BUILDING TECHNOLOGIES PROGRAM

Sonoma House: Monitoring of the First U.S. Passive House Retrofit

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December 2012

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Definitions

AC	Air conditioner
ACH	Air change per hour
ARBI	Alliance for Residential Building Innovation
Btu	British thermal unit
CARB	Consortium for Advanced Residential Buildings
CDD	Cooling degree days
CFL	Compact fluorescent lamp
CFM	Cubic feet per minute
COP	Coefficient of performance
DEG	Davis Energy Group
DHW	Domestic hot water
EEM	Energy efficiency measure
EER	Energy efficiency ratio
EF	Energy Factor
ERV	Energy Recovery Ventilator
HDD	Heating degree days
HERS	Home Energy Rating System
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, ventilation, and air conditioning
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light emitting diode
MEL	Miscellaneous electric load
PH	Passive House
PV	Photovoltaic system
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SRCC	Solar Rating and Certification Corporation
TMY3	Typical Meteorological Year 3 (weather data set)

Foreword

The Sonoma Deep Retrofit is a single story deep retrofit project in the marine climate of Sonoma, California. The design was guided by Passive House (PH) principles, which promote the use of very high levels of wall, ceiling, and floor insulation along with tight envelope construction to maintain a comfortable indoor environment with little or no need for conventional heating or cooling. These concepts are gaining increasing attention and traction in California from custom home builders and may present an avenue for builders to reach Building America Program Management Milestone (PMM) goals. This research project presents a unique opportunity to both identify and evaluate deep retrofit measures that are practical and potentially cost effective for the retrofit market, as well as review the cost effectiveness of the PH design approach for achieving energy savings in deep retrofits. The Sonoma House was monitored both at the building and system level over one year to verify expected savings and system performance. The Sonoma house is the first certified PH in California, and the first PH retrofit in the United States. Source energy savings are estimated at 56% compared to the pre-retrofit case.

Acknowledgements

Davis Energy Group would like to acknowledge the U. S. Department of Energy Building America program and their funding and support of development of this technical report as well as research that informed it. In addition, we would like to thank the builder Rick Milburn of PassivWorks, formerly Solar Knights Construction, for his cooperation throughout the design, construction, and monitoring stages of this project. We would also like to acknowledge Lawrence Berkeley National Laboratory, who worked with Davis Energy Group to provide additional monitoring data for total and net building electricity use and PV production.

1 Introduction

1.1 Background and Motivation

Builder Rick Milburn of PassivWorks[1] of Napa, California, formerly Solar Knights Construction, collaborated with a building owner to develop a plan for retrofitting an existing house in Sonoma to Passive House (PH) program standards[2]. The PH concept uses very high levels of wall, ceiling, and floor insulation along with tight envelope construction to maintain a comfortable indoor environment with little or no need for conventional heating or cooling.

Davis Energy Group (DEG), technical lead for Building America research team Alliance for Residential Building Innovation (ARBI), adopted the project as a Building America deep retrofit opportunity. The goal was to identify and evaluate retrofit measure packages that achieve significant energy savings over pre-retrofit conditions and that are practical and potentially cost effective for the retrofit market. In addition, the project afforded the chance to review the PH design approach as a Building America strategy. The Sonoma house is the first certified PH in California, and the first PH retrofit in the United States.

Gaps and barriers related to high performance building envelopes and low load homes identified by the Building America Space Conditioning and Enclosures Standing Technical Committee members include:

- Lack of availability and documented performance of high efficiency, small capacity heating and cooling equipment for low load situations
- Research on distributed space conditioning
- Identify air tightness strategies and effectiveness of these strategies.

Passive House concepts are gaining increasing attention and traction in California from custom home builders. However, there has also been some controversy over the merits of the PH approach in reaching for net zero energy goals, especially in cold climates where the incremental cost of achieving minimal heating loads may not be warranted (Straube 2009). The PH theory tends to push the BEopt efficiency curve much farther to the right before applying PV than is suggested by NREL analysis. Note that Building America savings goals are based on efficiency only and do not credit PV or other onsite renewable energy generation.

The Building America program is interested in evaluating what measures and strategies used in PH homes are found to be commercially viable and support progress toward Building America goals. The Sonoma deep retrofit will be used as a case study to determine which of the energy efficiency measures (EEMs) are commercially viable in a marine climate and how effectively PH design features can contribute to exceeding Building America existing home milestones.

1.2 Research Questions

The primary evaluation objective of this study is to determine how effectively building retrofit measures can contribute to exceeding Building America Program Management Milestone (PMM) goals, specifically in retrofit applications, through monitoring energy performance, and

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[1] http://www.solar-knights.com/

[2] http://www.passivehouse.us/passiveHouse/PassiveHouseInfo.html

evaluating the market viability of the EEMs. Specific objectives of this project are to compare whole house, heating, cooling, and water heating energy use from measured data with simulation output, and to identify the cost benefit of individual measures to the extent possible.

The following research questions have been explored:

1. How well does the measured energy use match energy use from simulations and did the project achieve its energy-savings goals?
2. How commercially viable are deep retrofits in the local market?
3. How much does the solar water heater contribute to space and water heating loads and how well does the system perform?
4. How effective is the combination of the high performance envelope, energy recovery ventilator (ERV), and other measures at minimizing the heating and cooling load, and what are the energy savings?

2 House Description

The Sonoma Deep Retrofit is a one story, single family home located at 760 3rd Street East in Sonoma, California (Figure 1). Sonoma is located north from the San Francisco Bay Area, and has approximately 2,647 heating degree days and 717 cooling degree days based on a 65°F standard[3]. It is within the Building America marine climate zone (CZ) and IECC CZ 3. The 1,975 ft^2 home was originally built in the 1960s and consisted of two structures connected with an open breezeway. The breezeway was redesigned and enclosed to unite the two structures into a two bedroom, two bath, 2,380 ft^2 residence (Figure 2). Because the residence was originally purchased in a foreclosure sale, pre-retrofit performance data is unavailable for comparison.

Figure 1. The Sonoma House is the first certified Passive House retrofit in the United States

In early 2010, DEG assisted the builder and owner with EEMs and equipment selection during the design and construction process. The project team used EnergyGauge[4] to simulate the building's energy performance with various building components and provide feedback to the builder on cost-effective energy efficiency packages. Based on the builder's and owner's interest in PH, the retrofit measures included features that were not initially deemed cost effective by Building America criteria. The home was completed and systems were commissioned at the end of October 2010. The project team from DEG and Lawrence Berkeley National Laboratory (LBNL) began monitoring the building's energy performance once construction was completed and the building was occupied in November 2010.

A comprehensive monitoring system was installed to identify whole house and system performance, and data collection was initiated in December 2010. Key collected data includes:

- Contribution of the solar thermal system to space heating and water heating loads
- Efficiency of the water heating system

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[3] DOE Climate Zone 4 – Station 48351 - http://www.csd.ca.gov/Contractors/documents/Energy%20tab/References/DOE%20Climate%20Zones.pdf

[4] The model was later updated using BEopt v1.0, and eventually v1.1, after the release of the 2010 House Simulation Protocols and the complementary BEopt software versions.

- Efficiency of the tankless water heater
- Contribution of the ERV to space heating/cooling load reduction
- Mini-split heat pump cooling and backup heating electrical energy use, and
- Individual electrical end uses, whole house electrical use and generation from the photovoltaic system (courtesy of LBNL).

The monitoring teams from DEG and LBNL are sharing data from the project, and preliminary monitoring results were reported in a 2010 final Building America report (CARB 2010). LBNL monitoring results are also described in a presentation by LBNL (LBNL 2011).

