PG&E Residential Code Readiness Project: Redding, California Site Monitoring Report

Codes and Standards PGE 2018_3

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LEGAL NOTICE

Definitions

Acronym	Definition
AMY	Actual Meteorological Year
ASHRAE	American Society for Heating, Refrigeration, and Air Conditioning Engineers
DC	Direct Current
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
EF	Energy Factor
ft^2	Square feet
HVAC	Heating, Ventilation, and Air Conditioning
kW	Kilowatt
kWh	kilowatt-hour
LED	Light Emitting Diode
MADIS	Meteorological Assimilation Data Ingest System
NOAA	National Oceanic and Atmospheric Administration
PV	Photovoltaic
RH	Relative Humidity (%)
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year
U-value	Overall heat transfer coefficient
V	Volt
ZNE	Zero Net Energy

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EXECUTIVE SUMMARY

Project Overview

This report documents the installed efficiency measures, commissioning data, full year monitored energy end use, and comparison to building model projections for the 2,372 ft^2 PG&E Code Readiness home located in Redding, California (Climate Zone 11). The primary objective of the work was to support the installation of measures that are expected to become more prevalent under the 2019 Building Energy Efficiency Standards (Title 24, Part 6), future iterations of Title 24, Part 6, and to gather information on costs, occupied home energy use, and observed comfort.

The builder of this custom home (Mike MacFarland of EnergyDocs) is a well-known high-performance building contractor focused on high-quality residential HVAC and building shell retrofit projects with exemplary attention to detail. This project represents his vision of performance-optimized construction for the hot, northern Central Valley. His approach to new and retrofit construction projects is focused on quality work, optimized energy efficiency, and long-term durability. For this custom home, the photovoltaic system was sized to provide sufficient electrical generation to offset the estimated annual energy usage, as well as in preparation for the addition of an electric vehicle.

Under this PG&E Code Readiness project, the builder incorporated a variety of high performance building technologies and construction techniques, including:

1. High performance exterior walls: 2x6 framing, 24" on center (10% framing factor target); blown cellulose in cavity; R-13 rigid exterior insulation (~R-30 wall)
2. Thermal envelope air sealing: Attention to detail with continuous plywood wall sheathing, taped & sealed air barrier, caulked and foamed. Leakage target of 0.45 ACH50
3. Attic insulation: R-60 ceiling insulation with radiant barrier; energy heel truss design
4. Slab edge insulation: 2" Roxul rock wool continuous slab edge perimeter insulation (R-8 insulation level)
5. Efficient windows, low glazing area: 10% glazing area with U values ranging from 0.23-0.25, and SHGC from 0.20-0.30.
6. Mechanical space within conditioned space: HVAC equipment, all ducts, and water heating storage tank located in 570 ft^2 attic mechanical space in the thermal boundary
7. HVAC equipment: ¾ ton ducted mini-split heat pump with short, low static pressure ducts located in conditioned mechanical space (equipment sizing at 3,160 ft2/ton)
8. Mechanical ventilation: Heat recovery ventilator located within conditioned mechanical space; heat recovery minimizes ventilation thermal loads on conditioned space
9. Water heating: 1.25 ton CO_2 HPWH (2.65 EF rating); split system with storage tank located in 2nd floor mechanical space to minimize piping run lengths to hot water use points
10. Appliances: All-electric efficient appliances including an induction cooktop and heat pump clothes dryer
11. Lighting: All LED lighting

The PG&E Code Readiness project team, recognizing that this was a unique project implemented by a leading construction practitioner, supported this effort to better understand practical limits of energy efficiency in an extreme California climate.

Builder Feedback

Mike MacFarland was interviewed and made the following observations, which have been edited for brevity:

- I am extremely happy with everything, truly beyond my greatest expectations in all areas. I wouldn't do anything differently in terms of design and construction.
- As far as energy code recognition, clearly the big disconnect is the inability for models to recognize high quality installation practices, the value of robust commissioning using building performance test equipment, and the proper and skilled application of building science. The effects of this trio are obviously a significantly better performance in all areas from building durability, indoor air quality & comfort, and efficiency.
- The biggest challenge was the lack of knowledgeable real estate appraisers that completely crippled the homeowner's efforts to get a long term mortgage with a normal down payment. Extensive documentation of all of the performance and solar features of the home were provided to justify the loan amount. To this day and despite having a high performing home[1] built at the most reasonable cost possible, without profit and overhead, the owners have both a first and a second mortgage.
- The appraisers valued the project within an existing range of local standard production homes. Custom homes in the area were being evaluated at $30+ per square foot higher than being requested. The unreasonable appraisals forced the owners into a high interest second mortgage to cover the difference between construction costs and temporary construction loan payoff as a result.

Monitored and Modeled Energy Use

Monitored electrical consumption over the year (July 2017–June 2018) totaled 5,085 kWh and was dominated by cooling (33% of annual total) and appliances (21% of annual total). PV production for the year totaled 8,032 kWh, far exceeding consumption. Future use of an electric vehicle can be accommodated by the excess production.

Monitored cooling energy usage of 1,683 kWh exceeded building energy simulation model estimates by 43%. This is not surprising given that summer indoor setpoints were around 70°F which is 8-10°F lower than assumed by the model. All other monitored end uses were found to be 41-87% lower than estimated by the model, likely due, in part, to only two adults living in the house. On a whole-house basis, the model overpredicted actual monitored consumption by 55%.

Despite the extreme summer cooling setpoints selected by the occupants, indoor conditions were maintained within ±3 °F of setpoint[2] for the full duration of the monitoring period. This result is impressive given the HVAC system size and speaks to the quality of the HVAC design.

Key Project Takeaways

This project presents a robust case for what can be accomplished in high performance residential construction with thoughtful climate-specific design, careful engineering, exemplary construction practices and system commissioning. Translating all these elements

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[1] Far exceeding the performance of standard new homes

[2] 3°F represents the ACCA Manual RS comfort criteria for single zone systems

to the mainstream construction industry will be challenging. Some of the measures are not viable from a builder cost-effectiveness perspective. Aggressive HVAC equipment sizing to the extent implemented here is not realistic for a production builder who must rely on multiple trades doing all facets of their work properly to achieve the level of downsizing in this project. Despite all these limitations, documenting this project is a valuable example of what can be achieved with high-performance residential construction.

FIGURE 1: INTERIOR OF ENTRY

FIGURE 2: PV PANELS

INTRODUCTION

This report presents information on the installation, commissioning, and monitoring of the Redding Code Readiness project. The home, designed and built by EnergyDocs, was occupied and monitored for a full year from July 2017 through June 2018. Evaluations of the data include indoor comfort, energy use by end use, and end use comparisons to an existing CBECC-Res simulation model of the home used for energy code compliance documentation.

BACKGROUND

This project was completed under PG&E's Code Readiness program to demonstrate, evaluate, and better understand implementation issues and costs associated with new residential technologies and systems that may be components of homes built under the 2019 Building Energy Efficiency Standards (Title 24, Part 6), and future iterations of Title 24, Part 6.

PROJECT DESCRIPTION AND LOCATION

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 square-foot home has four bedrooms and three full baths was permitted under the 2013 Building Energy Efficiency Standards and constructed between August 2016 and May 2017. The floor plan is shown in Figure 3. 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.

Photovoltaics were added to provide sufficient electrical generation to offset the estimated annual electricity usage and the future anticipated use of an electric vehicle. Since the home is an all-electric design, the determination of zero net energy on an annual basis is a straightforward process.

