

All-Electric High-Performance Home: Redding, California Site Monitoring Report

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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, and full year monitored energy end use over a 12-month period for a 2,366 ft² all-electric Zero Net Energy custom home located in Redding, California. As the California Title 24, Part 6 energy code is increasingly moving towards efficient and grid-friendly all-electric homes, this project is an important case study documenting how these homes of the future should perform. In addition, the house was located within the Wildland Urban Interface and incorporated elements to be responsive to building in this environment.

The project was completed with funding support from Pacific Gas and Electric's (PG&E's) Codes and Standards program to document and better understand how best practice residential construction design and implementation can be completed, and what the performance and cost implications are of the design decisions. The builder of this custom home (Mike MacFarland of Energy Docs) is a well-known high-performance building contractor and consultant focused on high-quality residential HVAC and enclosure performance. This project represents his vision of performance-optimized construction for the hot, northern Central Valley with a focus on detailed design, quality construction, and long-term durability. Mr. MacFarland completed detailed design specifications for the home, but relied on local contractors to implement the design, with minimal input and direction from Energy Docs. Findings from the project are useful to showcase what can be achieved in new home construction and provides value for future Title 24, Part 6 code change activities, designer and contractor training curriculum, and possible utility program design.

For this custom home, the photovoltaic system was sized to provide sufficient electrical generation to offset the estimated annual energy usage of this all-electric design (excluding energy use related to homeowner amenities such as in ground pool and hot tub).

In this 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 with blown in blanket fiberglass cavity insulation and R-4 rigid exterior insulation (resulting in an ~R-25 wall)
2. Thermal envelope air sealing: Attention to detail with continuous plywood wall sheathing, taped & sealed air barrier, caulked and foamed. Leakage target of 1.0 ACH50.
3. Attic insulation: R-60 ceiling insulation with radiant barrier; energy heel truss design
4. Raised floor construction with R-19 insulated foundation wall (3 inches of polyisocyanurate)
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 the indirectly conditioned crawlspace contained HVAC equipment and all ducts.
7. HVAC equipment: one ton slim duct mini-split located in crawlspace (equipment sizing at 2,366 ft²/ton)
8. Mechanical ventilation: Heat recovery ventilator located within laundry room closet (heat recovery minimizes ventilation thermal loads on conditioned space and improves air quality due to filtration).

9. Water heating: 1.25 ton CO₂ heat pump water heater (HPWH) with a 3.84 Energy Factor rating; unit is a split system with thermal engine located outside and 83 gallon storage tank centrally located in laundry room to minimize distribution losses.
10. Appliances: All-electric efficient appliances including an induction cooktop and heat pump clothes dryer
11. Lighting: All integrated LED lighting

This work builds on a prior PG&E project completed in 2018¹ when Mr. MacFarland served as the general contractor on a similar sized custom home in Redding where an ultra-high-performance wall system was implemented. The current project intentionally backed off on some of the more aggressive measures implemented in the 2018 project and required the installers to follow detailed framing and HVAC designs without the direct oversight of a leading high performance building contractor .

Builder and Homeowner Feedback

Mike MacFarland provided the following observations as well as feedback from the homeowners on house performance and comfort.

- In terms of working with local tradespeople to implement the design, Mr. MacFarland provided detailed designs, but allowed the contractors to implement the work. For example, detailed stud-by-stud framing plans were provided, and the framing contractor was directed to follow them precisely. Similarly, the plumber was provided with all the non-standard fittings and piping materials specified in the design to avoid any procurement issues for the plumber in not having the specified smaller diameter piping and fittings on hand. The HVAC contractor was a skilled installer with prior experience in high performance installations and was able to implement the design and properly adjust for site variables and any field complications. All of these steps helped improve installation coordination without the need for Mr. MacFarland's on-site supervision.
- From the homeowner's perspective, they were very happy with the energy performance and the comfort level, giving the home an "A" grade. When they first moved in during the summer of 2019, there were a few short intervals on the hottest days of the year (109F and up) that the temperature inside would increase several degrees above setpoint, but that was short lived and hasn't happened since. The 2020 Summer was consistently comfortable with all rooms remaining at similar temperatures. The centrally located water heater with small diameter piping resulted in very fast hot water delivery with less than 10 seconds wait at the master bathroom, and reduced wait times at other bathrooms and kitchen.
- As far as energy code recognition, Mr. MacFarland sees a major disconnect in the ability for energy compliance 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 these three elements resulted in significantly better performance in all areas from building durability, indoor air quality & comfort, and efficiency, as well as meeting WUI constraints.

Monitored Performance

Monitored electrical consumption over the year (August 2019–July 2020) totaled 14,980 kWh with PV generation during that period totaling 12,392 kWh (83% of the way to Zero

¹ <https://www.etcc-ca.com/reports/pge-residential-code-readiness-project-redding-home-site-monitoring-report>

Net Energy (ZNE). Energy usage included 5,426 kWh for “plug” loads (of which 3,486 kWh was used by the pool pump and hot tub). Excluding these two lifestyle choice amenities, the house would have easily achieved ZNE. Space conditioning energy use amounted to only 2,612 kWh for the year, which is impressive for the extreme climate in Redding, which is in Climate Zone 11.

Despite the low summer cooling setpoints selected by the occupants (typically 70°F), indoor conditions were maintained within ± 3 °F of setpoint² for the full duration of the monitoring period. This result is impressive given the HVAC system size and highlights the quality of the HVAC design and implementation.

Key Project Takeaways

This project presents a robust case for what can be accomplished in high performance residential construction with a focus on thoughtful climate-specific design and careful engineering, while relying on local tradespeople to implement the design. Whereas the previous 2018 Redding house represented a cutting-edge integrated design approach with a corresponding level of construction detailing and commissioning in the field, this project was an evolutionary step in moving best practices towards the production home environment. The production home environment would seem to be the logical beneficiary of this strategy as a construction process duplicating identical house plans is well suited to replication based on precise design documentation³. However, it is the author’s impression that in many cases the design community has not been directed to pursue this approach.

The resulting performance of the all-electric ZNE design demonstrates that HVAC and water heating energy use, which are the primary elements the Title 24, Part 6 Standards address, can be effectively targeted, but occupant miscellaneous uses will remain a significant challenge in many cases. The aggressive HVAC equipment sizing demonstrated in this project (and the prior Redding home) are important to highlight as achievable, but this level of equipment right sizing is not realistic for a production builder who must rely on multiple trades doing all facets of their work properly to achieve such significant reductions. Despite these limitations, documenting this project is a valuable example of what can be achieved with high-performance climate-specific design and thorough commissioning.

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

³ It can be argued that the additional design time to create exterior wall framing plan details for the framing crew to successfully implement Advanced Framing is an additional project cost. If Advanced Framing is compared to traditional construction practice, the difference in board feet of exterior wall framing material can be 250% different (30% vs. 12% framing factor), and at [recent lumber pricing](#) of \$1,000/board foot, that added material represents lumber savings of \$2,600 on a 2,400 ft² home similar to this one. For a single custom home, the cost of design would likely match or exceed the value of the lumber saved. However, the lifetime energy cost of additional thermal bridged studs in walls would well exceed the initial cost, meaning a \$10 stud placed into the wall may cost the homeowner an additional \$10 to \$30 in energy expense over only a typical 30-year mortgage term (depending on energy costs, climate, and whether there is an exterior foam layer). For a production builder applying the same framing plan on multiple homes would result in first cost savings proportional to the number of times the plan is built.

INTRODUCTION

This report presents information on the installation, commissioning, and monitoring of a high performance Zero Net Energy (ZNE) custom home built in Redding, California. This home, completed in July 2019, was designed by Mike MacFarland of Energy Docs, who built a prior advanced ZNE Redding that was also evaluated as part of Pacific Gas and Electric Company's (PG&E) Code Readiness program. The earlier home, referred to here foreword as Redding1, was completed in spring 2018 and monitored from the summer of 2018 through the summer of 2019.⁴ Both of these homes are impressive as true all-electric ZNE designs with reasonable photovoltaic sizing, far exceeding the energy performance of typical mixed fuel new homes built under the 2019 Title 24 code which do not address the impacts of gas heating, water heating, and miscellaneous uses.

The key distinctions between Redding1 and the second home (Redding2) are that Mr. MacFarland was intimately involved in all aspects of the Redding1 design and construction process as he served as the general contractor. For Redding2, some of the most aggressive efficiency measures were relaxed or eliminated to improve the cost effectiveness and mainstream construction industry acceptability. In addition, Mr. MacFarland's involvement in the process was limited to design, limited feedback during the construction process, and some diagnostic testing of the completed home.

Although this report concentrates on the Redding2 design and operational performance, the report references aspects of the Redding1 home design and performance where appropriate. Both houses were all-electric designs with a goal of zero net energy for typical expected usage assumptions.