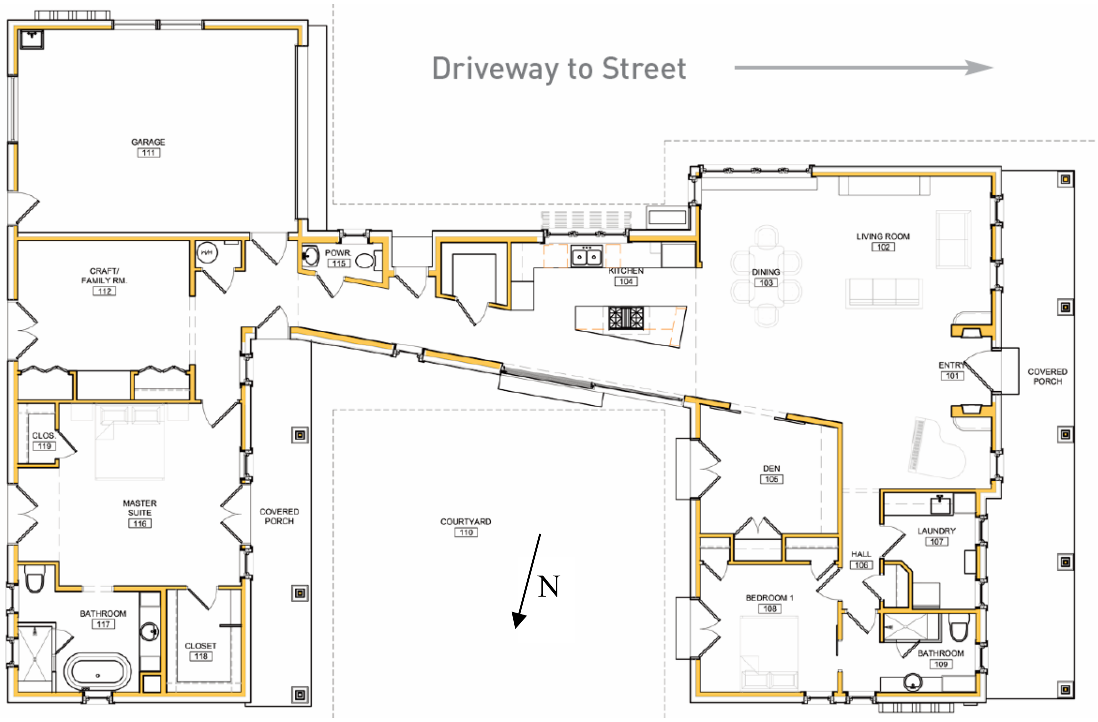

Figure 2. Remodel floor plan

2.1 Energy Efficiency Measure (EEM) Details

Table 1 summarizes the EEMs measures incorporated in the Sonoma House as well as pre-retrofit conditions.

Table 1. Building Energy Efficiency Measures

Measure	Pre-Retrofit	Post-Retrofit
Basic Building Characteristics		
Building Type / Stories	Single family, 1 story	Single family, 1 story
Conditioned Floor Area	1,937	2,380
Number of Bedrooms	2	2
Envelope ***(See Appendix A for details)***		
Exterior Wall Construction	2 × 4 16 in. oc	New: 2 × 6 24 in. oc (~75% of existing walls remain)
Exterior Wall Insulation	R-11 cavity insulation	R- 21 cavity (new) R-15 cavity (existing) + R-16 EPS + radiant wall/air gap
Wall to Garage	R-11 cavity insulation	R-15 cavity + R-22 EPS
Foundation Type & Insulation	Slab - Uninsulated	Slab - AeroGel and/or EPS (min R-13) above existing slab w/ R-16 at slab edges
Roofing Material & Color	Asphalt shingles - dark	Metal roof/custom Bilt Zincalume
Ceiling Insulation	Vented, R-19	Unvented, none
Roof Deck Insulation	None	Minimum of R-42 blown in rafters & R-11 of rigid at deck
Radiant Barrier	No	Yes
House Infiltration - Blower Door Test	N/A	0.40 ACH_{50} tested (0.60 target)
Thermal Bypass Inspection - QII	N/A	Yes
Glass Properties: U-Value / SHGC		
All Windows	Single metal pane: 1.28 / 0.08[5]	Optiwin triple pane: 0.105 / 0.52
Sliding Glass Door @ Kitchen	N/A	Optiwin triple pane: 0.093 / 0.52
HVAC Equipment		
Heating Type & Efficiency	Natural gas combined hydronic fan coil	Solar thermal w/ Mitsubishi Mr. Slim mini-split HP backup - HSPF 8.2
AC Type & Efficiency	None	Mitsubishi Mr. Slim mini-split 1-ton HP / SEER 17, EER 10.3
Heating & Cooling Distribution	Ductwork	Hydronic: central ducted; mini-split: ductless
Duct Location & Insulation	Attic, R-4	Conditioned attic
Mechanical Ventilation	Kitchen & bath fans	UltimateAir ERV
Water Heating Equipment		
Water Heater Type & Efficiency	Storage gas (≈0.58 EF) (combined hydronic)	Rinnai RC80HP1 tankless (0.82 EF)
Tank Capacity/Gallons		N/A
HW Distribution		Standard, uninsulated
Solar Water Heater Type & Solar Fraction		3 Heliodyne 4 × 6 collectors, 80 gal
Appliances & Lighting		
ENERGY STAR Appliances	None	Dishwasher/refrigerator/washer
Dryer Fuel	Electric	Electric
Oven / Range Fuel	Gas	Gas
Fluorescent Lighting Package	100% incandescent	100% high efficacy w/ LEDs & fluorescent
PV System		
PV Solar System Type & Capacity	None	10 Sanyo 215N PV modules 2.15 kW

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[5] U-value and solar heat gain coefficient (SHGC) are based on default values from Table 116-A and Table 116-B of the California 2008 Building Energy Efficiency Standards (CEC, 2008).

Thermal Envelope

Slab: In most cases the existing concrete slab was maintained and a new slab was poured where necessary. Two styles of above-slab insulation were used. Floor type #1 received an application of 1½ in. of expanded polystyrene (EPS) insulation above 0.6 in. Aerogel Spaceloft insulation below the plywood substrate. A $4^5/_8$ in. layer of EPS without the Aerogel was installed over floor type #2. A 3¾ in. of rigid stone wool insulation board was applied to the entire exterior perimeter. Figure 3 presents the materials used in floor type #1.

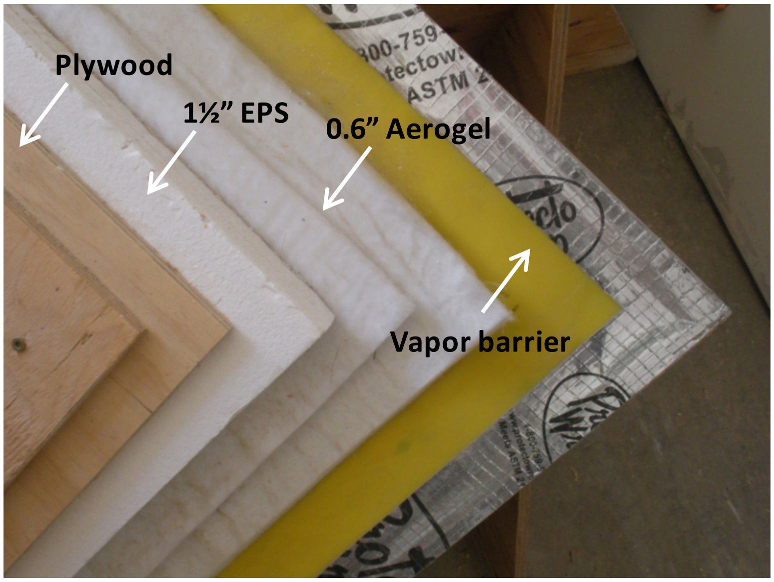

Figure 3. Floor layers above slab for floor type #1

Walls: Approximately 75% of the existing 2 × 4 walls were retained and insulated with R-15 blown-in fiberglass insulation. All newly constructed walls were of 2 × 6 construction, 24 in. on center, and insulated with R-21 blown-in fiberglass. All exterior walls are clad with wood siding and have a vented airspace under the siding, a minimum of 3¾ in. of foil-faced EPS rigid foam board insulation (taped and sealed with a Grace Ice & Water shield), and a Stego Wrap vapor barrier (Figure 4 and Figure 5). The wall to the garage was installed with 5 in. of EPS instead of 3¾ in. See Appendix A for details of the wall assemblies.