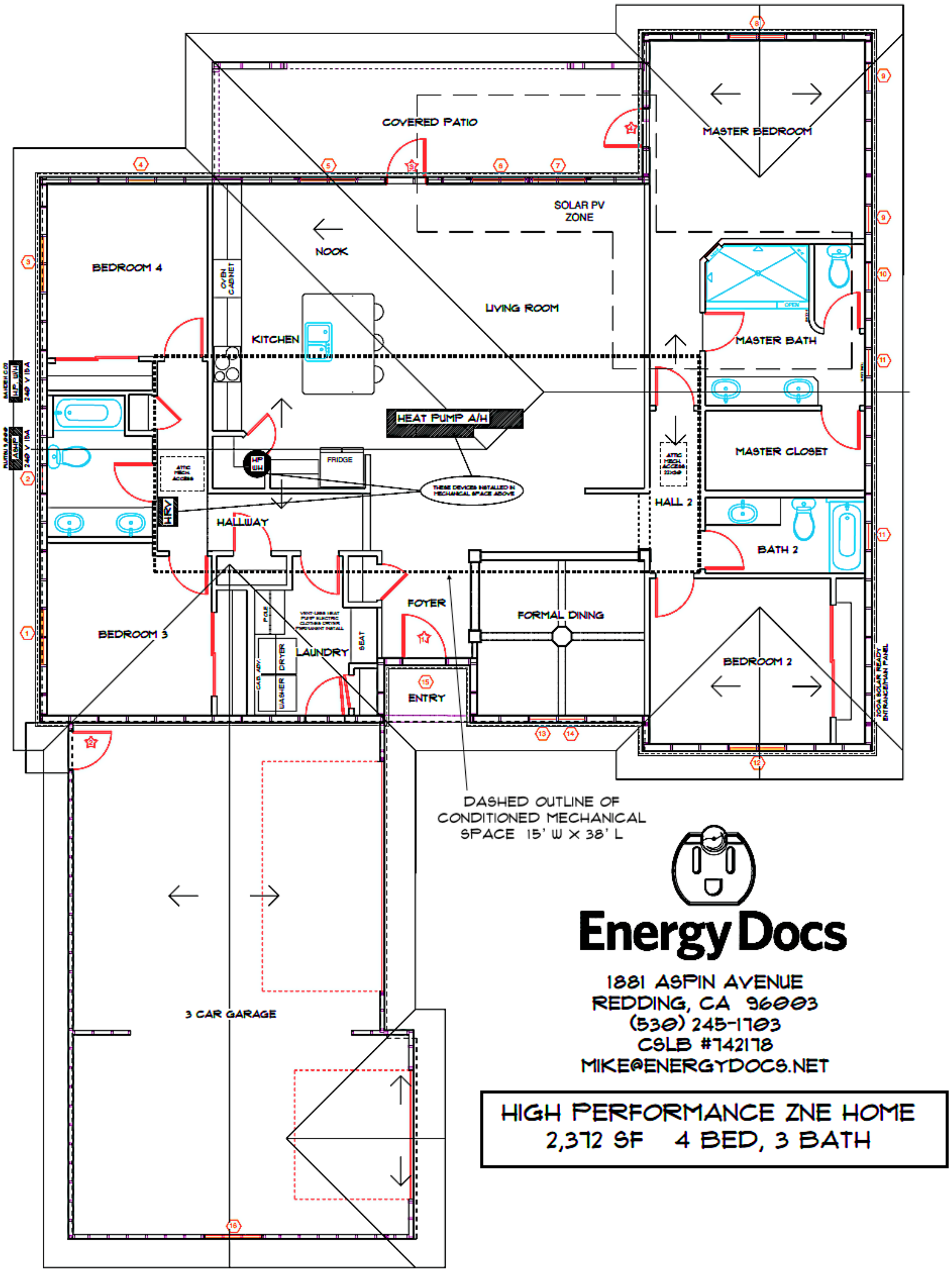

FIGURE 3. REDDING HOUSE FLOOR PLAN.

Building and System Descriptions

The builder incorporated a broad range of high performance building technologies, construction techniques, and energy efficiency measures. Table 1 below highlights a comparison of the key measures installed and what mainstream builders who design to the Title 24, Part 6 requirements typically install.

Table 1. Comparison of typical 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 ft^2/ton) Rated at 12.2 HSPF
Cooling equipment	Typical 14 SEER/ 11.7 EER with sizing at ~ 600 to 800 ft^2/ton	Mini Split rated at 21.5 SEER
Water heating equipment	Typical 0.60 EF gas storage water heater	1.25 ton split system CO_2 HPWH (2.65 EF); storage tank located in 2nd floor mechanical space to minimize piping runs to use points
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
Photovoltaic	Builder option	5.32 kWdc WSW facing; 7 in 12 roof pitch

The following sections provide details on some of the installed energy efficiency measures.

THERMAL ENVELOPE

Exterior framed walls are 2x6 construction (24" on center) and were built utilizing advanced framing techniques. Measured wall framing factor[3] for this house was 11.7%. This represents a ~60% reduction in wall framing content relative to a sample of other recent California walls surveyed in the field. Two 2x6, 24" on center advanced wall systems surveyed in 2014 were found to have framing factors of 21.3 and 21.4%. Framing factors around 15% are considered optimal but are only achieved if the framer focuses on minimizing excess lumber in the construction of the exterior walls. Most framing contractors are reluctant to aggressively frame homes to minimize framing in the walls, partly due to the common practice for the framing contractor's bid to only cover labor so there is no incentive to save on lumber.

The walls are insulated with blown cellulose in the cavities, and the house is wrapped with two inches of polyisocyanurate rigid insulation, resulting in a cavity path weighted R-value exceeding R-30. Significant attention was paid in the framing, air sealing, and insulation process to maximize the value of the insulation and minimize thermal shorts.

The attic construction utilized a raised heel truss to accommodate R-60 blown ceiling insulation to the outside edge of the wall below. Attic radiant barrier on the roof sheathing was installed. The slab edge perimeter is insulated with 2" of Roxul rock wool insulation, resulting in R-8 edge insulation. Total glazing area is 10% of floor area, which is very low relative to standard production housing. Window U-factors range from 0.23 to 0.25, and SHGC ranges from 0.20 to 0.30.

The envelope was carefully air-sealed with a goal of achieving a final blower door measured envelope leakage around 0.5 air changes per hour at a 50 (ACH50) Pa pressure differential. Typical California production housing is typically in the range of 3.5 to 5.0 ACH50.

MECHANICAL SYSTEMS

Heating and Cooling: Space heating and cooling is provided by a Fujitsu ¾ ton ducted mini-split heat pump (outdoor unit model number: AOU9RLFC, indoor unit: ARU9RLFC) with short duct runs all located in conditioned space. The unit was rated at 12.2 HSPF and 21.5 SEER. Indoor mini-split components (and the water heater storage tank and mechanical ventilation unit) were in a 570 ft^2 mechanical room centrally located above the first floor living area. The ¾ ton sizing for this sized house, results in an impressive cooling design sizing of over 3,150 ft^2/ton. This compares to industry standard HVAC contractor design practice with air conditioner sizing in the range of 600-800 ft^2/ton.

Mechanical and Fresh Air Ventilation: Mechanical ventilation is provided by a Broan HRV200TE heat recovery ventilation device located in the mechanical space. The system provides fresh air per ASHRAE 62.2 ventilation requirements, while reclaiming a large fraction of the energy in the exhaust air stream (rated sensible recovery efficiency of 81% at 32 °F). Airflow is rated at 255 Cfm at 50 Pa static pressure, but can be set by the user.

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[3] Fraction of the net exterior wall area that is wood (rather than insulation).

Water Heating: Domestic hot water is provided by a Sanden heat pump water heater (HPWH) that utilizes CO_2 as the working refrigerant. The 43-gallon Sanden CO_2 unit (model number GS3-45HPA-US) is rated at a 4.5 COP and 2.65 Energy Factor.

Lighting and Appliances

The home incorporates all high-efficacy LED lighting meeting the 2016 Title 24, Part 6 code requirements throughout the home[4]. Luminaires that accept replacement lamps were not used in the home. All appliances, listed in Table 2, are electric including an induction cooktop and a heat pump clothes dryer.

Table 2. Installed appliances.

Appliance	Manufacturer	Model Number
Induction Cooktop	General Electric	PH9030DJBB
Double Oven	General Electric	PT9550SF6SS
Microwave/Hood	General Electric	PVM9005SJ2SS
Refrigerator	General Electric	PFE28PSKDSS
Clothes Washer	Whirlpool	WFW9290FW
Clothes Dryer	Whirlpool	WED9290FW
Dishwasher	General Electric	GDT695SSJ0SS
Garbage Disposal	Insinkerator	Contractor 333-1

Photovoltaic System

A 5.3 kW (DC) west-southwest-facing solar electric system consists of 19 Solar World 280 W modules and 19 Siemens M250 micro inverters. The PV system was sized to offset anticipated annual electrical energy usage including a future electric vehicle.

Assessment Objectives

The primary evaluation objective was to gather builder input (cost and install feasibility) on the measures that were identified as potential future energy code updates and monitor the electric end uses of this all-electric home for one year. The focus of the evaluation includes:

1. Collect builder input on measure cost and installation issues.
2. Determine if there are any constructability and commissioning concerns.
3. Measure whole building energy consumption, from the grid as well as PV production.
4. Measure the relative contribution of electrical end uses to ZNE performance.
5. Understand the seasonal energy used for space conditioning and water heating.
6. Measure indoor temperature and relative humidity.