The Redding, California climate is noteworthy as it is one of the more severe summer climate zones within PG&E service territory, and therefore provides a challenging environment to demonstrate the load reduction and aggressive HVAC sizing strategies that Mr. MacFarland employs. The Redding climate has fairly moderate winters (2,556 heating degree days)⁵, but summers are very hot with average July and August maximum temperatures of 97°F or above⁶.

BACKGROUND

PROJECT DESCRIPTION AND LOCATION

The Redding2 home is a 2,366 ft² single story design with four bedrooms and three bathrooms. The project was permitted under the 2016 Title 24 Building Energy Efficiency Standards and constructed between October 2018 and July 2019. The floor plan is shown in Figure 1. The home was built to replace one lost in the 2018 Redding Carr Fire, and since it is located in a Wildland Urban Interface zone, it was designed with fire resistive construction and with extra attention paid to maintaining indoor air quality when outdoor conditions are poor (i.e. fire events). A balanced heat recovery ventilation system combined with high

⁴ https://title24stakeholders.com/wp-content/uploads/2019/06/final_code_readiness_report_redding.pdf

⁵ <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?caredd+nca>

⁶ <http://www.usclimatedata.com/climate/redding/california/united-states/usca0922>

efficiency filter intake⁷ was used to exchange indoor air with filtered outside air for the home and conditioned crawlspace.

The design also included 7.0 kWdc of south-facing photovoltaics in an attempt to fully offset the annual home energy consumption, based on typical assumptions, realizing that the family of four had some energy usage anomalies that would make achieving zero net energy challenging.

A floor plan of the 2,366 ft² single story design is shown in Figure 1. The footprint and floor area are very similar to Redding1 design. The primary design difference between the two houses is the use of a conditioned crawlspace in Redding2, while Redding1 was slab-on-grade construction. Moving to a crawlspace design became more feasible at this site due to significant pre-construction excavation onsite related to Carr Fire clean-up activities. The sealed crawlspace design was therefore easily completed (limited excavation needed) without any added cost relative to conventional slab-on-grade construction. It also allowed for a conditioned mechanical space for centrally locating all HVAC equipment for efficient room air delivery while eliminating distribution system thermal losses.

Normally projects of this type that have a focus on energy efficiency and advanced construction techniques tend to look at costs and cost effectiveness relative to conventional practice as this is the type of information needed to support energy code change proposals. That aspect of the project is deemphasized here with more of the focus on the benefits of an integrated design process that is tailored towards improved energy and comfort performance while simplifying construction processes and therefore achieving cost tradeoffs. A case in point would be the crawlspace design and resulting compact central HVAC design being facilitated by the post- Carr Fire site condition. Mr. MacFarland indicates that the cost of this custom home is in line with conventional custom homes in the area, yet the integrated focus of the design resulted in improved performance.

⁷ A 20" x 20" x 1" filter grille was installed in the outdoor ceiling above the front porch area allowing for various filter types to be installed. During summer/fall wildfire seasons, a high MERV filter was in place and monitored indoor air quality showed a significant reduction in indoor PM 2.5 particles during this time. At other times of the year with good outdoor air quality, less restrictive low MERV filters can be installed which require much less replacement.

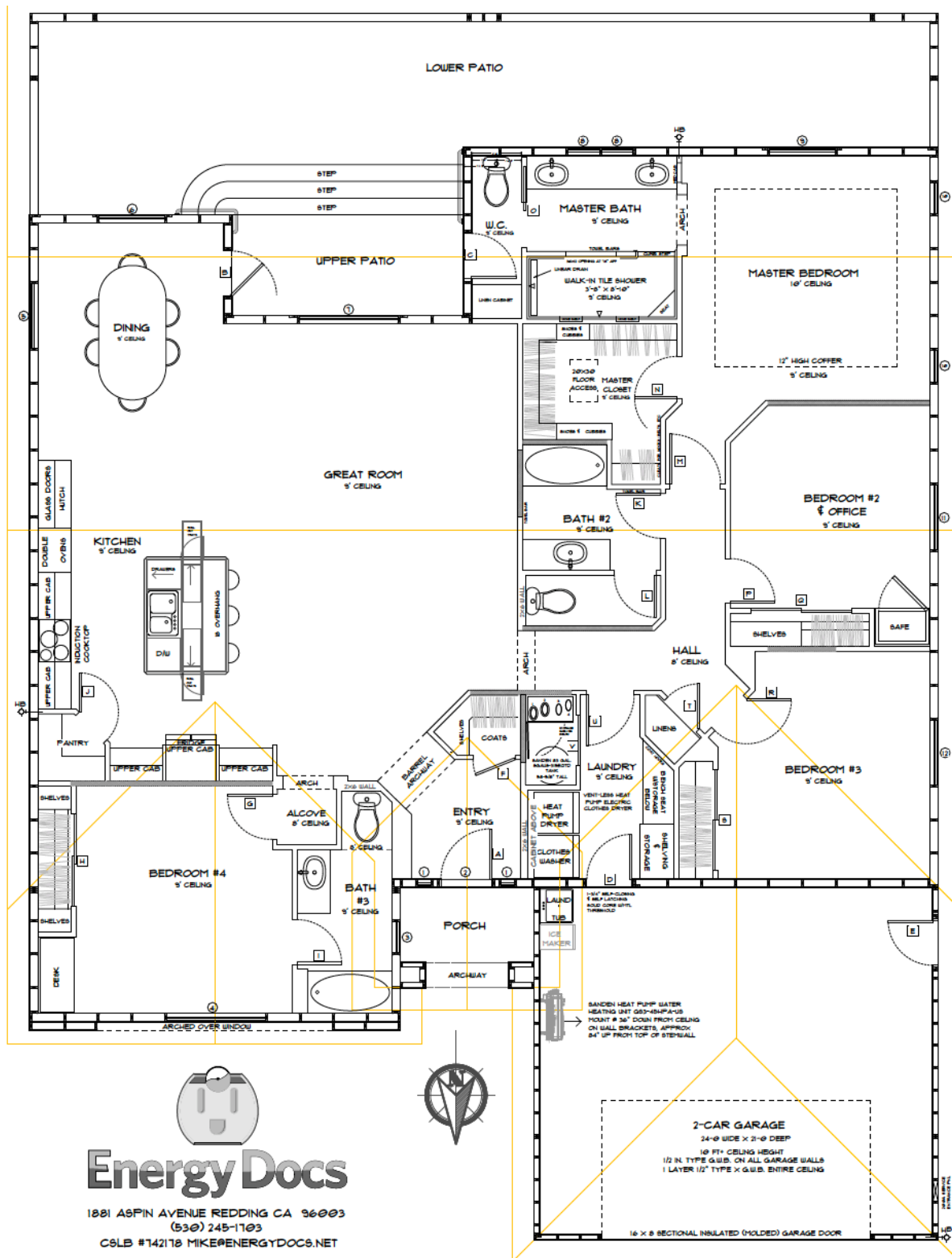


FIGURE 1. REDDING2 HOUSE FLOOR PLAN.

BUILDING AND SYSTEM DESCRIPTIONS

Installed measures in the Redding2 home are compared to current construction specifications (in effect at the time the permit was secured) and also to Redding1 specifications in Table 1 below.

TABLE 1: COMPARISON OF REDDING2 EFFICIENCY MEASURE SPECIFICATION RELATIVE TO TYPICAL DESIGNS AND REDDING1

Measure	Typical Base Specification	Implemented Measure Redding2	Redding1 Measure
Wall Construction	2x6, 16" O.C. construction, R-19 cavity + R-4 rigid exterior; typical 25-30% framing factor	2x6, 24" O.C. (low framing factor); Blown fiberglass in cavity; R-4 rigid exterior insulation (~R-25 wall); detailed framing plan provided for contractor to follow	2x6, 24" O.C. (11.7% framing factor); Stabilized Cellulose in cavity; R-13 rigid exterior insulation (over R-30 wall)
Attic Insulation	R-38 ceiling insulation with radiant barrier	R-60+ ceiling insulation with radiant barrier; energy heel truss design	Same as Redding 2
Slab edge/foundation wall insulation	None	3" Polyiso (R-19) continuous interior foundation wall and 2' perimeter insulation on soil, 4" concrete "rat" slab over 15 mil poly vapor barrier	Slab on grade: 2" Roxul Rockwool exterior rigid insulation on slab edge (R-8)
Air Sealing	Typical air sealing practice results in ~ 5.0 ACH50 envelope leakage level	Continuous plywood wall sheathing, taped & sealed air barrier, caulking/foaming, etc. Leakage at 1.0 ACH50	Continuous plywood wall sheathing, taped & sealed air barrier, caulking/foam, etc. Leakage at 0.52ACH50
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, 2% West Facing	10% glazing area with typical U=0.23-0.25, SHGC=0.20-0.30
Mechanical Equipment Location	Furnace/air handler located in attic (unconditioned)	HVAC and hot water storage tank plus all hot distribution lines located within conditioned space,	Same as Redding2
Heating equipment	Typical 80% AFUE gas furnace	1 ton ducted mini-split heat pump with compact ducts located in conditioned crawlspace (sizing at 2,366 ft2/ton)	¾ ton ducted mini-split heat pump with compact ducts in conditioned mechanical space above
Cooling equipment	Typical 14 SEER/ 11.7 EER with sizing at ~ 600 ft2/ton	1 ton ducted mini-split heat pump with compact ducts located in conditioned crawlspace	¾ ton ducted mini-split heat pump in conditioned mech. space (3,163 SF/ton)
Water heating equipment	Typical 0.60 EF gas storage water heater located in garage	1.25 ton CO ₂ HPWH (3.84 EF) evaporator unit located in attached Garage; 83 gal storage tank in Laundry room mechanical space to minimize piping to use points.	1.25 ton CO ₂ HPWH located outside; 43 gal storage tank in mechanical space to minimize piping
Mechanical Ventilation	Typically bathroom exhaust fans provide airflow meeting ASHRAE 62.2-2013	Heat recovery ventilator with filtered intake for PM 2.5 reductions; system located within conditioned space to minimize thermal loads. Continuous system airflow @ 190% of required.	Same as Redding2
Duct location and leakage	R -8 ducts located in unconditioned space; typical duct leakage of 5%	R-8 ducts in conditioned space; target duct leakage of <1%	Same as Redding2
Appliances	Typically gas cooking/gas dryer; some appliances EnergyStar	All-electric efficient appliances including induction cooktop and ventless heat pump clothes dryer	Same as Redding2