Under the California Title-24 energy code, a Home Energy Rating Systems (HERS) credit was taken for Quality Insulation Installation (QII). This credit is similar to the ENERGY STAR® Thermal Bypass Checklist with the intent to ensure proper installation of insulation materials and minimize thermal bypass. Insulation quality and air barriers were inspected by a certified HERS rater before drywall was installed.

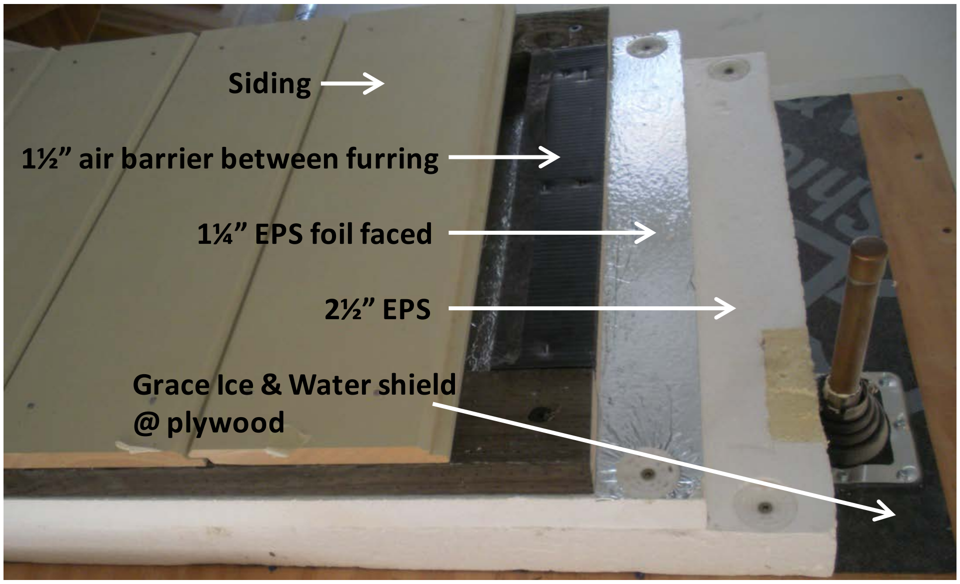

Figure 4. Wall construction

Figure 5. Exterior wall showing foil-faced EPS and furring for siding

Conditioned Attic Space: The attic was converted to a conditioned, non-vented attic with 10-15 in. of netted blown cellulose in between the roof trusses and at knee walls (Figure 6). In addition, 2½ in.-3½ in. of EPS rigid insulation was installed at the roof deck, which also extends over the top of the exterior walls. See Appendix A for details of the roof assemblies.

Figure 6: Netted blown insulation at roof and kneewall

Windows: The home's windows and doors are manufactured by Optiwin; a German company specializing in German PassiveHaus standard compliant windows and doors. The windows are low-E triple paned, with dual sealing surfaces, a solar-heat gain coefficient of 0.52, and a U-value of 0.105. The large sliding glass door at the north wall of the kitchen has a slightly lower U-value at 0.093. Total fenestration is 590 ft^2, nearly 25% of the total wall area. Overhangs around the entire building are 2 ft 6 in. deep at a minimum, allowing solar gain during the winter months and minimizing it during the summer.

Air Tightness: The building envelope was designed with the purpose of preventing building air leakage through the envelope and also facilitating moisture drainage. Passive House building standards require homes to meet the air tightness requirement of ≤ 0.6 Air Changes per Hour at 50 Pascal pressure (ACH_{50}). After envelope construction, the home's envelope was leak tested by a certified HERS rater and found to have an ACH_{50} of 0.40 and CFM_{50} of 151, the equivalent of $0.24*10^{-4}$ specific leakage area.

Mechanical and Electrical Systems

The primary energy source for water heating and space heating is solar thermal energy, with a tankless water heater serving as backup for water heating and an air-source mini-split heat pump serving as the backup space heating system. The schematic of these integrated systems is depicted in Figure 7.

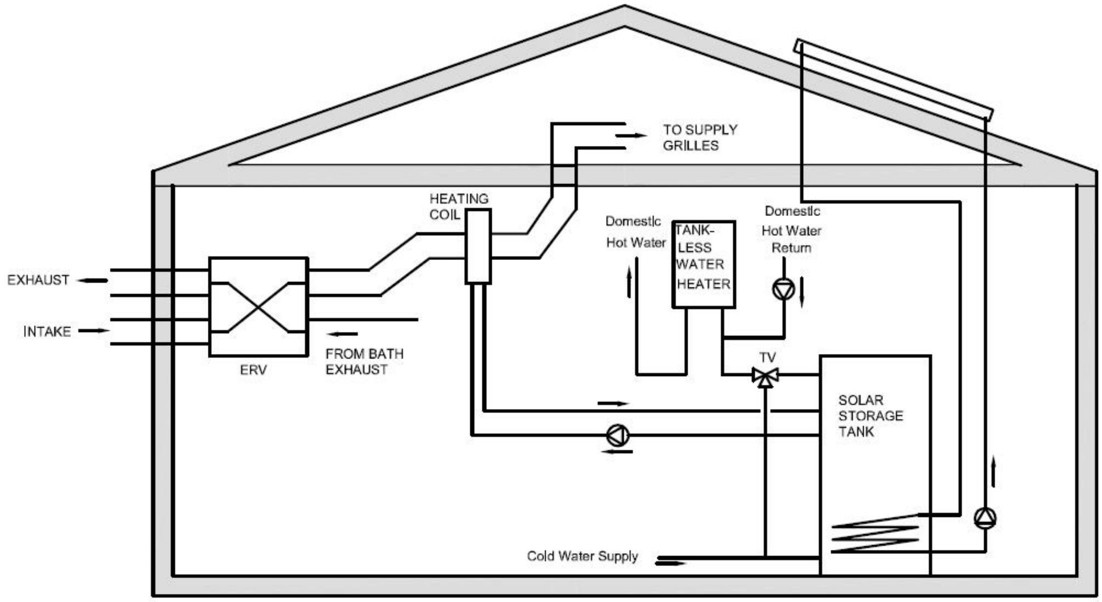

Figure 7. Mechanical schematic

<u>Solar Thermal for water and space heating:</u> Three 4 ft by 6 ft Heliodyne Solar Thermal Rooftop collectors supply hot water to an 80-gal storage tank. The thermal storage tank supplies preheated water to the domestic hot water supply and a hydronic coil located in the ductwork for the ERV system during heating season. The integrated hydronic heat exchanger was designed to provide most of the space heating demand. Domestic hot water takes precedence over space conditioning. The control strategy was custom designed for this project. The solar thermal water storage tank, tankless hot water heater, and circulations pumps are housed in an interior mechanical closet (Figure 8).

Figure 8. Mechanical closet containing solar thermal storage system and tankless water heater

Backup space heating and cooling**:** A 1-ton ductless Mitsubishi Mr. Slim mini-split air source heat pump rated at SEER 17 and 8.2 HSPF provides a backup source for heating and supplies space cooling. The system design for a ductless, single indoor head unit was based on the tight envelope and low expected heating and cooling load.

