	4,813	3,484	2.24	36,869	33,385	1.47	130	180
Jan 2018	31	28,370	4,838	3,018	2.49	36,226	33,208	1.64	136	190
Feb	28	27,948	5,270	2,994	2.37	36,212	33,218	1.56	125	174
Mar	31	27,194	5,764	2,888	2.56	35,846	32,958	1.69	89	126
Apr	30	21,352	5,160	1,752	2.84	28,264	26,512	1.87	92	134
May	31	28,656	5,261	1,372	3.42	35,289	33,917	2.25	71	103
Jun	30	18,732	5,540	1,368	3.2	25,640	24,272	2.11	100	143
Jul	16	30,174	4,845	1,990	3.31	37,009	35,019	2.18	0	0
							Annual		**1,207**	**1,704**
							Savings/yr			**497**