In addition to the energy efficiency measures, photovoltaic systems were installed on each house. Redding1 installed 5.32 kWdc of PV oriented south-southwest, while Redding2 installed 7.0 kWdc of south facing PV.

In terms of the installed measures, the biggest changes between the two house designs can be seen in the wall construction (R-4 exterior insulation in Redding2 vs. R-13 in Redding1) and the use of a perimeter insulated conditioned crawlspace in Redding2 (vs. R-8 edge insulated slab on grade construction in Redding1). Low glazing area (as a percentage of floor area), reduced wall framing factor, ducts in conditioned space, high efficiency heat pump water heating, and a filtered heat recovery ventilator were common to both designs. With a tight, thermally efficient design, and optimized HVAC duct design, both houses achieved aggressive mechanical equipment sizing with Redding1 featuring a ¾ ducted mini-split heat pump, and Redding2 a one ton ducted mini-split heat pump. Conventional air conditioner sizing for this size newly constructed home would more typically fall in the 4 ton range.

CONDITIONED CRAWLSPACE

Crawlspace designs are much less common than slab on grade construction in most of California. This is primarily due to cost and ease of construction. Although the Redding1 house used slab on grade, the gradually sloping Redding2 lot combined with a deep hole left from recent wildfire debris removal made a raised foundation a much more affordable option than it would have normally been. Figure 2 shows the indirectly conditioned crawlspace during construction. A subgrade PVC drainage piping system was installed at the low end of the crawlspace before the installation of the 15 mil polyethylene vapor barrier. Three inches (3") of polyisocyanurate foam (R-19) was attached to the interior side of the foundation walls using 12" carriage bolts. Three inches of R-Max (R-19) was also placed directly on top of the vapor barrier around the perimeter of the home in a 2-foot-wide band to meet the Title 24 insulation requirements for a conditioned crawlspace.



FIGURE 2: CRAWLSPACE PERIMETER INSULATION AND SEALED VAPOR BARRIER

THERMAL ENVELOPE

Exterior framed walls are 2x6 construction (24" on center) and were built utilizing advanced framing techniques. These techniques should result in more than a 50% reduction in wall framing content relative to typical California production home 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%, while the Redding1 house, with similar framing approach, was measured at 11.7%). Framing factors around 15% are considered optimal but are only achieved if the framer aggressively focuses on minimizing excess lumber in the construction of the exterior walls. Most framing contractors are reluctant to 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 reduce lumber use.

Since the framing work was intentionally less supervised than for Redding1, every wall of this high performance home had a detail page similar to Figure 3 so that the framing contractor would have a detailed construction plan to follow. This was a critically important step because tolerances are much tighter on advanced framed walls with single top plates than conventional designs with double top plates. The location of every stud was shown on the floor plan and it was the framing contractor followed the plans precisely. A key element

of a good framing design as shown in Figure 3, is locating and sizing the window width to fit cleanly within planned stud intervals. A final determination of the wall framing factor was not calculated, but it is estimated to be close to the Redding1 level.

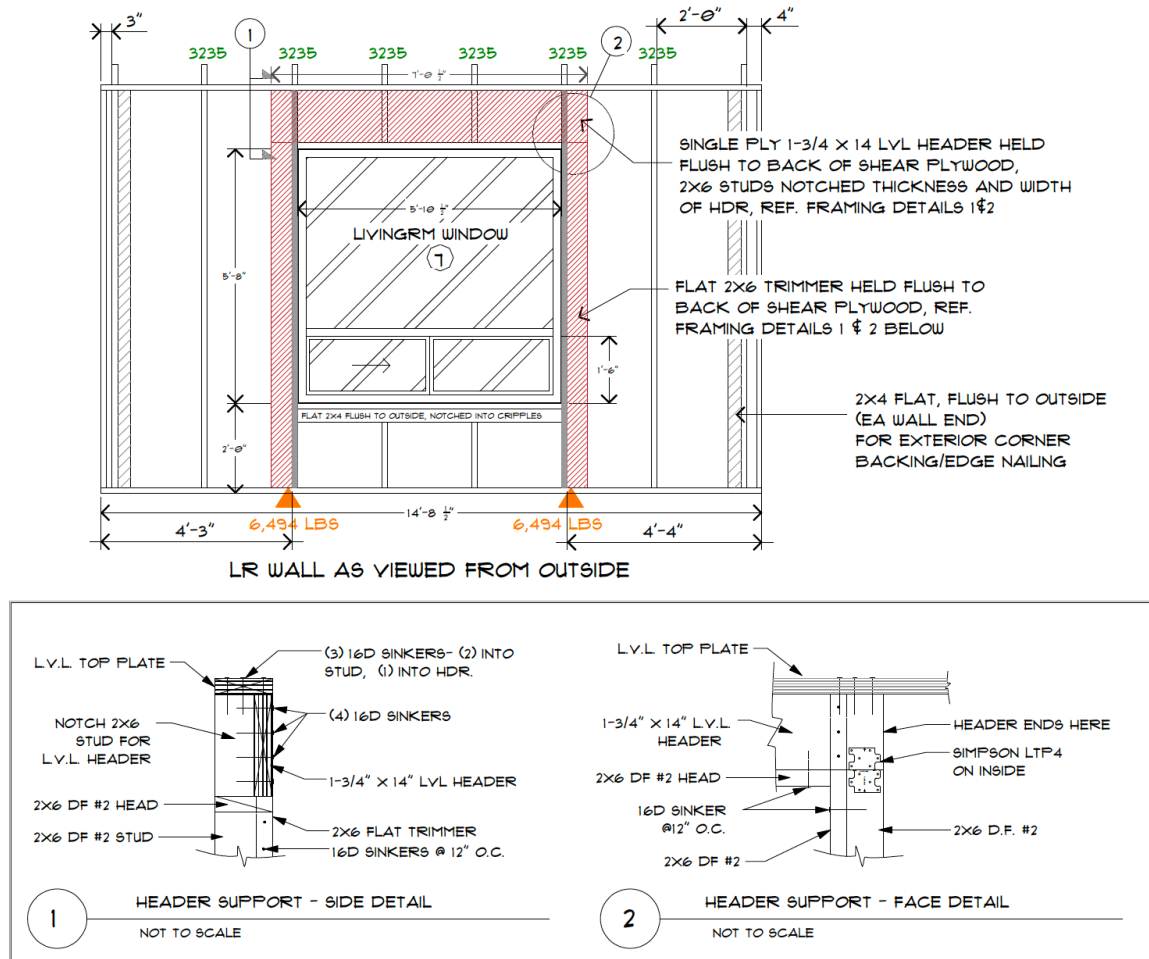


FIGURE 3: TYPICAL WALL FRAMING DOCUMENTATION

The walls were insulated with blown fiberglass in the cavities, and the house was wrapped with one inch of expanded polystyrene (R-4), resulting in a cavity path weighted R-value of about R-25. Significant attention was paid in the framing, air sealing, and insulation process to 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 also installed. Total glazing area was equal to 10% of floor area, which is very low relative to standard production housing which is more commonly in the 15-18% range. Window U-factors range from 0.23 to 0.25, and SHGC ranges from 0.20 to 0.30.