Backup water heating: A Rinnai tankless water heater was installed downstream of the solar thermal storage tank supply to provide supplemental heating to maintain the hot water supply temperature to the home. A push button demand recirculation pump was also installed to reduce waste cold water supply to the master bathroom, the furthest location from the mechanical closet.

ERV: The ERV is manufactured by UltimateAir with a varying flow rate of 70 to 210 cubic feet per minute (CFM). The ERV fan is set to operate continuously to deliver 70 CFM of fresh air ventilation and to ramp up to deliver 200 CFM when any of the exhaust fans are activated. The ERV is connected to ductwork exhausting air from bathrooms, laundry, and kitchen, and supplying air to all bedrooms and living areas. The ductwork was sealed and tested by a certified HERS rater to be less than 6% of airflow.

The original HVAC system design prior to ARBI involvement called for ground loop thermal heating to temper outside air before entering the ERV system. The horizontal ground loop would have consisted of two lines of 150 ft of ¾ in. PEX tubing located 5 ft underground where the expected soil conductivities would be between 0.5 and 0.7 BTU/ft-^{o}F-hr. A 50-watt pump would circulate water to a heat exchanger placed at the inlet side of the ERV. The team's analysis indicated that the payback on this design would be minimal (i.e., pre-heating intake air with ground loop thermal heating is an expensive investment with little return) in such a mild climate.

Lighting and Appliances

The 2008 California Title 24 standards for residential lighting require a certain percentage of high efficacy fluorescent fixtures in kitchens, but allow either fluorescent fixtures or incandescent fixtures with vacancy sensor (or dimmers in some rooms) in other locations. The builder used a combination of LEDs, hard-wired fluorescent linear fixtures and CFL ceiling cans to exceed Title 24 requirements. The dishwasher, refrigerator and clothes washers were all replaced with new ENERGY STAR and CEE Tier II rated appliances.

Photovoltaic System

A 2.15 kW rooftop PV system, consisting of ten Sanyo 215N PV modules provided onsite electricity and are mounted on the South-facing roof and controlled with a Grid-Tied SMA SB8000US inverter. The installed system was sized to provide about 2/3 of the total estimated house load.

2.2 Preliminary Savings Estimations

Based on an evaluation of the home using BEopt v1.1, the post retrofit case performed 56% better than the pre retrofit case without PV and 69% better with PV. This exceeds the 2013 PMM of 30% for existing homes in marine climates. Evaluation using BEopt was limited due to the following system features that couldn't be modeled in BEopt:

- Vented wall cavities with reflective air spaces
- Solar thermal heating of ERV inlet air.

While heat pumps are easily modeled in BEopt, the lack of data on performance curves for mini-split units that have variable speed fans and compressors and electronic expansion valves most likely results in underestimated mini-split performance.

3 Methodology

3.1 General Technical Approach

The general approach of this research is to employ system commissioning, short term tests, long term monitoring, and detailed analysis of results to identify the performance attributes and cost effectiveness of the whole house measure package. Whole house energy usage from simulations is compared to monitored performance in an attempt to identify the applicability of individual measures to Building America retrofit standards. The house was monitored for a full year.

The water heating system was monitored to determine solar fraction of the solar thermal system as a percentage of domestic hot water load, the overall efficiency of the water heating system, the heat delivered by the solar thermal system to the ERV, and the gas consumption by the tankless water heater. The ERV was monitored to determine energy consumption and its contribution to the heating and cooling load. Mini-split heat pump energy delivery was not directly measured as it is extremely difficult to measure airflow at the indoor unit given the variable nature of the supply fan. The power consumed by the unit was monitored to quantify run times and energy consumption.

Whole house electrical energy usage was monitored by DEG. During construction, LBNL's desire to monitor individual electrical circuit loads left little room in key electrical panels areas for simultaneous monitoring efforts. A mutual agreement was reached with LBNL to provide systems monitoring data in return for electrical energy usage data.

Control settings for the hydronic and ventilation systems were verified, and operation of the heat pump, controls, fan, and other components, checked. Long-term monitoring also provided "continuous commissioning" support in identifying failure of any components.

Monitoring data has been carefully reviewed and analyzed in an effort to respond to the research questions and to identify sources of energy savings, such as from reduced heating and cooling load, improved equipment efficiency, etc.

3.2 Measurements

The site was equipped with a Data Electronics data logger and modem for continuously collecting, storing, and transferring data via telephone lines. Sensors were scanned every 15 seconds, and data summed or averaged (as appropriate) and stored in data logger memory every 15 minutes. Data was downloaded to a server every 24 hours, and range checks were automatically performed to identify problems with monitoring sensors or the systems being monitored.

Monitoring Data Points

Table 2 lists all the measurement points that were monitored on a continuous basis. Total house electricity and PV production were measured by LBNL and provided to DEG for analysis. Location of key data points are shown in the diagram in Figure 9.

Short Term Tests

Short-term tests were conducted to verify air-tightness with blower door testing and to develop performance data for the ERV fan. Duct leakage was verified by a HERS rater.

Table 2. Measurement Points List

Point No.	Abbrev.	Description	Location	Sensor Type	Sensor Mfg./Model	Channel	# of Cond.
1	TAO	Temp, air, outdoor	Target is under East Eave	RTD, 4-20ma	Gen Eastern	1+	4
2	RHO	RH, air, outdoor	Target is under East Eave	RH, 4-20mA	Gen Eastern	1-	"
3	TAI1	Temp, air, indoor, living area	Next to T-Stat 1	RTD, 4-20ma	ACI	2+	4
4	RHI1	RH, indoor, living area	" "	RH, 4-20mA	ACI	2-	"
5	TAI2	Temp, air, indoor, sleeping area	In living and dining room	RTD, 4-20ma	ACI	3+	4
6	RHI2	RH, indoor, sleeping area	" "	RH, 4-20mA	ACI	3-	"
7	TAERVL	Temp, air, ERV leaving	ERV supply duct before HC	RTD, 4-20ma	Vaisala	4+	4
8	RHERVL	RH, air, ERV leaving	" "	RH, 4-20mA	Vaisala	4-	"
9	TACL	Temp, air, coil leaving	Duct leaving HC	TT	Omega, Thermex	10+	2
10	TWSL	Temp, water, solar storage leaving	Mechanical Room	Immersion Thermocouple	Omega, Thermex, or Watlow Gordon	5+	2
11	TWCS	Temp, water, cold water supply	Mechanical Room			5-	2
12	TWHL	Temp, water, water heater leaving	Mechanical Room			6+	2
13	TWHE	Temp, water, water heater entering	Mechanical Room			6-	2
14	TTNK	Tank midpoint temperature	Mechanical Room			7+	2
15	TWCE	Temp, water, coil entering	Supply line to heating coil			7-	2
16	TWCL	Temp, water, coil leaving	Return line from heating coil			8+	2
17	ECP	Power, coil pump	Mechanical Room	Power Meter	Wattnode	D1	
18	INSOL	Solar radiation (incident to solar water heater surface)	On roof adjacent to solar	Pyranometer	Licor LI-200	12+	2
19	EERV	Power, ERV	Attic in ERV cabinet	Power Meter	Wattnode	D2	2
20	ECOND / EFAN	Power Mini-split	At condenser or power panel	Power Meter	Rochester RIS 1000	D3	2
21	FWC	Flow, cold water supply to solar storage tank	Mechanical Room	Flow meter	Onicon F-1300	D8	3
22	FWD	Flow, domestic hot water	Mechanical Room	Flow meter	Onicon F-1300	D9	3
23	FWH	Flow, water, heating coil loop	Mechanical Room	Flow meter	Onicon F-1300	D6	2
24	SCIRC	Status, domestic hot water recirculation pump	Mechanical Room	Current status meter	Hawkeye	D4	2
25	GAS	Flow, gas, water heater	Mechanical Room	Gas Meter with Pulser	Equimeter	D5	2