[4] This exceeds the requirements of the 2013 Title 24, Part 6 cycle the house was permitted under

7. Monitor the Sanden CO_2 heat pump water heater, a highly efficient electric water heating technology.

MONITORING EVALUATION

Electrical energy use at the house was monitored by a circuit-level monitoring system installed during construction of the house. As required by the project research needs, the house was wired to provide improved disaggregation of electrical end uses, such as keeping all hardwired lighting on a circuit separate from plug loads.

In addition to the electrical end use monitoring, separate dedicated monitoring of the advanced Sanden CO_2 heat pump water heater (HPWH) was completed. This unit is new to the California market and offers the potential for noticeable efficiency improvements over existing conventional HPWH technology without the use of supplemental electric resistance heating. The installed unit was monitored to characterize performance and hot water loads.

FIELD MONITORING PROCESS

The house was first occupied at the beginning of June 2017. Monitoring began on July 1, 2017 to avoid any anomalies often seen directly following move-in. The home was occupied throughout monitoring by a working couple who maintain variable working schedules, with one member of the two-adult household working frequent night shifts.

The general evaluation approach was to employ system commissioning and long term high resolution electrical end use monitoring to document performance attributes over twelve months. Equipment electrical end uses were measured, as well as local weather, indoor temperature at the thermostat, and HVAC supply temperature. Table 3 chronicles the installation and commissioning of the monitoring equipment, as well as issues or changes during the monitoring period. None of the events listed in Table 3 significantly affected collection of the electrical usage data.

TABLE 3: HOUSE MONITORING SYSTEM HISTORY

Date	Description
6/2/2017	Homeowner move-in and PV activation.
6/9/2017	Monitoring system installation.
7/3/2017	Complete energy and temperature monitoring system commissioning.
7/15/2017	Complete detailed HPWH monitoring system commissioning.
8/1/2017	SiteSage voltage reference moved to a different breaker for stability. This temporarily resulted in inversion of the solar power measurement. No data lost.

TEST PLAN

The site was equipped with a SiteSage eMonitor and Gateway for continuously collecting, storing, and transferring electrical end use data. The Gateway connected to the internet using a cellular modem with data uploaded to the SiteSage servers at one-minute intervals. After the twelve-month monitoring period, the SiteSage equipment remained on site, providing the occupants continued access to real-time and historical energy use. The house was instrumented with 54 sensors, monitoring 46 measurement points. Table 4 lists all the measurement points that were monitored on a continuous basis.

TABLE 4. MEASUREMENT POINTS.

CATEGORY	DESCRIPTION	TYPE	LOCATION
Solar	Solar	50A CT	Main Panel
Mains	Mains	150A CT	Main Panel
Appliances	Clothes Dryer	50A CT	Main Panel
	Clothes Washer	20A CT	Main Panel
	Dishwasher	20A CT	Main Panel
	Garbage Disposal	20A CT	Main Panel
	Refrigerator and Island Plugs	20A CT	Main Panel
	Future Pool Pump	20A CT	Main Panel
Cooking	Hood and Microwave	20A CT	Main Panel
	Oven	50A CT	Main Panel
	Cooktop	50A CT	Main Panel
DHW	Water Heater Power (SiteSage)	20A CT	Main Panel
	Water Heater Power (PowerScout)	100A CT	Mech. Space
	Mains Water Temperature	Thermocouple	Mech. Space
	Supply Water Temperature	Thermocouple	Mech. Space
	Heat Pump Inlet Water Temperature	Thermocouple	Mech. Space
	Heat Pump Outlet Water Temperature	Thermocouple	Mech. Space
	Supply Water Flow Rate	Ultrasonic	Mech. Space
	Heat Pump Water Flow Rate	Ultrasonic	Mech. Space
HVAC	Mini-Split Heat Pump	20A CT	Main Panel
	HRV and Bath Fans	20A CT	Main Panel
	Ceiling Fans	20A CT	Main Panel
	Temperature at Thermostat	IC	Mech. Space
	Relative Humidity at Thermostat	IC	Mech. Space
	Temperature in Supply Plenum	IC	Hallway
	Relative Humidity in Supply Plenum	IC	Hallway
Plugs	Bath 2	20A CT	Main Panel
	Bath 3	20A CT	Main Panel
	Bedroom 2 and Halls	20A CT	Main Panel
	Bedroom 3 and Adjacent Loft Area	20A CT	Main Panel
	Bedroom 4	20A CT	Main Panel
	Counters and Nook	20A CT	Main Panel
	Exterior	20A CT	Main Panel
	Garage	20A CT	Main Panel
	Living Room; Dining Room; and Foyer	20A CT	Main Panel
	Master Bath	20A CT	Main Panel
	Master Bedroom and Closet	20A CT	Main Panel
	Security System	20A CT	Main Panel
	Smoke and CO Alarms, SiteSage, and Wi-Fi	20A CT	Main Panel
Hardwired Lights	Bedrooms 2, 3, and 4	20A CT	Main Panel
	Garage and Exterior	20A CT	Main Panel
	Master Suite	20A CT	Main Panel
	Laundry, Baths, Hall, and Mech. Space	20A CT	Main Panel
	Living Room, Dining Room, Kitchen, and Entry	20A CT	Main Panel

The HPWH was monitored using a custom radio frequency (RF) and Modbus gateway. Ultrasonic flow meters, immersed thermocouple probes, and a Dent PowerScout 3037 power transducer were connected to a datalogger (DataTaker DT50) to provide detailed monitoring of the unit's operation. Sensors were read by the gateway through a Serial/Modbus connection to these instruments at four second intervals, allowing for calculation of high resolution hot water usage data.

This high-resolution data was needed to properly capture hot water events which are often of very short duration. Figure 4 presents the monitoring system configuration with flow and temperature measurements located on both the energy flows from the water heater storage tank, and the energy flows between the storage tank and the outdoor unit. (Flow and temperature sensing points are shown as "F" and "T" in the figure.)

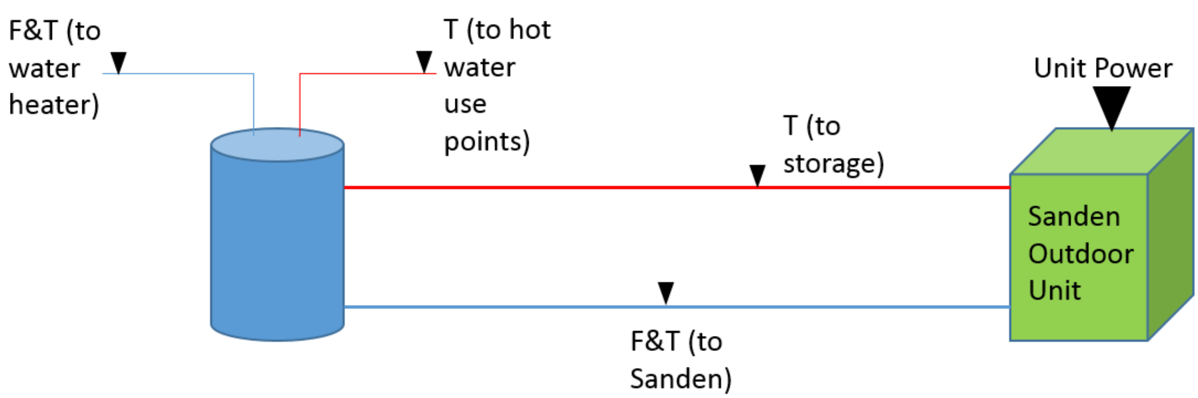

FIGURE 4. SCHEMATIC OF HPWH MONITORING.

Wireless temperature and relative humidity sensors installed at the thermostat and in the HVAC supply plenum were also logged by the RF/Modbus gateway. The RF/Modbus gateway was connected to the internet using a cellular modem.

The Frontier monitoring server automatically collected data from the SiteSage and RF-DAQ at regular intervals, stored the data on a secure server, checked the data for common sensor and equipment issues, and automatically notified logging status on a daily basis.

THERMOSTAT DATA

This site was not equipped with a logging thermostat. Instead, a temperature/humidity (T/RH) sensor was installed next to the thermostat to collect indoor temperature data, and in the supply plenum to determine heat pump operating mode.

WEATHER DATA

Outside air temperature and humidity were measured at these nearby weather stations (NOAA call signs and distance from the house): F0355 (1 mile), C5599 (2.2 miles), CI224 (2.8 miles), KRDD (8.5 miles). Outdoor dry bulb air temperatures presented are those produced by NOAA's MADIS data quality and control analysis. When data was not available from the closest station, or of inadequate quality, data from the next closest station was used. The Frontier monitoring server downloaded weather data from an online repository once daily.