The envelope was air-sealed with a goal of achieving a final blower door measured envelope leakage around 1.0 air changes per hour at a 50 (ACH50) Pa pressure differential. The attention to detail was not as high as Redding1, despite Mr. MacFarland conveying the air-

sealing process to the workers. California production housing envelope leakage 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 1.0 ton Mitsubishi ducted mini-split heat pump (SEZ-KD12NA4 Indoor Unit, SUZ-KA12NA Outdoor unit), rated at 10.0 HSPF and 16.0 SEER, with short duct runs all located in conditioned space. The one ton sizing for this house size, results in an impressive cooling design sizing of over 2,300 ft²/ton. This compares to industry standard HVAC contractor design practice with air conditioner sizing in the range of 600-800 ft²/ton.

Mechanical and Fresh Air Ventilation: Mechanical ventilation is provided by a Broan HRV200TE heat recovery ventilation device located in the laundry room. 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.

Water Heating: Domestic hot water is provided by a Sanden heat pump water heater (HPWH) that utilizes CO₂ as the working refrigerant. The 83-gallon Sanden CO₂ unit (model number GS3-83SSAQA) is rated at a 5.0 COP and 3.84 Energy Factor. Unlike in Redding1, where the outdoor unit was in the back of the house, the Redding2 unit was installed high up in the garage (as shown in Figure 4) to take advantage of warmer inlet air conditions. This location also allows for the cooler exhaust air from the unit to naturally fall downwards, avoiding any possibility of inlet air contamination.⁸

⁸ Whereby cool exhaust air can recirculate contributing to lower evaporator inlet temperatures and operating efficiency.



FIGURE 4: SANDEN EVAPORATOR UNIT GARAGE LOCATION

LIGHTING AND APPLIANCES

The home incorporates all high-efficacy LED lighting meeting the 2016 Title 24, Part 6 code requirements throughout the home. 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	PT9551SLSS
Microwave/Hood	General Electric	PVM9005SJSS
Refrigerator	General Electric	PFE28PSKSS
Clothes Washer	Whirlpool	WFW8620HW
Clothes Dryer	Whirlpool	WHD560CH
Dishwasher	General Electric	GDT695SSJSS
Garbage Disposal	Insinkerator	Contractor 333-1

PHOTOVOLTAIC SYSTEM

The 7.0 kWdc solar electric system consists of 20 Solaria Power XT 350R-AC modules and 20 Enphase IQ7+ Microinverters. The PV system was sized to offset anticipated annual energy use, not accounting for added features including a hot tub and an in-ground pool.

ASSESSMENT OBJECTIVES

The primary evaluation objective of the project was to document energy performance over a one-year period and provide information on measure cost and installation feasibility.

Additional details of the evaluation include:

1. Measure whole building energy consumption, as well as PV production.
2. Document the end use breakdowns for space conditioning, water heating, lighting, plug loads, and appliances and look at seasonal variations.
3. Compare Redding1 and Redding2 energy use to qualitatively inform how occupancy, use patterns, and house design may impact results.
4. Collect input on constructability, commissioning concerns, and homeowner feedback.

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. The electrical panel layout shown in Figure 5 was intentionally disaggregated to a greater degree than normally found in new homes to better support the monitoring objectives of the project.

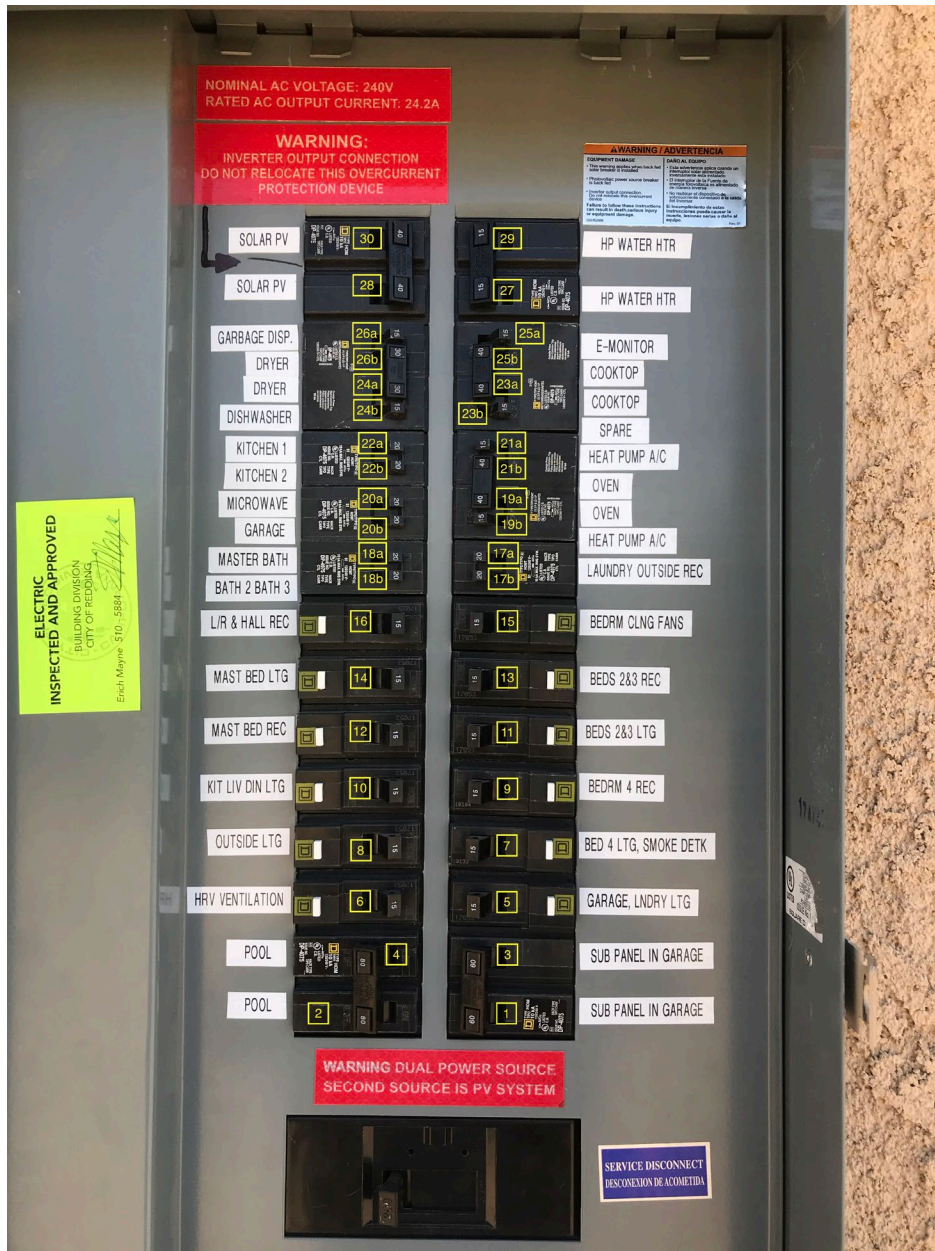


FIGURE 5: 200A SERVICE ENTRANCE PANEL

FIELD MONITORING PROCESS

The house was first occupied in July 2019. Monitoring formally began on August 1, 2019 to avoid any start-up anomalies often seen around initial house occupancy. The home was occupied throughout monitoring by a family of four with two adults (one working part time) and two teenagers.

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. Table 3 lists all the measurement points that were monitored on a continuous basis.

TABLE 3. MEASUREMENT POINTS.

Category	Description	Type	Location
Solar	Solar PV	50A CT	Main Panel
Mains	Mains	150A CT	Main Panel
Appliances	Heat Pump Clothes Dryer	50A CT	Main Panel
	Clothes Washer and Laundry Room Plugs	20A CT	Main Panel
	Garbage Disposal	20A CT	Main Panel
	Dishwasher	20A CT	Main Panel
	Refrigerator and Island Plugs	20A CT	Main Panel
Cooking	Induction Cooktop	50A CT	Main Panel
	Oven	50A CT	Main Panel
	Microwave and Range Fan	20A CT	Main Panel
DHW	Heat Pump Water Heater	20A CT	Main Panel
HVAC	Ceiling Fans	20A CT	Main Panel
	HRV	20A CT	Main Panel
	Heat Pump AC	20A CT	Main Panel
	Temperature in Return Plenum	IC	Hallway
	Temperature in Supply Plenum	IC	Hallway
Plugs	Pool Pump	50A CT	Pool Sub Panel
	Hot Tub and RV	50A CT	Garage Sub Panel
	Garage	20A CT	Main Panel
	Bathrooms 2 and 3	20A CT	Main Panel
	Bedrooms 2 and 3	20A CT	Main Panel
	Bedroom 4	20A CT	Main Panel
	Kitchen Circuit 2	20A CT	Main Panel
	Livingroom and Hallway	20A CT	Main Panel
	Master Bedroom	20A CT	Main Panel
	Master Bathroom	20A CT	Main Panel
	Outdoor	20A CT	Main Panel
	Bedrooms 2 and 3	20A CT	Main Panel
	Bedroom 4 Lighting, Smoke Detector, and Ceiling Fan	20A CT	Main Panel
Hardwired Lighting	Garage and Laundry Room	20A CT	Main Panel
	Kitchen, Living Room, and Dining Room	20A CT	Main Panel
	Master Bedroom	20A CT	Main Panel
	Outdoor Lighting and Fans	20A CT	Main Panel

The Frontier Energy monitoring server automatically collected data from the site at regular intervals, stored the data on a secure server, checked the data for out of range conditions, and automatically notified Frontier staff on the 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 (heating or cooling).