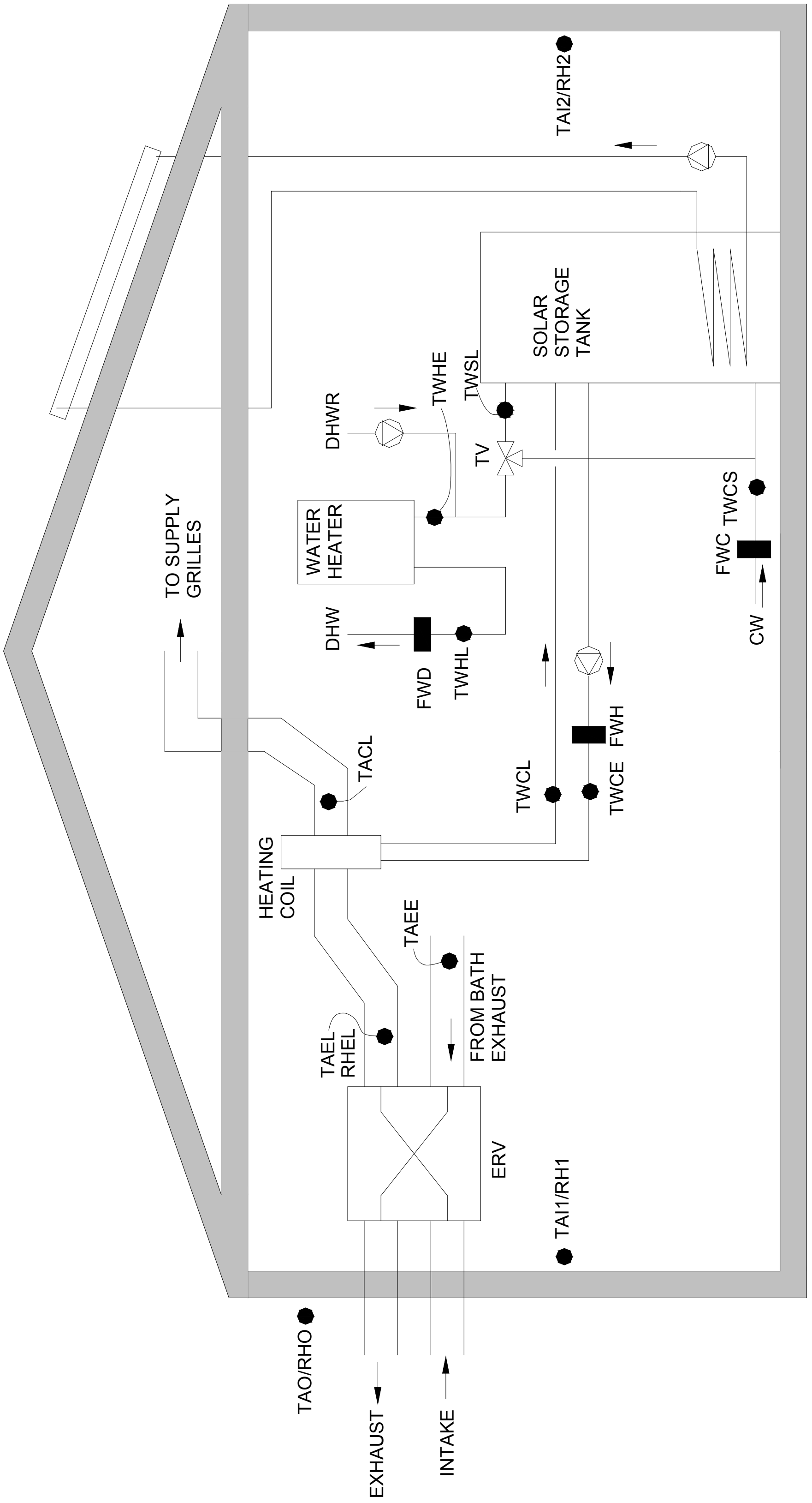

Figure 9. Sensor location schematic

3.3 Equipment

Data Logger Specifications

A Model DT-800 Data Electronics data logger was used to collect and store monitoring data. Analog inputs are single-ended type (all referenced to ground). Digital inputs are used for power monitors and status signals; high speed counter inputs were used with water flow meters. The data loggers are provided with an RS232 communications interface and battery backup. They also include integral cold junction circuitry for direct measurement of Type T thermocouples.

Manufacturer: dataTaker, Inc.
Model: DT-800
Analog Inputs: Up to 36 single-ended and 24 double-ended
Digital Inputs: 16 total, 8 bidirectional, 1 kHz
Analog Accuracy: 0.02% of reading plus 0.02% of full scale.
Memory: 2 MB flash, 4 MB SRAM, 24 system variable registers

Sensor Types and Specifications

Standard specifications for the sensor types used are listed in Table 3. Sensor selection was based on functionality, accuracy, cost, reliability, and durability. Specific model numbers are listed as examples; similar models by other manufacturers may be used. Signal ranges for temperature sensors correspond approximately to listed spans.

Table 3. Sensor Specifications

Type	Application	Mfg/Model	Signal	Span	Accuracy
RTD	Outdoor temp and RH	GE MRHT3	4-20 mA	32 - 132°F	±1.5%
				0 – 100%	±2%RH
RTD	Indoor / Duct temperature / RH	Vaisala HM*60	4-20 mA	32 - 132°F	±1.5%
				0 – 100%	±2%RH
Type T Thermocouple	Immersion Water temperatures	Gordon Watlow Type T special limits	~11mV @ 500ºF	Range =	0.4%
				-328 to 662ºF	
	Surface / Air temperatures	Omega		-99 to 500 ºF	
24VAC Relay	Fresh air Damper Status, zone damper status	Hawkeye	dry contact	n/a	n/a
Small power monitor	Fan and condenser power	WattNode	pulse	CTA/40	±0.5%
		WNA-1-P-240-P			
Large power monitor	Total house power, PV production	Watt Node	pulse	CTA/40	±0.5%
		WNB-3D-240-P			
Flow meter	Water flow	Onicon F-1300	pulse	varies by meter	±0.5%
Pyranometer	Insolation	LiCor	Analog	varies by sensor	±5%
Pressure Transducer	Air Pressure	Auto Tran	4-20mA	0-4inWC	±1%FS
Diaphragm Gas meter	Tankless gas use	IMAC/Rockwell	Pulse	250 SCFM	±1ft^3

3.4 Computation of Monitoring Variables

Whole house electricity use: Electricity supplied to the house and electricity produced by the PV system is used to identify total house electric use. PV system efficiency is calculated from monitored energy data and insolation values.

Water heating system performance**:** Heat transferred from the solar water heater to the tankless water heater, and from the tankless water heater to the house is measured to determine the actual solar fraction and the overall efficiency of the water heating system. Losses from the recirculation system are treated as part of the DHW load. Gas flow into the water heater is measured with a dedicated gas meter.

For total domestic hot water load (Btu) delivered to the house, the following equation is used:

Equation 1: $Q_{delivered} = FWD * (TWHL - TWCS) * 8.33$ *(Btu)*

Where:
FWD = domestic hot water flow (gallons)
TWHL = supply water temperature from water heater (°F)
TWCS = cold water supply temperature (°F)

The value of 8.33 in Equation 1 represents both the specific heat of water, 1 Btu/°F-lb, and the density of water, 8.33 lbs/gal, at a certain temperature. Over the range of expected temperatures the less than 0.5% variation is considered to be within acceptable measurement error.

Equation 2 is used to calculate total energy (Btu) provided by the tankless water heater.

Equation 2: $Q_{tankless} = FWD * (TWHL - TWSL) * 8.33$ *(Btu)*

Where:
TWSL = supply water temperature from solar storage tank (°F)

Energy consumption of the gas water heater and recirculation pumps is converted to Btu using Equation 3 and Equation 4. Recirculation pump energy use (EPMPR) is calculated based on pump status, SCIRC.