Instrumentation Plan

Datalogger Specifications

The SiteSage system of logging devices was used to monitor electrical energy at this site. A SiteSage eMonitor supports 14 total current transducer (CT) channels and can be expanded using 10-channel expansion pods to a maximum of 44 CT channels. The eMonitor is designed to be installed in the breaker panel. It draws power and measures a voltage reference from being wired directly to a breaker in the electrical panel. Real and apparent power are calculated for each channel and stored locally. A SiteSage sPod data acquisition microcontroller accommodates additional analog and digital sensor inputs, such as temperature and relative humidity sensors. The eMonitor and sPod connect wirelessly to the SiteSage Gateway, which uploads data it receives from connected devices over the internet to a SiteSage cloud server every minute.

One SiteSage eMonitor with three expansion pods and one Gateway were installed at the site. The Gateway was connected to the internet via a cell modem. The time that an eMonitor can retain local data without overwriting values varies with the number of channels, but for this site, approximately 20 days of one-minute interval data could be stored before overwriting old data.

The RF/Modbus gateway is a custom data logging solution built on a Linux-based single-board computer platform. This RF-DAQ gateway can collect data from radio frequency (RF) and Modbus/Serial sources and delivering that data over the internet to an FTP server. Local storage can be expanded using an SD card. The RF-DAQ gateway deployed at this site has sufficient capacity to store several years of data.

Sensor Types and Specifications

Table 5 lists the types of sensors used for the various monitoring points and their performance specifications. Sensor selection was based on functionality, accuracy, cost, reliability, and durability.

Datalogger Installation

The SiteSage system was installed in an electrical enclosure in the garage adjacent to the back of the main electrical panel. Power connections were secured and labeled to prevent inadvertent disconnection. Equipment was marked with a Frontier Energy contact name and phone number to call in the event of problems.

Commissioning and Calibration

After the completion of monitoring system installation in June 2017, the monitoring system was activated, and sensor reporting was field verified. Communications between the dataloggers and the web were also tested and verified. Setup of the SiteSage system was completed in its web interface to label the different channels and associate them with the correct sensors.

TABLE 5. GENERAL SENSOR SPECIFICATIONS.

TYPE	APPLICATION	MFG./MODEL	SIGNAL	SPAN/SIZE	ACCURACY
Current Transducer	Circuit power	YUANXING CTSA010	mV	20 A 50 A	±1% from 5 to 130% of rated current
Current Transducer	Mains power	YUANXING LCTC0250	mV	150 A	±1% from 5 to 120% of rated current
Temperature and Relative Humidity IC	Indoor T/RH and Supply Plenum T/RH	TE Connectivity HTU21D(F)	RF	41 to 140 °F 20 to 80 %RH	±0.7 °F ±3% RH
Power Monitor	HPWH Power and power factor	Dent Powerscout 3037	Modbus	100 A	±0.2% of reading
Ultrasonic Flow Meter (2)	Flow to water heater (cold) and to HPWH outdoor unit	Onicon F-4600	Modbus	0.25 to 25 gpm	1 to 25 gpm: ±1% of reading 0.25 to 25 gpm: ±2% of reading
Immersion Thermocouples	Supply and return water temperatures	Omega Type T	MA	N/A	±0.9°F

RESULTS

The following results summary focuses on the builder reported costs for the code readiness measures, energy end use data, indoor setpoints and comfort, and comparison of monitored energy use to a CBECC-Res building energy simulation model provided by the builder.

The scope of the evaluation presented here is intended as a high level performance summary. The one minute interval SiteSage data offers a wealth of information that could be analyzed in more detail. Additionally, the modeling could be undertaken in a much more sophisticated manner by utilizing actual weather data (instead of long term average data) and better mimicking actual setpoints. Both of these efforts were beyond the scope of this effort. One that will be addressed in a separate report is the detailed monitoring of the Sanden unit performance over the course of the year.

MEASURE COSTS

Table 6 summarizes actual builder costs for the implemented measures at the Code Readiness site. Costs provided by Mr. MacFarland are broken down into labor and material incremental costs above "conventional practice" builder cost estimates. Incremental construction costs outside of the PV system total over $40,000. It should be noted that the builder's goal is designing and constructing this house was not exclusively for energy efficiency. Long-term home durability (life cycle construction "efficiency") was a key design principle at play. For example, the full sheathing of the house with 5/32" plywood instead of oriented strand board was a major additional cost but results in a much more robust house.

TABLE 6. SUMMARY OF BUILDER REPORTED MEASURE INCREMENTAL COSTS.

Measure		Incremental Labor Cost		Incremental Material Cost		Incremental Cost
Energy Heel Truss	$	844	$	151	$	995
Mechanical room framing (570 ft^2 area)	$	3,000	$	284	$	3,284
Gable end furring for 2" exterior foam	$	1,584	$	-	$	1,584
Window bucks/plywood wrap for 2" ext foam	$	2,147	$	411	$	2,558
Full plywood sheathed exterior	$	4,584	$	2,623 *	$	7,207
2" Polyisocyanurate exterior foam installed	$	2,344	$	1,678	$	4,022
CO2 Heat Pump Water Heater	$	263	$	2,000 **	$	2,263
Air sealing beyond minimum code practices	$	2,344	$	549	$	2,893
Attic/wall blown insulation exceeding code	$	2,100	$	217	$	2,317
Roxul foundation wrap, concrete smooth siding, flashing step	$	4,369	$	1,625	$	5,994
1x4 vented rainscreen installation	$	3,225	$	1,414	$	4,639
Mechanical heat recovery ventilation system	$	1,425	$	1,617	$	3,042
Appliances: Ventless HP clothes dryer	$	-	$	600	$	-
Solar PV- 5.32 kW	$	2,375	$	7,673	$	10,548
Total	$	30,064	$	20,842	$	50,906

* Normally oriented strand board is used for sheathing; builder finds plywood a more durable product

** cost relative to a standard HPWH

BUILDING COMMISSIONING

Testing and verification was completed by both the builder and the project HERS rater providing an initial check on construction quality.

- Building envelope leakage: Measured leakage during the final blower door test was found to be 209 cfm at 50 Pascal pressure difference, equal to envelope air leakage rate of 0.53 ACH50 (builder).
- Duct leakage test: 3.0% total duct leakage at 25 Pascal pressure difference; 16 cfm out of a total maximum airflow of 523 cfm. All leakage within conditioned space (HERS rater).
- Fan efficacy measured at a maximum of 0.14 W/cfm; under normal operating conditions, fan efficacy was found to be slightly higher (HERS rater).
- Total external duct static pressure of 0.20" with manufacturer specified limit of 0.36" (builder).
- Heat recovery ventilation system ducted into every living space with excellent room mixing and high ventilation effectiveness as tested with CO_2 tracer gas decay methods. Initially measured at 118 cfm supply, 102 exhaust, with a fan power of 26 W (builder).
- Insulation Quality Inspection (builder).

ELECTRICAL ENERGY MONITORING RESULTS

With the SiteSage system installed and end uses disaggregated, it is possible to get a precise picture of energy usage breakdown and usage patterns. One-minute interval data logging provides a wealth of information. Consistent with the intended high-level scope of this report, the authors chose to focus on aggregated results.

Figure 5 presents the electrical energy consumption data over the full monitoring period in bar chart format and Table 77 and 8 present the data in tabular form. Cooling is the predominant load at 1,683 kWh (33% of the total 5,085 kWh consumed) which is not surprising for the Redding climate where mid-summer peak dry bulb temperatures average over 100°F. Space heating energy usage is very low in this super-insulated home, amounting to just under 250 kWh over the year. It should be noted that both winter and summer thermostat setpoints are lower than typical, resulting in increased cooling energy usage and reduced heating energy use. Appliances represent the second largest end use at 1,087 kWh. The remaining loads (DHW, plugs, lighting, cooking, and ventilation) total only 2,069 kWh over the twelve months. The advent of efficient lighting technologies in recent years, such as LEDs, has reduced this historically significant end use to less than 8% of annual consumption (under 400 kWh for the year).

The 201 kWh consumed by the Code Readiness energy monitoring system over the year is not attributed to the total household consumption.