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 was 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 was installed and connected to the internet via the homeowners WiFi. 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.

SENSOR TYPES AND SPECIFICATIONS

Table 4 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 2019, 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 4. 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

RESULTS

The following results presentation focuses on the energy end use data, indoor setpoints and comfort, and builder reported costs for the installed advanced measures.

The scope of the evaluation presented here is intended as a high-level performance summary. The one-minute interval SiteSage data collected during the full year monitoring period offers a wealth of information that could be further analyzed in more detail.

INCREMENTAL COST OVERVIEW

Table 5 summarize key incremental costs as estimated by Mike MacFarland. This comes with a caveat as Mr. MacFarland feels that site conditions and homeowner budget target defined the scope and direction of the design, which complicates a comparison to industry standard practice. With an integrated design approach, intelligent out-of-the-box decisions often impact other measures and associated costs. For example, working with the site conditions to economically integrate a conditioned crawlspace area with mechanical equipment centrally located facilitated a compact (and effective) duct installation which contributed to equipment downsizing, improved comfort, and reduced energy consumption.

Mike estimates that the ~150 incremental labor construction hours (both homeowner and contractor) expended represents an approximate 15% increase in time over industry standard construction practice for a house of this size and design. Overall project incremental costs of \$27,253 include the PV system cost, which represents about 2/3 of the total estimated added cost. Excluding the PV system costs, total incremental costs for the Redding2 design are estimated at \$8,815 (\$5,865 materials and \$2,950 labor). The elimination of gas service to the site represents an approximate \$4,000 cost savings due to

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excavation costs and costs associated with gas piping and venting of gas appliances. The fully sheathed exterior wall costs can be viewed as a zero-cost item since the City of Redding Building Department requires continuous exterior sheathing as a fire mitigation measure.

TABLE 5. SUMMARY OF BUILDER REPORTED MEASURE INCREMENTAL COSTS.

Measure	Incremental Labor Cost	Incremental Material Cost	Incremental Cost
Energy heel on trusses	\$ 400	\$ 250	\$ 650
R-38 upgrade to R-60 attic insulation	\$ 250	\$ 600	\$ 850
Fully sheathed exterior for continuous air barrier	\$ 2,400	\$ 1,900	\$ 4,300
Air barrier tape on exterior sheathing	\$ 240	\$ 120	\$ 360
Attic air sealing	\$ 560	\$ 120	\$ 680
Sanden Heat Pump Water Heater, plumbing	\$ 500	\$ 2,950	\$ 3,450
No gas service* (no gas lines or vents)	\$ (3,800)	\$ (500)	\$ (4,300)
Mechanical- ducted heat recovery ventilation (HRV) system	\$ 1,600	\$ 1,925	\$ 3,525
Solar PV- 7.0 kW	\$ 2,500	\$ 15,938	\$ 18,438
Smaller HVAC System, Heat Pump, less ductwork	\$ 800	\$ (1,500)	\$ (700)
Overall Incremental Cost	\$ 5,450	\$ 21,803	\$ 27,253
Total, excluding solar PV costs	\$ 2,950	\$ 5,865	\$ 8,815

Note: * Costs are estimated by Mr. MacFarland. PG&E waived gas service connection costs for Carr Fire victims.

BUILDING COMMISSIONING

A summary of diagnostic test results is provided here.

- Building envelope leakage: Measured leakage during the final blower door test was found to be 507 CFM50 equal to an envelope air leakage rate of 1.0 ACH50 based on 30,166 ft³ volume (conditioned crawlspace plus conditioned living area).
- Duct leakage test (HERS rater result): 5% total duct leakage = 20 CFM25 out of a total maximum airflow of 403 CFM with all leakage within conditioned space.
- Heat pump indoor fan efficacy measured at 0.25 W/CFM during maximum system airflow (100 W total).
- Total external static pressure of 0.18" (manufacturer limit of 0.20") with MERV 9 filter when measured at maximum system airflow (403 CFM/ton).
- Heat recovery ventilation system ducted into every bedroom and main living space, exhausting from bathrooms and crawlspace. System airflow verified at 190% of code minimum/ASHRAE 62.2 continuous whole building ventilation rate (116 CFM vs 61 CFM minimum) for improved IAQ.

In comparing these results to Redding1, the main differences are:

- Airtightness: Redding1 has about half the envelope leakage of Redding2 at the 50 Pa pressure differential (1.0 vs 0.5 ACH50).
- Exterior wall insulation: Redding1 has higher levels of wall insulation with the 2" Polyiso exterior foam and fully ventilated cladding with $\frac{3}{4}$ airspace, but at a much higher cost. The Redding2 wall construction is considerably more approachable for the production home builder.
- Foundation: the Redding1 slab on grade has exterior insulation vs. Redding2 with a raised floor foundation with interior insulation.
- Space conditioning: Redding1 has a $\frac{3}{4}$ ton ducted mini-split heat pump and Redding2 uses a different brand and a slightly larger one ton slim-duct heat pump.

ELECTRICAL ENERGY MONITORING RESULTS

With the SiteSage system installed and end uses disaggregated to a high level, it is possible to get a precise picture of energy usage by end use as well as the usage patterns. One-minute interval data logging provides a wealth of information. While this data is available for other uses such as PG&E's Residential Building Stock Assessment effort, for the scope of this report, the authors chose to focus on aggregated results. The following section provides tabular and graphical presentation of the Redding2 data over the course of the August 2019 to July 2020 monitoring period. Total consumption over the year amounted to 14,980 kWh with PV generation for the year totaling 12,392 kWh (83% to ZNE).

The following energy use results are presented in both graphical and tabular format. Both Redding1 and Redding 2 data are provided to allow for comparison, realizing that difference occupancy levels and amenities play a large role in defining energy usage.

Figure 6 presents the electrical energy consumption data over the full monitoring period in bar chart format with Redding1 data plotted above Redding2 data for comparison. Most striking is the variation in Plug Loads which is nearly a factor of ten higher for Redding2. This speaks highly to how household choices in auxiliary equipment (i.e. pools, hot tubs, etc.) can strongly influence usage.

Cooling, heating, DHW, and ventilation are all reasonably comparable for the two sites. Similar to Redding1, Redding2 cooling energy usage exceeds heating energy use by a factor of five or more.

Table 6 and 7 present the data in tabular form. For Redding2 plug loads and non-cooking appliances represent over half of the usage. Cooling, heating, and DHW are less than 25% of total usage, as compared to just over 50% of usage for Redding1. Major Plug load end uses include the hot tub and a pool (shown as a subset of Plug Loads), which total nearly 3,500 kWh/year. If these end uses were not installed, the home would have achieved ZNE for the year (108% ZNE).