Equation 3: $E_{dwh} = GAS * 1{,}013$ *(Btu)*

Equation 4: $E_{recirc} = EPMPR * 3{,}412$ *(Btu)*

Where:
GAS = gas use of water heater (ft^3)
EPMPR = electric use of recirculation pumps (kWh)

The effective thermal efficiency of the tankless water heater is calculated according to Equation 5. Electrical energy use of the tankless water heater was not measured and was ignored for this analysis. Field monitoring has shown that the annual impact of electrical consumption on tankless annual efficiency is on the order of 1-3% (Hoeschele et al, 2011).

Equation 5: Tankless effective thermal efficiency $= Q_{tankless} / (GAS)$

The solar Energy Factor (EF) and associated solar fraction are calculated according to methodology developed by the Solar Rating and Certification Corporation (SRCC). These values are calculated and reported on a seasonal basis according to Equation 6 and Equation 7. The solar collector pump power was not monitored but is estimated based on solar insolation values, tank temperatures, and rated pump power.

Equation 6: $SEF = Q_{delivered} / (E_{dhw} + E_{solar\ pump})$

Equation 7: $SF = 1 - EF / SEF$

Where:
SEF = Solar Energy Factor
$E_{solar\ pump}$ = electric use of solar collector circulation pump (in Btu)
SF = Solar Fraction
EF = average daily efficiency of the gas water heater

The contribution of solar thermal to space heating was calculated through flow and temperature sensors on the heating coil loop. Total delivered heating (Btu) is calculated using Equation 8.

Equation 8: $Q_{coil} = FWH * (TWCE - TWCL) * 8.33$ *(Btu)*

Where:
FWH = hot water flow through the hydronic coil (gallons)
TWCE = supply water temperature to the coil (°F)
TWCL = return water temperature from the coil (°F)

<u>ERV system performance</u>: ERV supply temperature and relative humidity measurements are used to determine its efficiency and impact on heating and cooling loads. Energy use was continuously monitored.

During the cooling season, Equation 9 is used to calculate the sensible load reduction due to the ERV. ERV airflow rates were measured once for the two possible airflow settings, and power measurements are used to identify changes in airflow and calculate the CFM using in the following equations.

Equation 9: $\dot{Q}_{ERV\_cool\_sensible} = CFM_{ERVs} * (TAO - TAERVL) * 1.08$ *(Btu/h)*

where:
CFM_{ERVs} = calibrated air flow of supply (cubic feet per minute)
TAERVL = supply air temperature (°F)
TAO = outdoor air temperature (°F)

Total cooling (sensible plus latent) is calculated based on calculated enthalpies of the supply and outdoor air streams.

Equation 10 through Equation 14 represent a non-iterative approximation of enthalpy based on supply and outdoor air temperature and relative humidity.

Equation 10: $X = (18.678 - Tc / 234.5) * Tc / (Tc + 257.14)$

Equation 11: $Y = 1 + X + 0.5*X^2 + 0.16393*X^3 + 0.041667*X^4 + 0.0123457*X^5$

Equation 12: $P_w = RH * 6.112 * Y / 100$

Equation 13: $W = 0.6219 * P_w / (1013.26 - P_w)$

Equation 14: $h = 0.24 * T_f + W * (1060.9 + 0.443 * T_f)$

where:
T_c = supply or outdoor air temperature in °C
T_f = supply or outdoor air temperature in °F
RH = percent relative humidity of the supply or outdoor air
P_w = water vapor partial pressure (hPa)
W = humidity ratio
h = enthalpy of supply or outdoor air (Btu/lbm)

The density of air in Equation 15 is calculated using the supply air temperature. Total cooling load reduction is calculated according to Equation 16.

Equation 15: $D_{air} = (518.67 / (459.67 + TAERVL)) * 0.075028$ *(lb/ft^3)*

Equation 16: $\dot{Q}_{ERV\_cool\_total} = CFM * (h_{outdoor} - h_{supply}) \text{ x } D_{air}$ *(Btu/h)*

During heating mode, Equation 17 is used to calculate the heating load reduction due to the ERV system.

Equation 17: $\dot{Q}_{ERV\_heat} = CFM_{ERV} * (TAERVL - TAO) * 1.08$ *(Btu/h)*

Equation 18 shows the total EER calculation for the ERV system.

Equation 18: $EER_{ERV} = \dot{Q}_{ERV} / EERV$

where:
EERV = power of ERV unit (kW)

The equation to calculate sensible effectiveness of the ERV is shown in Equation 19 according to AHRI Standard 1060 (AHRI, 2005).

Equation 19: $EFF_{ERV\_sens} = [\dot{m}_{ERVs} * (TAO - TAERVL)] / [\dot{m}_{ERVmin} * (TAO - TAI1)]$

where:
TAI1 = indoor or entering ERV exhaust air temperature in °F
$\dot{m}_{ERVs}$ = mass flow rate of the supply air (lb/hr)
$\dot{m}_{ERVmin}$ = minimum mass flow rate of the exhaust and supply air (lb/hr)

Since the ERV supply and exhaust airflow rates are balanced, Equation 19 can be simplified as shown in Equation 20.

Equation 20: $EFF_{ERV\_sens} = (TAO - TAERVL) / (TAO - TAI1)$

4 Results

4.1 System Commissioning

The focus of commissioning was to verify correct operation of the mechanical systems, verify correct operation of the monitoring equipment including sensors and communications, and record one-time measurements of pertinent data points.

The indoor unit for the mini-split heat pump was originally installed in the hallway bathroom, both for its central location between the living space and bedrooms and to be out of view from the main hallway. The design assumption was that the tight envelope conditions and continuous supply of air from the ERV would assist in evenly distributing heat and reducing thermal stratification within the home. In the month following system commissioning, it was observed that the location of the unit resulted in overheating of the bathroom and inadequate distribution of conditioned air throughout the rest of the home. The head unit was moved in January, 2011 into the main hallway. This appeared to resolve the issue of overheating the indoor space as there were no further complaints from the homeowner. Since indoor temperature was not monitored where the head unit was relocated, there was no way to properly evaluate the distribution of conditioned air from the mini-split heat pump.

4.2 Short Term Test Results

Following are results of short term tests conducted either by DEG or other consultants. Test results showed alignment with design expectations.

Table 4: Results of Short Term Tests

Short Term Test	Design Target	Results
Blower Door Infiltration	0.60 ACH_{50}	0.40 ACH_{50}

Measured building envelope leakage was below the PH target of 0.60 ACH_{50}. Leakage testing of the ERV ducts was completed by another HERS rater but the tested value was less than 6% of rated airflow (< 12 CFM).

ERV airflow measurements were made using an Alnor Model 6200 Low Flow Balometer. The ERV was set to deliver the maximum airflow of 200 CFM for testing purposes. Using the adjustable diffusers, the room-by-room airflows were reduced to a maximum of 40 CFM for measurement readings. In Bedroom 1 and the Master Closet, supplies were adjusted to lower flow rates (about 20 CFM) in accordance with the guidelines provided by the builder.

Results of these measurements are provided in Table 5. With various sources of measurement error such as indoor-outdoor pressure differences and pressure drop imposed by the balometer, the differences between the sum of the exhaust and supply airflows and the exhaust and supply/intake readings is not unusual. The larger discrepancy between the outdoor intake measurement, the sum of the supply measurements, and the outdoor exhaust measurement suggests the house may have been pressurized by drafts through open doors when the outdoor intake measurement was taken. A leak in the intake duct would also explain this difference, but based on observations, duct sealing was extremely thorough.

Overall, the data indicates that total airflow on both the exhaust and supply sides is within an acceptable range of 10% of the 200 CFM maximum.