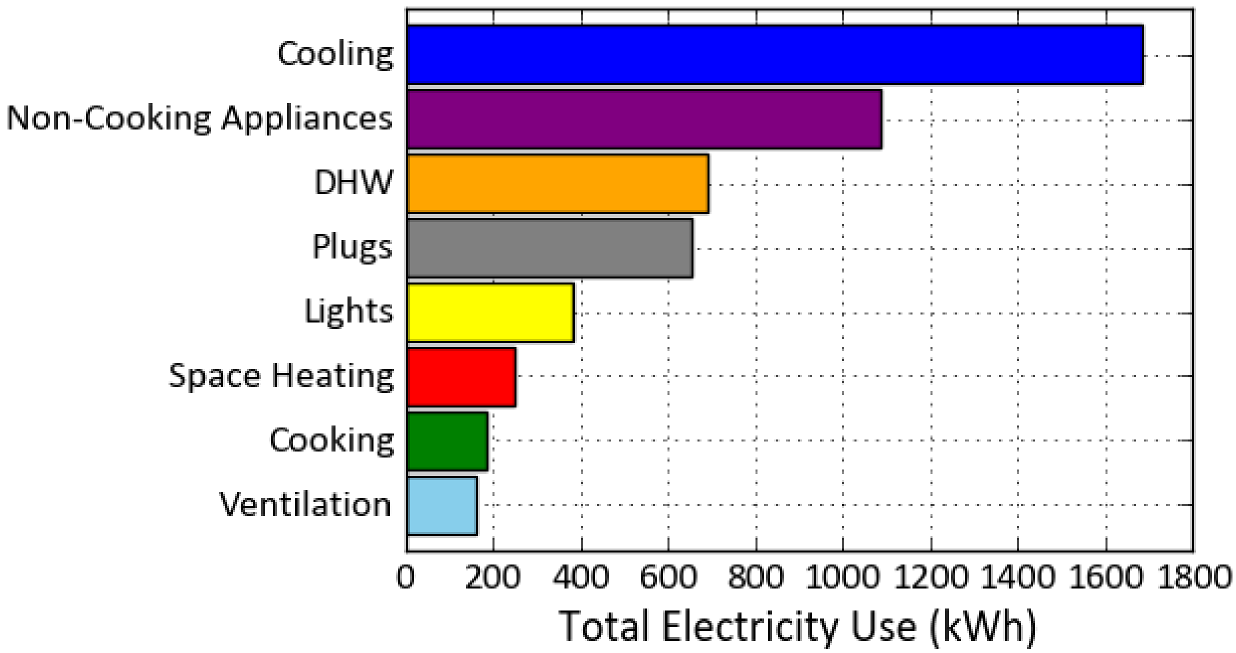

FIGURE 5. MONITORED ELECTRICAL END USES.

TABLE 7. ELECTRICAL ENERGY CONSUMPTION BY END USE CATEGORY.

END USE CATEGORY	% ELECTRICITY USE OF TOTAL	ELECTRICITY USE (KWH)
Cooling	33.1	1,683
Non-Cooking Appliances	21.4	1,087
DHW	13.5	688
Plugs	12.8	653
Lights	7.5	382
Space Heating	4.9	248
Cooking	3.6	184
Ventilation	3.2	162
Monitoring	N/A	201

Appliance end uses are further broken down in Table 8. The refrigerator end use represents about half of the appliance total. The heat pump clothes dryer is the second largest end use, with all remaining appliance end uses amounting to approximately 25% of the total.

TABLE 8. BREAKDOWN OF APPLIANCE ELECTRICAL ENERGY CONSUMPTION.

APPLIANCE	% ELECTRICITY USE OF TOTAL	% ELECTRICITY USE OF APPLIANCES CATEGORY	ELECTRICITY USE (KWH)
Refrigerator and Island Plugs	12.2	49.0	623
Clothes Dryer	6.7	26.7	339
Oven	2.3	9.1	116
Dishwasher	2.0	8.1	103
Cooktop	1.0	3.9	50
Clothes Washer	0.4	1.7	21
Microwave	0.4	1.5	19
Disposal	0.0	0.1	1

Figure 6 plots monthly energy consumption for all end use categories. Most loads are very consistent month-to-month, considering seasonal differences (e.g. lighting and plug loads increase in the winter). The energy use of the HPWH increases in the winter months as loads increase and efficiency drops, and HVAC energy use is most significant in the summer. Cooling extends for most of the year, primarily due to the very low setpoints employed by the occupants (averaged around 70°F). Low heating setpoints result in heating energy usage being very low.

In the second quarter of monitoring (October to December 2017), the builder noted that the 118 cfm HRV airflow was resulting in overly low indoor humidity levels due to dry outdoor conditions (indoor RH in the 30-35% range). Given that the original airflow was set high to help improve new home indoor air quality, the builder reduced airflow by approximately 1/3 and changed the ventilation control from continuous operation to intermittent (20 minutes every hour) on December 5, 2017. In the third quarter of monitoring (January to March 2018) the ventilation control was changed back to continuous on March 15, 2018.

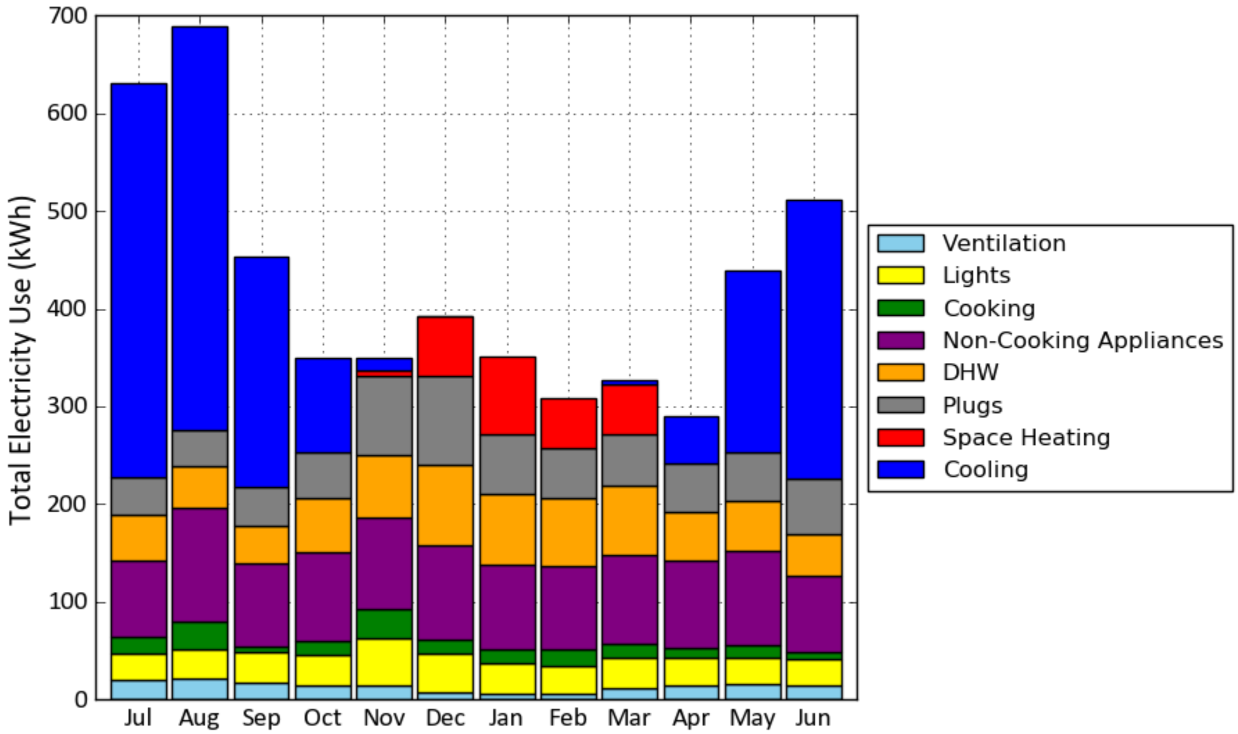

FIGURE 6. MONTHLY ELECTRICAL ENERGY CONSUMPTION.

Figure 7 breaks down monthly occupant-supplied plug loads in more detail. The largest among the plug loads is the Living Room, Dining Room, and Foyer circuit, which accounts for 64% of all energy used by plug loads and 9.4% of the total household energy use.

As the four bedroom/three bathroom home only had two, full-time employed occupants for the duration of monitoring, most plug loads outside the master suite and common areas of the house were very small or infrequent. Only four plug load circuits used more than 5% of total plug load annual energy use:

- the Living, Dining, and Foyer circuit (64.3% of all plug use),
- the Security System circuit (8% of all plug use),
- the Kitchen Counters and Nook circuit (6.2%), and
- the Bedroom 3 (hobby room/office) circuit (6.1%).