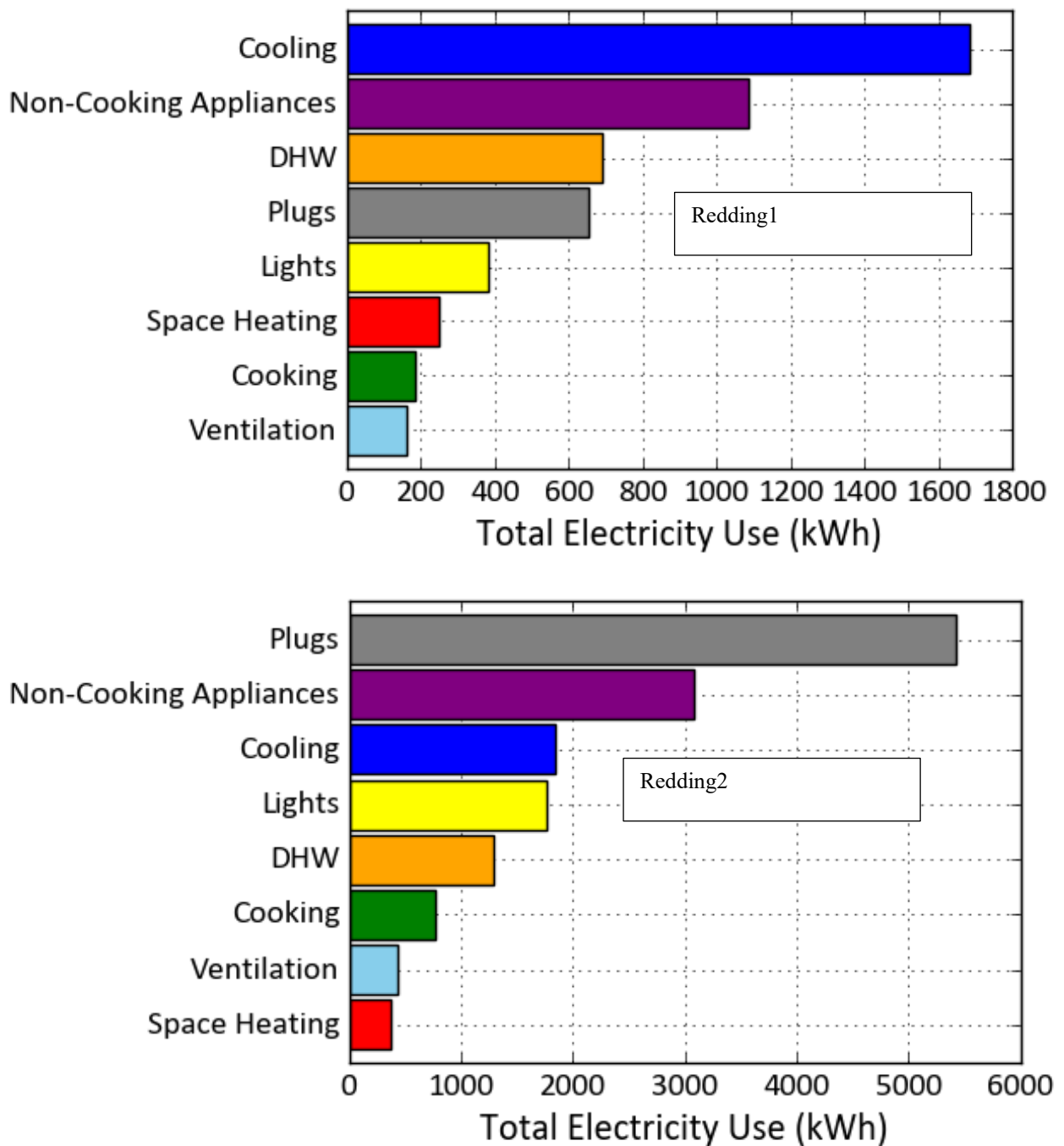


FIGURE 6. MONITORED ELECTRICAL END USES (TOP = REDDING1, BOTTOM = REDDING2).

Note: Key highlights in comparing data in Figure 6. For Redding 2 vs 1: Considerably more laundry (clothes washer and dryer), cooking usage, and lighting (all presumably due to household size of 4 vs 2), and presence of pool and hot tub which totaled nearly 3,500 kWh.

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TABLE 6. ELECTRICAL ENERGY CONSUMPTION COMPARISON BY END USE (REDDING1 AND REDDING2).

END USE CATEGORY	REDDING1		REDDING2	
	ELECTRICITY USE (kWh)	% ELECTRICITY USE OF TOTAL	ELECTRICITY USE (kWh)	% ELECTRICITY USE OF TOTAL
Cooling	1,683	33	1,845	12
Non-Cooking Appliances	1,087	21	3,079	21
DHW	688	13	1,288	9
Plugs	653	13	5,426	36
Hot Tub	0	0	1,903	13
Pool	0	0	1,583	11
Lights	382	8	1,767	12
Space Heating	248	5	767	5
Cooking	184	4	437	3
Ventilation	162	3	369	2

Appliance end uses for the two houses are further broken down in Table 7. For Redding2, the heat pump clothes dryer is the largest appliance end use at 36% of all appliance electrical consumption. The annual usage is nearly four times higher than Redding1 reflecting the larger household size, as well as higher laundry needs. Kitchen cooking usage also is considerably larger for Redding2 (oven, dishwasher, island plugs).

TABLE 7. BREAKDOWN OF APPLIANCE ELECTRICAL ENERGY CONSUMPTION (REDDING1 AND REDDING2).

APPLIANCE	Redding1		Redding2	
	ELECTRICITY USE (kWh)	% OF TOTAL USE	ELECTRICITY USE (kWh)	% OF TOTAL USE
Refrigerator and Island Plugs	623	12.2	1,234	8.2
Heat Pump Clothes Dryer	339	6.7	1,380	9.2
Oven	116	2.3	451	3.0
Dishwasher	103	2.0	305	2.0
Cooktop	50	1.0	180	1.2
Clothes Washer	21	0.4	159	1.1
Microwave	19	0.4	136	0.9

Figure 7 presents a stacked bar plot of monthly energy consumption for all end use categories. Redding2 usage shows much less seasonal variability than Redding1 due to high and fairly constant plug loads and non-cooking appliances. Redding2 monthly data clearly highlights the magnitude of non-standard end uses not associated with space conditioning and water heating in otherwise highly efficient new homes.

Figure 8 breaks down monthly occupant-supplied plug loads in detail. For Redding2, plug loads are dominated by four circuits: Living Room/Dining Room/Foyer, Hot Tub/RV⁹, Pool¹⁰, and Garage. These four represent over 80% of the house's plug load usage over the year.

⁹ Mike MacFarland communications with the owners suggested the RV contribution to this end use was minimal.

¹⁰ After commissioning of the pool by the pool contractor prior to the 8/1/19 monitoring start up, Mr. MacFarland reduced circulation times to further improve the energy performance of the variable speed pool pump.

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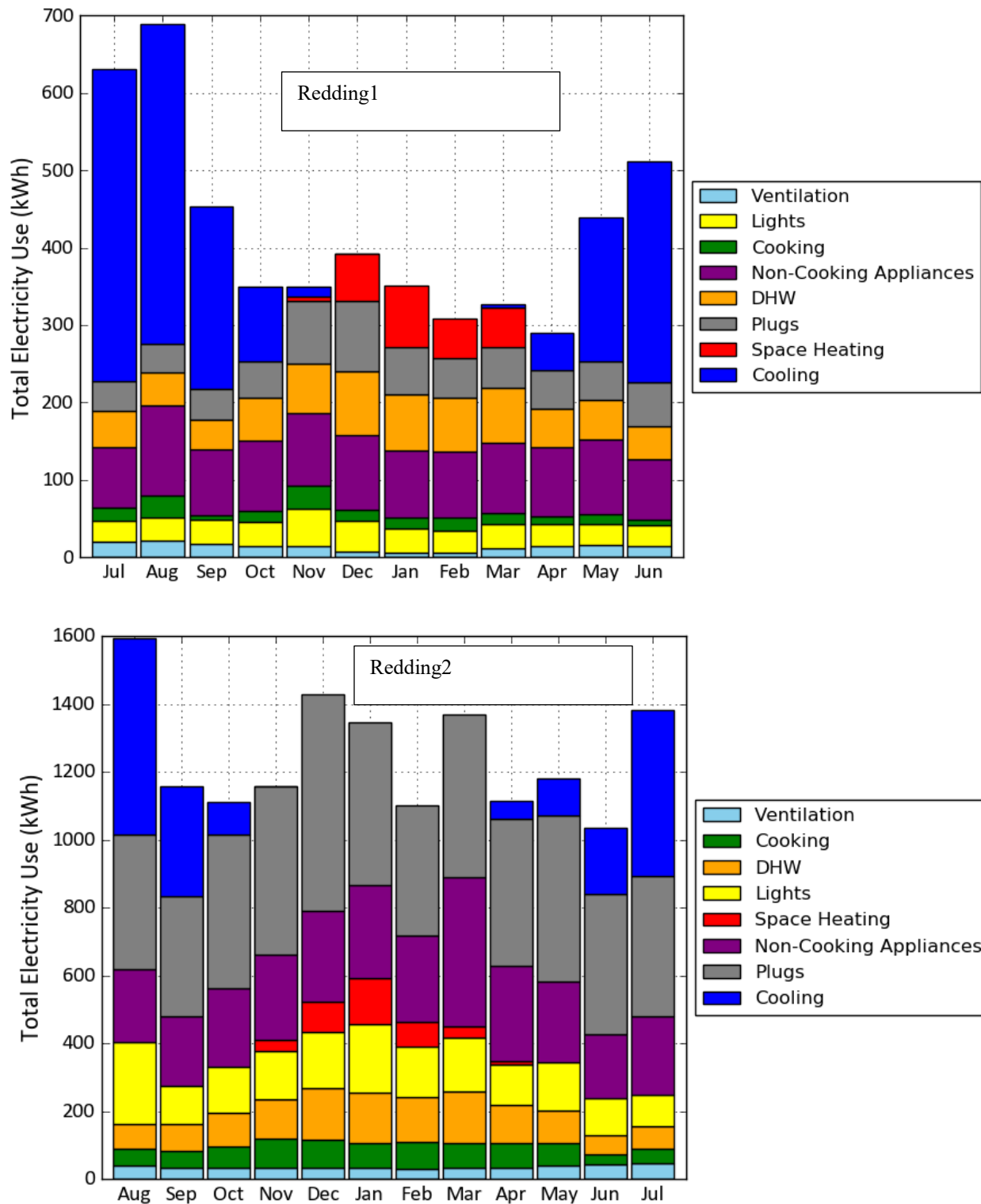


FIGURE 7. MONTHLY ELECTRICAL ENERGY CONSUMPTION (TOP = REDDING1, BOTTOM = REDDING2).