Table 5. Results of ERV One-Time Testing

	Room	CFM	% Difference
Exhaust:	East Bath	30	
	Laundry	36	
	Kitchen	40	
	Powder	40	
	M. Bath	38	
	Total	**184**	**8%**
Supply:	Bedroom 1	28	
	Den	31	
	Living	35	
	Craft/Family	32	
	M. Bedroom	34	
	M. Closet	21	
	Total	**181**	**10%**
Outdoor Exhaust:		**190**	**5%**
Outdoor Intake:		**173**	**14%**

4.3 Monitoring Results and Discussion

Solar Water Heating

The three solar collectors and 80-gal storage tank serve both domestic hot water and a heating coil for space heating located within the ERV ductwork. The majority of this analysis focuses on the contribution to domestic hot water. Complete water heating monitoring data was available for the majority of 2012, from the second week in January through the end of December. Since the solar circulation pump was not directly monitored, estimates of total operating hours were made based on the first order collector performance equation, monitored insolation, and technical information published by the SRCC for the installed collectors. The rated power of the pump was used to calculate total pump energy.

Table 6 shows the relative contribution of the solar system to both space heating and domestic hot water. Over the course of the year, the system supplied almost identical quantities of energy to each end use.

Table 6. Annual Contribution from Solar Thermal System by End Use

	Space Heating	Domestic Hot Water
Energy Delivered (kBtu)	3,540	3,485
% of Total	50.4%	49.6%

Analysis shows that domestic hot water solar fraction was 76% on an annual basis with monthly solar fractions reaching 90% in the summer (see Figure 10). Even during the winter months, solar fractions were over 60% and monthly average tank temperature was greater than 90°F. Average daily hot water use was relatively low, under 30 gal/day except in December. This is significantly less than the DOE EF water heater test assumption of 64.3 gal/day per household. However, the Sonoma House had only a single occupant, where the 64.3 gal/day assumes three people. Figure 11 shows that a majority of the draws (55%) are less than one gallon; however, over 50% of the total annual draw volume was from draws greater than 10 gallons.

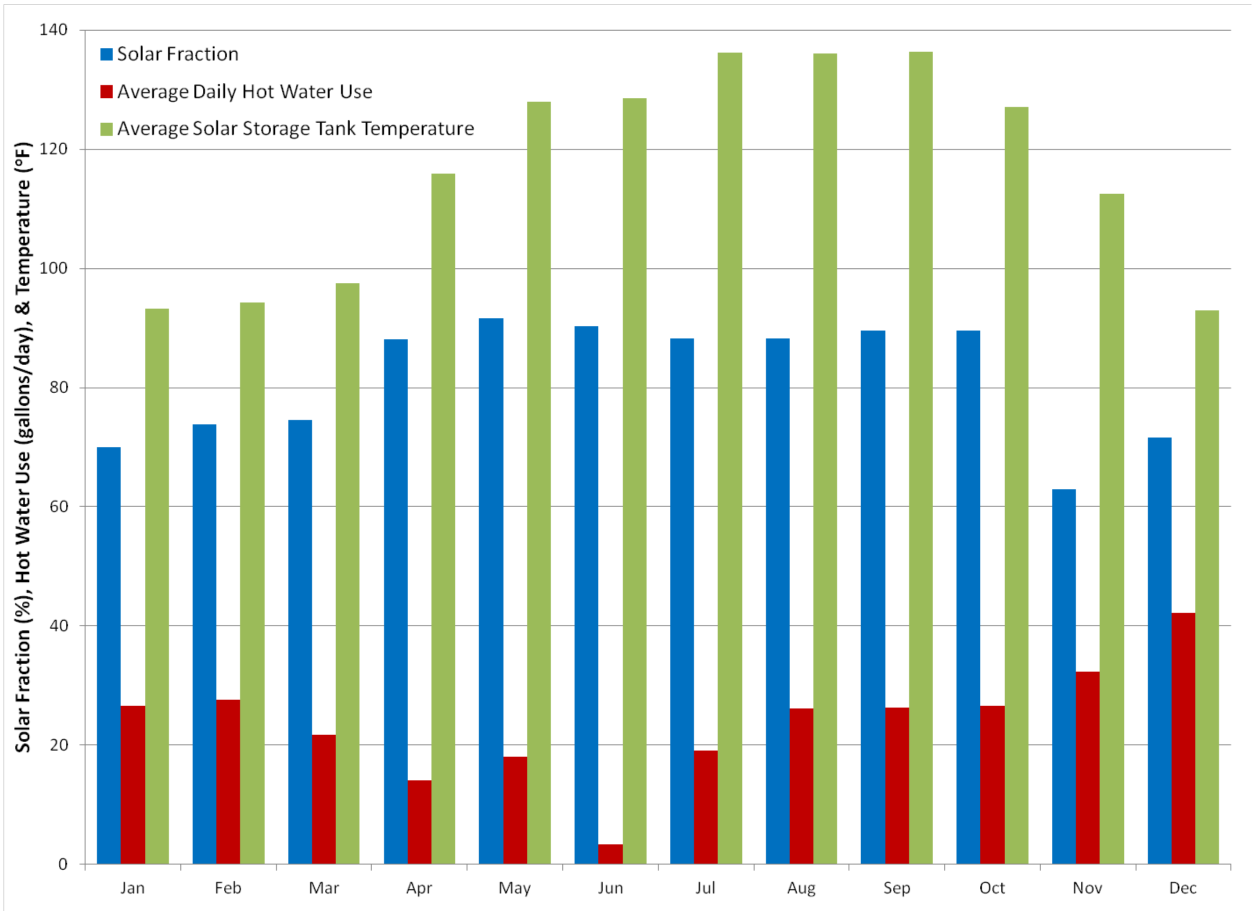

Figure 10. Monthly solar fraction and hot water use for the domestic hot water system