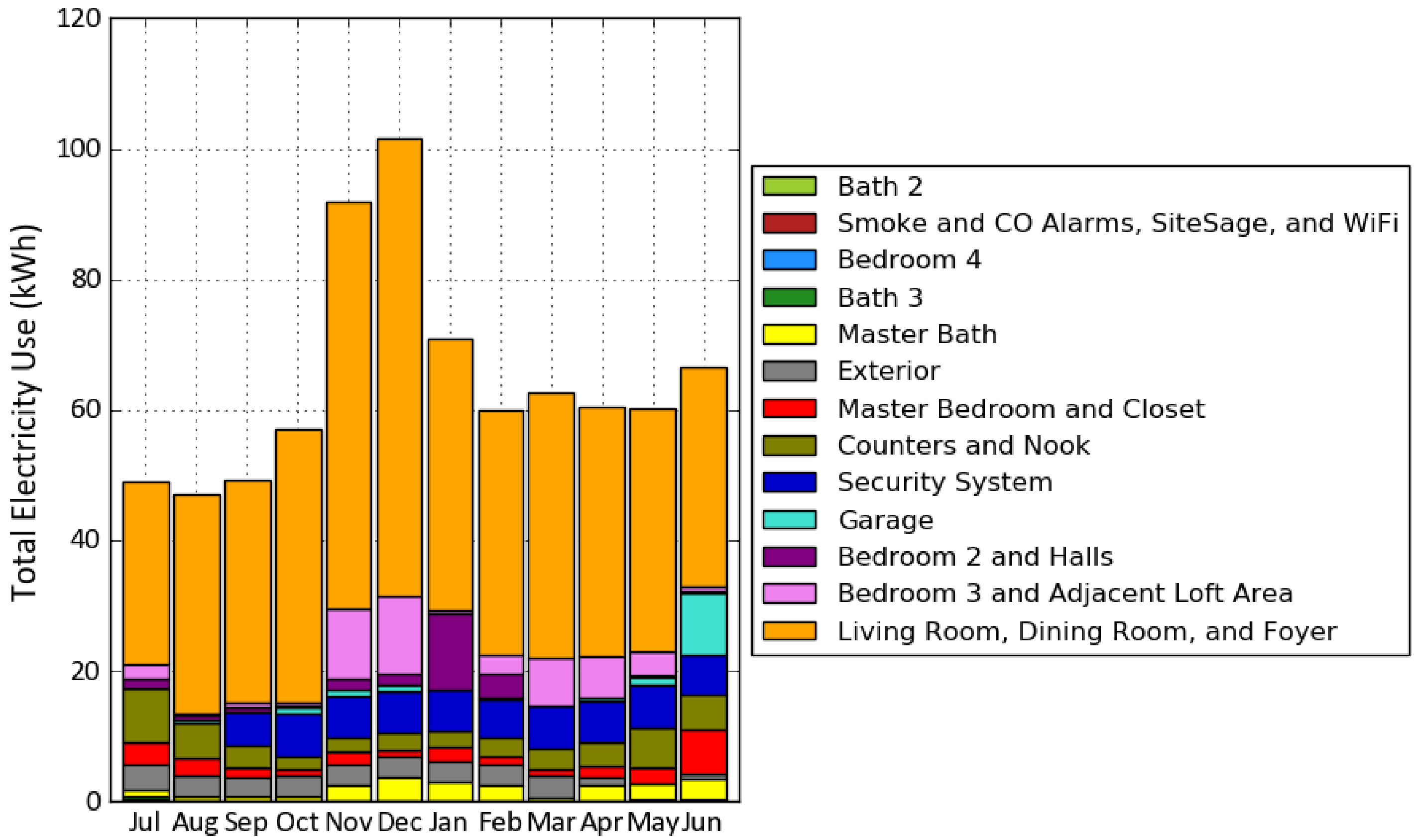

FIGURE 7. MONTHLY ELECTRICITY PLUG LOAD BREAKDOWN.

Figure 8 shows daily energy consumption by end use superimposed above daily outdoor temperature profiles plotted as minimum, average, and maximum values. On a daily level, it is possible to see more of the natural variability in plug, appliance and lighting loads.

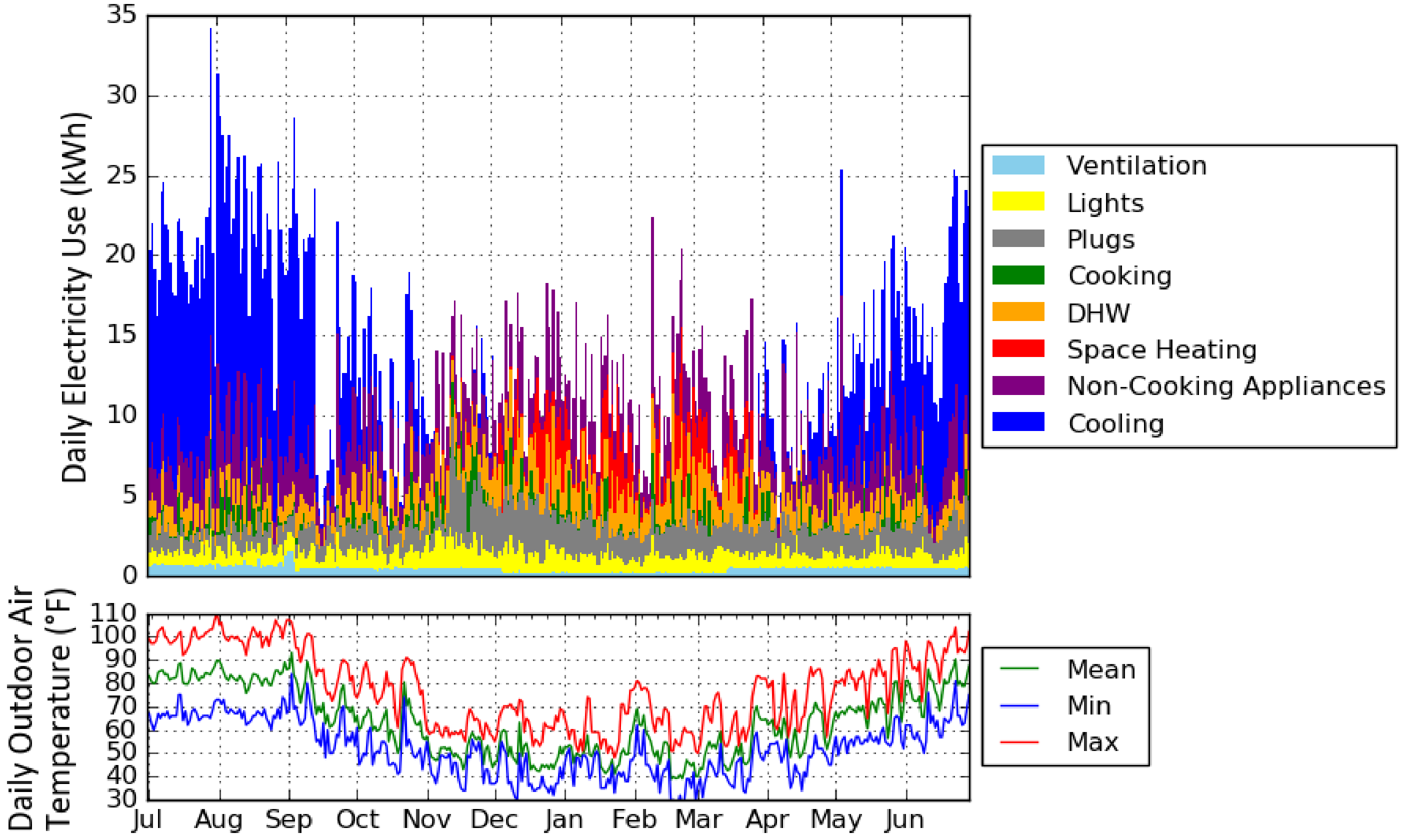

FIGURE 8. DAILY ENERGY USAGE BY END USE WITH OUTDOOR TEMPERATURE PROFILES.

Figure 9 plots the daily minimum, average, and maximum of the daily indoor and outdoor temperatures. Mid-summer outdoor conditions show consistent temperature exceeding 100°F, and mid-winter high temperature are typically in the 50-60 range, with lows approaching 30°F.

There is a significant period in mid-September where the temperatures are setback to 73 °F. This is also accompanied by a significant decrease in energy use to levels typical of no occupancy.

The occupants maintained lower setpoints in both heating and cooling than typically assumed in design models. This was partly due to one member of the household who worked night shift and desired low, summer mid-day temperatures for sleeping. The inferred setpoints, based on HVAC system operation on the one-minute data intervals are approximately 70 °F for summer 2017, 65 °F and 63 °F in the winter, and 66 °F in the early summer of 2018.