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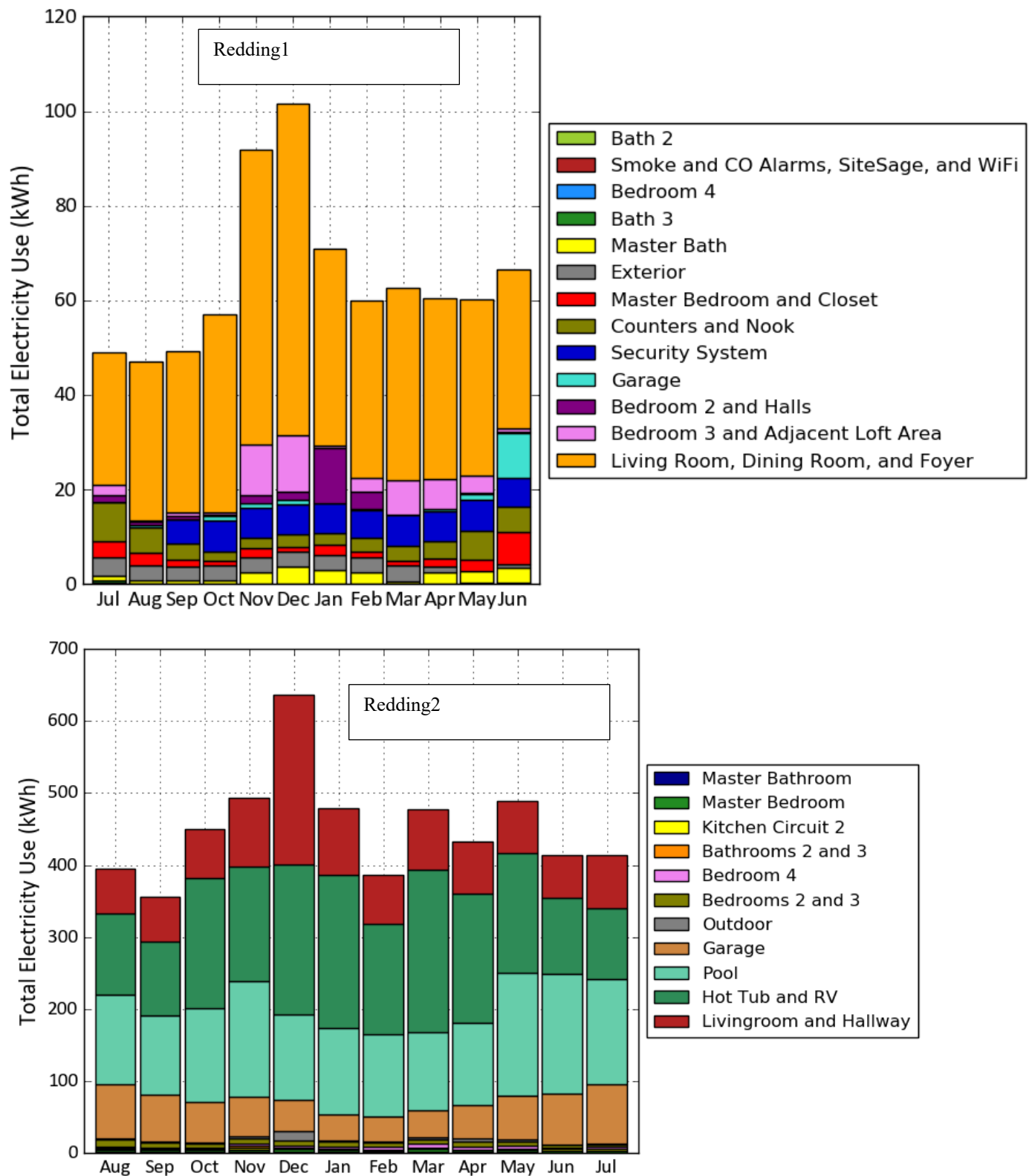


FIGURE 8. MONTHLY ELECTRICITY PLUG LOAD BREAKDOWN (TOP = REDDING1, BOTTOM = REDDING2).

Figure 9 and Figure 10 show daily energy consumption by end use superimposed above daily outdoor temperature profiles for Redding1 and Redding2, respectively. On a daily level, it is possible to see more of the natural variability in HVAC, plug, appliance and lighting loads. The lower portion of the graph shows heating and cooling energy usage by day. Both sites maintained setpoints throughout the year at a mean indoor temperature close to 70°F (green line in bottom plot).

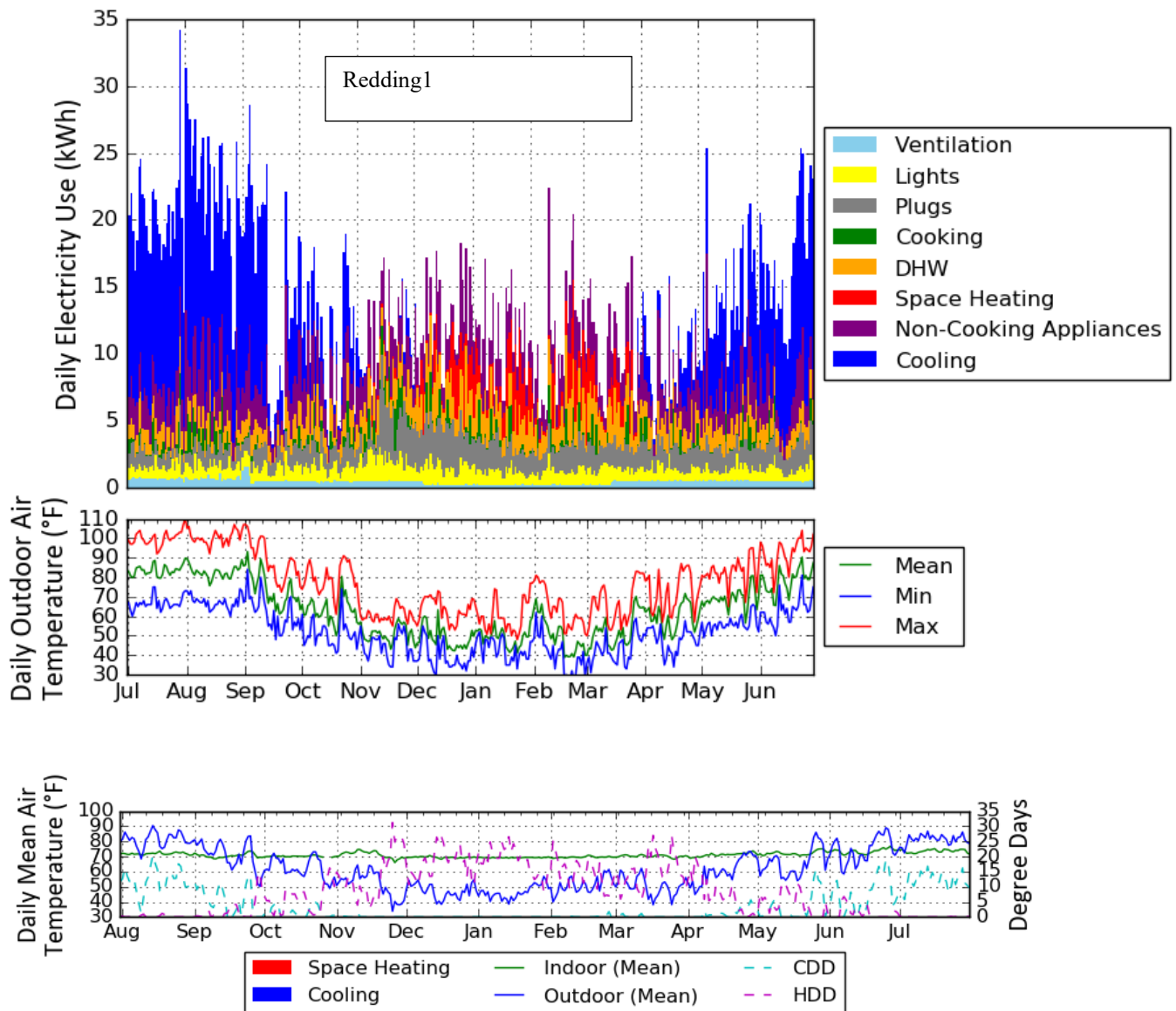


FIGURE 9. REDDING1 DAILY ENERGY USAGE BY END USE WITH INDOOR AND OUTDOOR TEMPERATURE PROFILES.

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Redding2's peak indoor temperature during a June 2020 heat spell approached 78°F, on a day with a maximum outdoor temperature of 110°F.