Despite these low cooling setpoints, the ¾-ton mini-split heat pump (serving a house nearly 2,400 ft^2 in size) maintained indoor conditions effectively relative to the setpoints, as evidenced by daily indoor maximum and minimum temperatures always within 3 °F of each other.

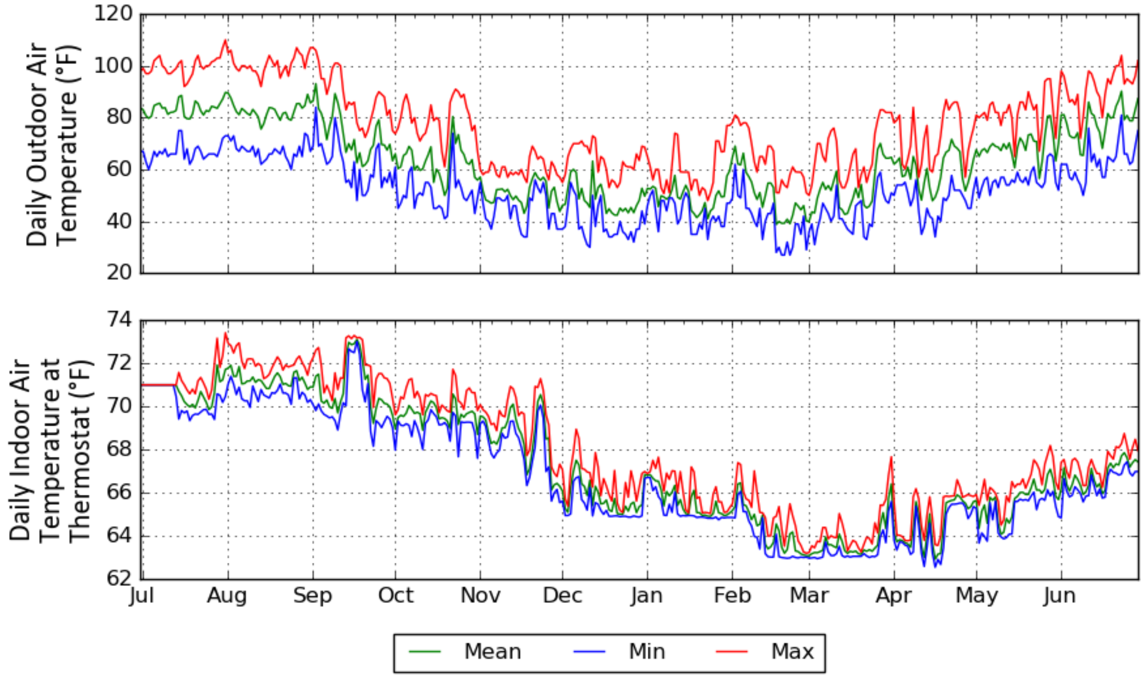

FIGURE 9. OUTDOOR AND INDOOR TEMPERATURE PROFILES.

PV SYSTEM PERFORMANCE

Figure 10 presents daily PV production relative to total daily household electrical energy consumption. Energy consumption (including the monitoring component) for the year totaled 5,291 kWh while PV production totaled 8,052 kWh. During this period, the PV system offset 152% of the home's electricity use. Daily PV production covered daily consumption except for mid-winter periods when solar generation was at a minimum and a couple summer days.

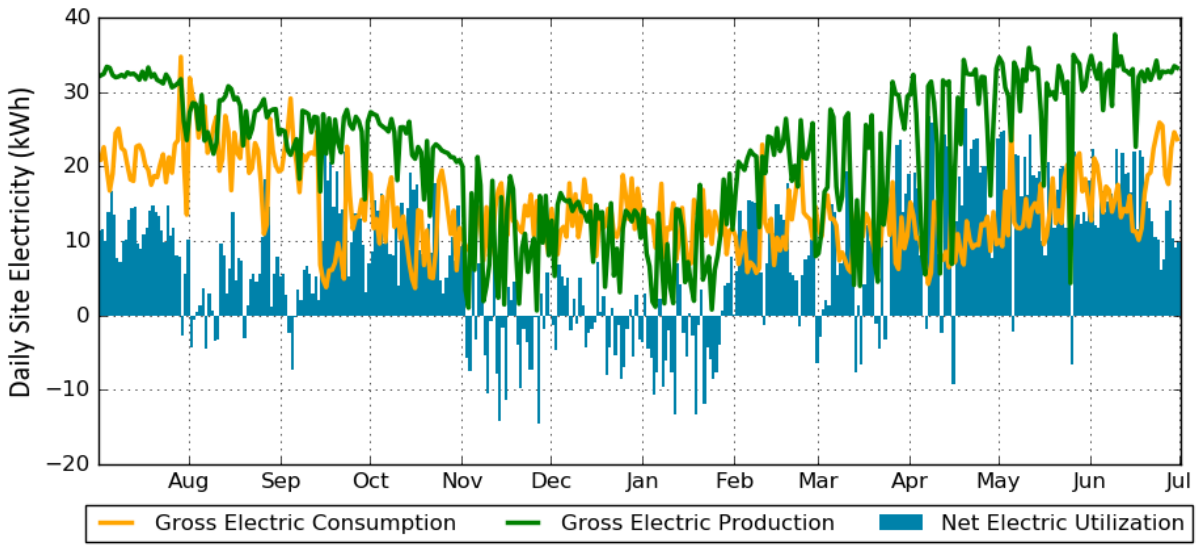

FIGURE 10. DAILY HOUSE ELECTRICAL ENERGY USAGE AND PV GENERATION.

HPWH DETAILED PERFORMANCE MONITORING

The Sanden CO_2 heat pump water heater installed at the site is an emerging technology of interest to PG&E's code readiness effort and future Title 24, Part 6 code proposal development activities. The CO_2 thermodynamic process results in higher efficiencies than conventional HPWH technology utilizing conventional refrigerants. In addition, CO_2 is a natural refrigerant with very low global warming potential. Unlike standard HPWH's, the CO_2 unit does not have backup electric resistance heating to supplement the compressor's heat output. It is a split system with a water storage tank located inside conditioned space with the outdoor unit located outside. Tank water is pumped from the storage tank to the outdoor unit, heated, and hot water is returned to the storage tank.

The monitoring of the unit for this project involved high resolution data collection that allows for detailed performance characterization. The performance of the Sanden unit will be presented in more detail in a separate report. This report provides a snapshot of the performance of the system over the twelve-month monitoring period. Household hot water loads averaged 22.6 gallons per day. The calculated COP for delivering hot water to the storage tank averaged 3.04, with an annual electrical consumption of 716 kWh.

Similar to conventional HPWHs, performance varies with outdoor temperature. Figure 11 plots monthly average efficiency (COP, defined as the energy delivered by the outdoor unit to the storage tank divided by the total energy consumed) as a function of monthly average outdoor temperature. The plotted data are divided into three "seasons" with a clear trend towards improved efficiency at higher outdoor temperatures. With a split system configuration, where the storage tank is decoupled from the outdoor unit, piping energy losses will contribute to increased energy usage. Preliminary calculations indicate that approximately 20% of the system parasitic losses (piping losses plus tank standby losses) are associated with the 33 foot insulated piping run from the outdoor unit to the storage tank.

A forthcoming report on Sanden unit performance will address performance issues in more detail. This report will also be published through the ETCC website in the future.

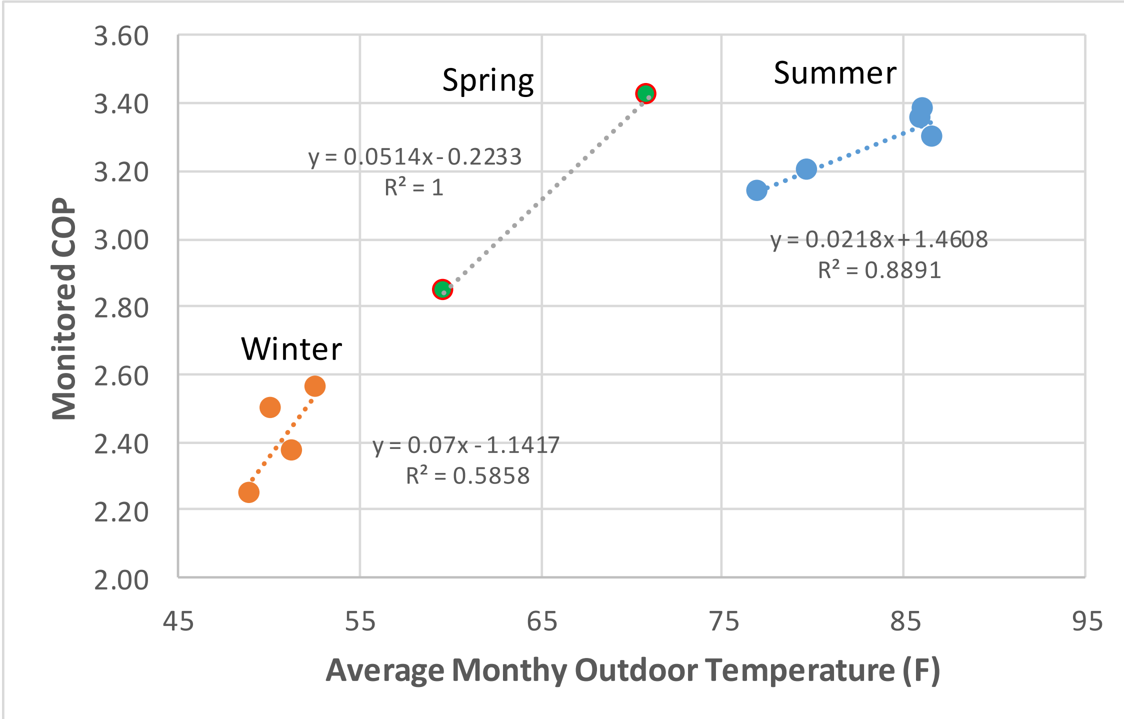

FIGURE 11. AVERAGE MONTHLY COP AS A FUNCTION OF OUTDOOR TEMPERATURE.

COMPARISONS TO SIMULATION MODEL

In cases where detailed end use data is collected for a project, it is always of interest to compare monitored energy use to computer simulation modeled usage. Such an effort can range in scope from simple to complex. For this study and project scope, the team focused on a simple approach. A CBECC-Res 2013 Title 24 compliance model of the house provided by the builder was used. Input variables such as real weather data, actual thermostat setpoints, default occupancy assumptions, and assumed window ventilation usage were not adjusted from the model assumptions.

Figure 12 and Table 9 compare measured electricity use with the CBECC-Res model projections using the Typical Meteorological Year (TMY) weather file used for climate zone 11. On an annual whole-house basis, actual electricity use was approximately 55% lower than modeled. The only end use greater than modeled was cooling (43% higher than modeled), but this can be largely attributed to maintained setpoints about 8-10°F lower than assumed under the compliance model assumptions. All other end uses were 41% to 87% lower than modeled. These large differences may seem surprising but should be viewed from the perspective that the model assumes "typical" usage patterns and occupancy characteristics, while each household is indeed unique.

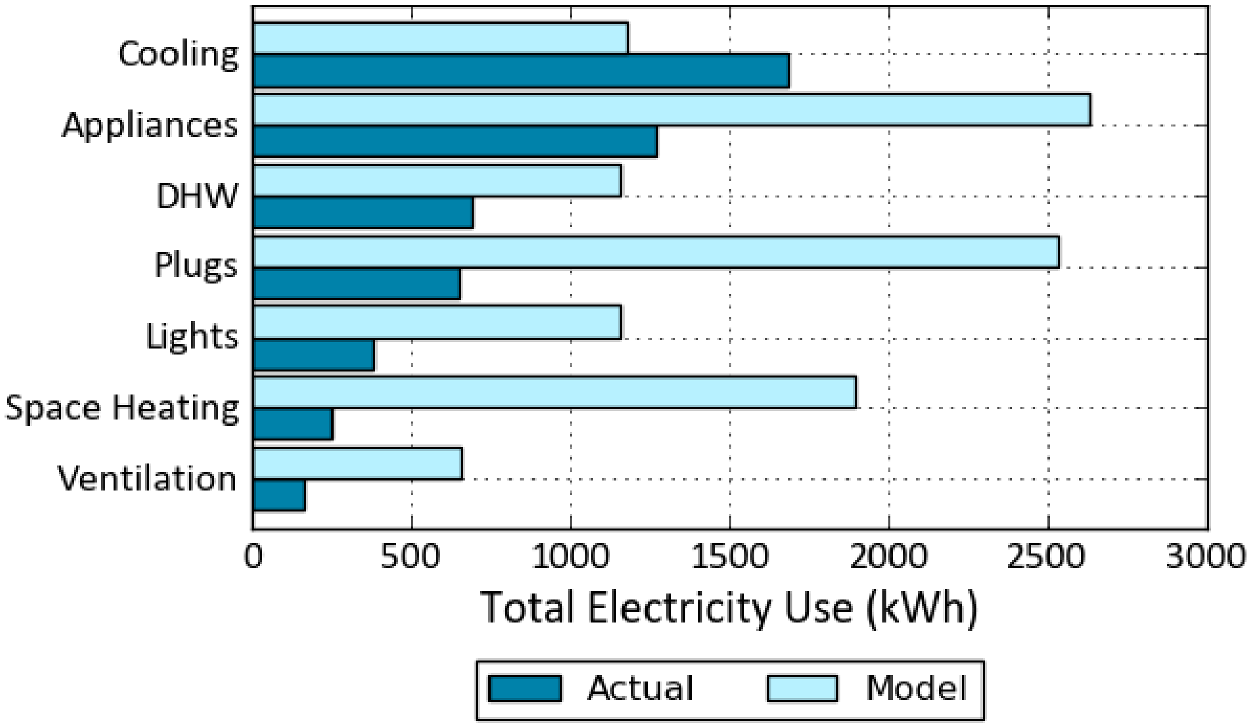

FIGURE 12. COMPARISON OF MONITORED TO MODELED ENERGY USE BY ENERGY SOURCE TYPE.

TABLE 9. COMPARISON OF MONITORED TO MODELED ENRGY USE BY END USE.

END USE CATEGORY	ACTUAL END USES (KWH)	MODELED END USES (KWH)	% DIFFERENCE FROM MODEL
Total	5,089	11,208	-54.6
Space Heating	248	1,893	-86.9
Ventilation	162	657	-75.3
Plugs	654	2,534	-74.2
Lights	382	160	-67.1
Appliances	1,272	2,630	-51.6
Cooling	1,683	1,177	+43.1
DHW	688	1,158	-40.6

CONCLUSIONS

This code readiness effort was focused on assessing the performance of a cutting edge residential project in an extreme California climate. Although the project may not represent what near term mainstream construction practices will be in California, it does show what can be done. The results are quite impressive and point to this home as one of the more impressive California ZNE demonstrations to date. Annual system PV production exceeded household consumption by 52%, which will be applied to offsetting future electric vehicle usage.

Incremental costs over “conventional” construction practice was estimated at $50,906, which includes $10,548 for the 5.32 kW PV system. This upfront expenditure eliminates all house energy bills and also provides excess PV generation for future electric vehicles. Some of the measures could have been done in a less costly manner (e.g. plywood exterior wall sheathing), but from the builder’s viewpoint durability and long-term reliability were key design elements. Successful demonstrated performance of this house has led the builder to move forward with additional projects in the Redding area.

Overall performance as documented by the end use monitoring was quite impressive. Cooling energy use at the extremely low observed indoor conditions amounted to 1,683 kWh/year. With the exception of the cooling energy usage, all other household end uses were 40-80% lower than the compliance model estimates. Overall household monitored energy usage was 55% lower than projected by the compliance model.

In terms of interior comfort, the occupants maintained lower setpoints in both heating and cooling than typically assumed in design models. The inferred setpoints, based on HVAC system operation on the one-minute data intervals, were approximately 70 °F for summer 2017, 65 °F and 63 °F in the winter, and 66 °F in the early summer of 2018. Despite these low cooling setpoints, the ¾-ton ducted mini-split heat pump (serving a house nearly 2,400 ft^2 in size) maintained indoor conditions effectively relative to the setpoints, as evidenced by daily indoor maximum and minimum temperatures always within 3°F of each other.

This project presents a robust case for what can be accomplished in high performance residential construction with thoughtful climate-specific design, careful engineering, and high-level construction practices and system commissioning. Translating all these elements to the mainstream construction industry will be challenging. Some of the measures are not currently cost-effective for a builder to include. Aggressive HVAC equipment sizing to the extent implemented here are not realistic for a production builder who must rely on multiple trades doing all facets of their work properly to even approach the level of downsizing in this project. Even with these limitations, this project is a valuable example of what can be achieved in cutting edge high-performance residential construction.