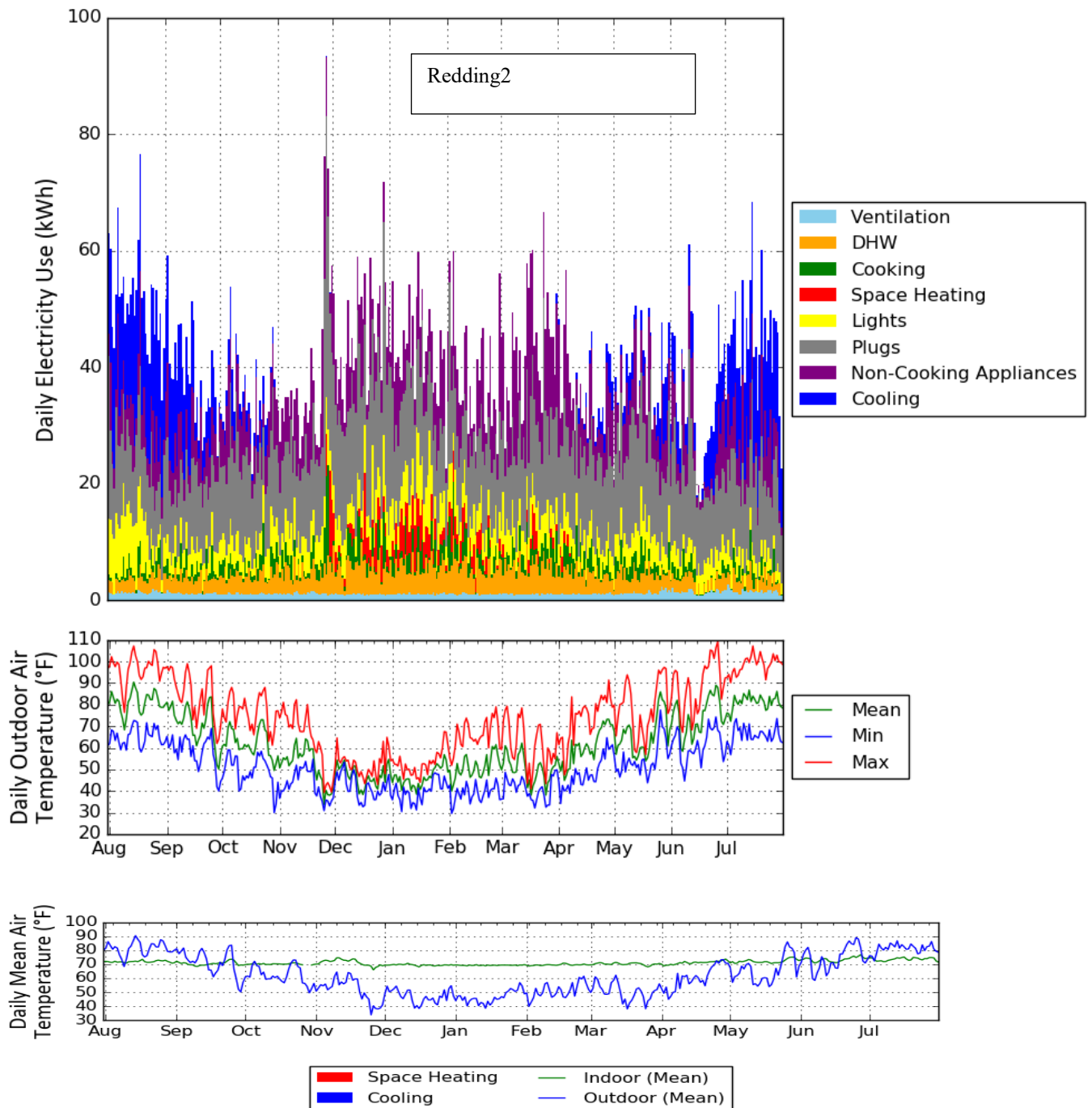


FIGURE 10. REDDING2 DAILY ENERGY USAGE BY END USE WITH INDOOR AND OUTDOOR TEMPERATURE PROFILES.

PV SYSTEM PERFORMANCE

Figure 11 presents Redding2 daily PV production relative to total daily household electrical energy consumption with values exceeding 0 kWh indicating a net daily delivery to the grid. For Redding2 energy consumption for the year totaled 14,980 kWh and PV production totaled 12,392 kWh (as compared to Redding1 where usage was 5,291 kWh and PV production totaled 8,052 kWh). During this period, the PV system offset 83% of the home's electricity use (relative to 152% for Redding1). The pattern of usage and generation shown in Figure 8 indicates that the Redding2 site was sporadic in being a positive contributor to the grid for much of the year, with the exception of mid-winter months when daily consumption consistently exceeded PV output.

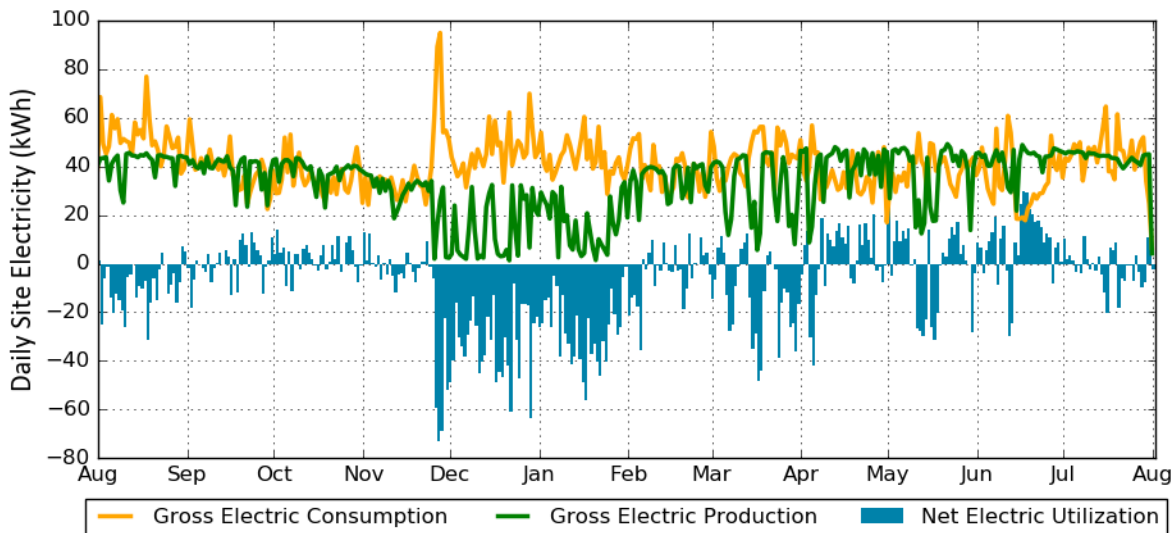


FIGURE 11. DAILY HOUSE ELECTRICAL ENERGY USAGE, PV GENERATION, AND NET IMPACT ON GRID.

CONCLUSIONS

This project was focused on assessing the performance and costs of a high performance all-electric home design in the Redding climate, while relaxing some of the energy efficiency stringency found in the Redding1 home. The implemented Redding2 design, in many respects represents what could be achievable from production builders with more careful designs and attention to construction details. The aggressive (i.e. right-sized) HVAC equipment sizings (i.e. high ft²/ton) demonstrated in both Redding1 and 2 are quite impressive, but would be challenging for production builders to implement given higher liability concerns, uncertainty on how occupants will operate the homes, and the general uncertainty the HVAC contractor must assume on construction quality elements outside their control. Although the HVAC sizing was intentionally aggressive in order to demonstrate what can be achieved, there is nothing to suggest that more conservative sizing (as low as 1,200 ft²/ton, or ~2 tons for this house) would negatively impact the measured results.

Nevertheless, intelligent HVAC designs with compact distribution systems with ducts in conditioned space, and carefully tuned airflows are an effective strategy in advanced HVAC designs and should be achievable in production home environments where design costs can

be shared over many houses of the same floor plan. Likewise, the construction team can easily repeat duct (or framing) layouts from one house to the next identical house. Compact centralized water heater designs with short “right sized” piping provides rapid hot water delivery to all use points without the need for a more complicated hot water recirculation system. Both measures contribute to higher owner comfort satisfaction, an important goal for any production builder.

Considering that the Redding2 home is continuously comfortable with full time occupancy, and over 100% of the annual energy consumption (excluding pool and hot tub) is produced on site with a modest sized solar array, this becomes an example of true ZNE all-electric construction that the building industry is capable of providing today.

To achieve results like these, conventional practices must change in residential construction of leaving the enclosure, HVAC and hot water system design, installation and commissioning up to subcontractors. Although many tradespeople have gone through utility or third party sponsored “quality” construction training programs, the lack of a consistent design ethos centered around these principles complicates the delivery of improved residential building performance. For example, a framing contractor cannot elect to apply advanced framing to a conventionally designed home, since advanced framing is a holistic design process. This project illustrates that while the residential construction industry appears capable of building these high performance all-electric homes today, it is the design community and other industries that need further evolution in high performance design and building performance documentation for these to become more commonplace.