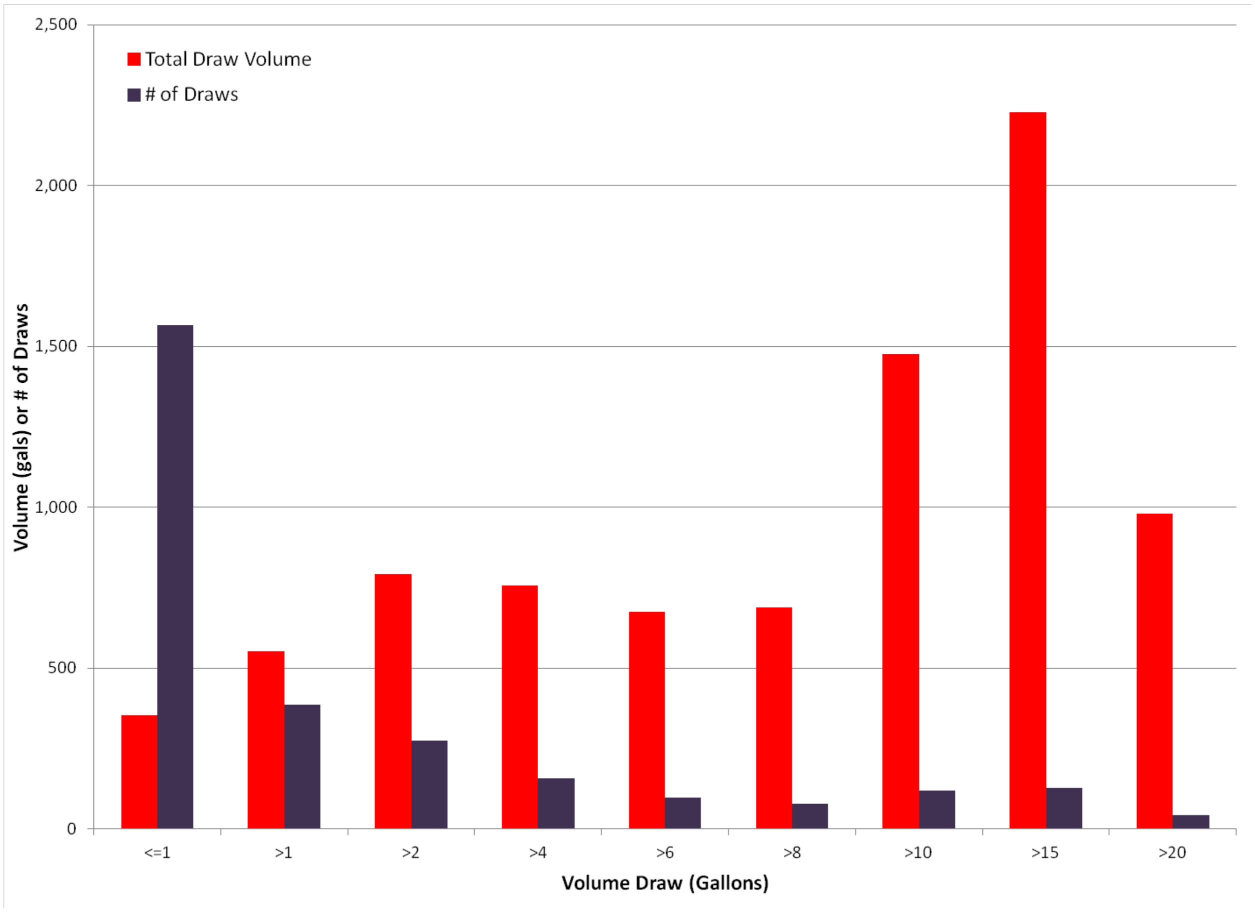

Figure 11. Total 15 minute domestic hot water volume draw by size

While gas water heating use was low because of the large contribution from the solar thermal system, the observed tankless water heater efficiencies were very low. Average annual efficiency was 48% and average monthly summer efficiencies were as low as 26%. This is partially a result of tankless cycling due to high entering water temperatures coming from the solar pre-heat tank. Tankless water heaters fire the burner whenever flow is sensed through the heat exchanger. Once flow has been initiated, water temperature is measured to determine the firing rate. When the tankless entering temperature is close to or above the water heater setpoint, the tankless water heater will fire on momentarily before determining that water heater setpoint is met and shutting off. In this situation, most of the firing energy results in heating the heat exchanger, not the flowing water.

Tankless efficiencies are also affected by hot water draw volumes. Figure 12 shows 15-minute tankless efficiencies as a function of total 15-minute hot water draw volume. Typically, tankless water heaters operate at lower efficiencies when draws are small, due to the fact that heat exchanger thermal cycling reduces efficiency. However, this relationship is not readily apparent from the data. Due to the resolution of the gas meter, which only logs at increments of one cubic foot of gas, and the resolution of the data, at 15-minute averages, it is difficult to fully distinguish full load water heater operation from part load. As a proxy, full load 15-minute data was identified by isolating any 15-minute period during which the tankless consumed greater than 3 cubic feet of gas and the temperature difference across the tankless heat exchanger was greater than 20°F. The full load data points are also shown in the graph below. The "higher gas use" data set does reveal an increase in operating efficiencies with the majority of points above 70%. These values are in the range for what is expected from a tankless with an EF of 0.82.

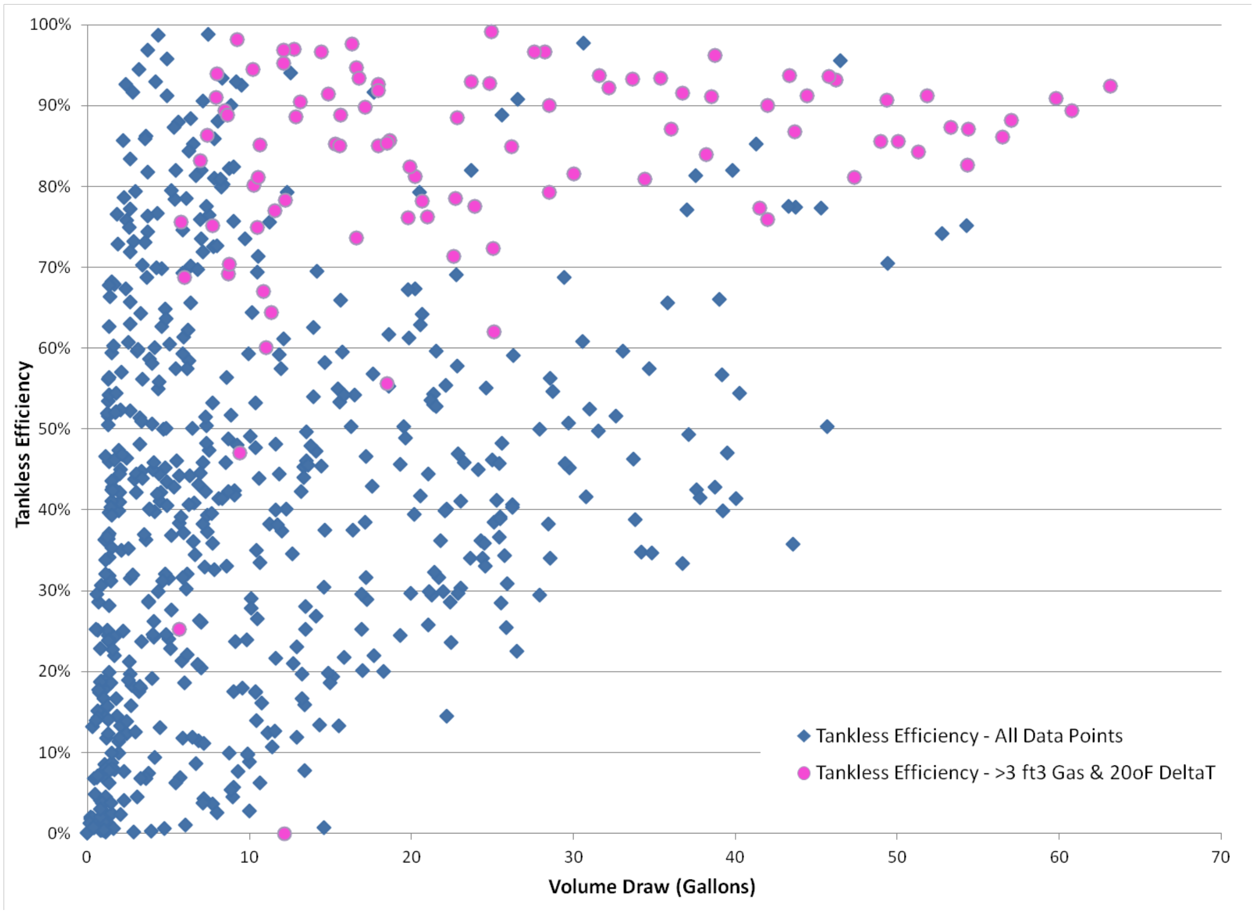

Figure 12. Tankless water heater 15-minute efficiency versus hot water draw

Figure 13 and Figure 14 show water heating system operation for a typical summer and winter two-day period, respectively. During the summer, even with large hot water draws, the supply water from the storage tank is hot enough to supply the load. However, the tankless still fires on initiation of any single water draw, resulting in unnecessary gas usage and low efficiencies. The water from the storage tank is tempered with cold water through the mixing valve. There are some draws that don't coincide with measured gas use, due to the resolution of the gas meter, which records on increments of 1 cubic foot. In the winter, lower tank temperatures and larger hot water draws result in higher operational efficiencies, but still fairly low for draws below 10 gallons. Note that due to temperature decay in the pipes, temperature measurements in between water draws will not be relevant.

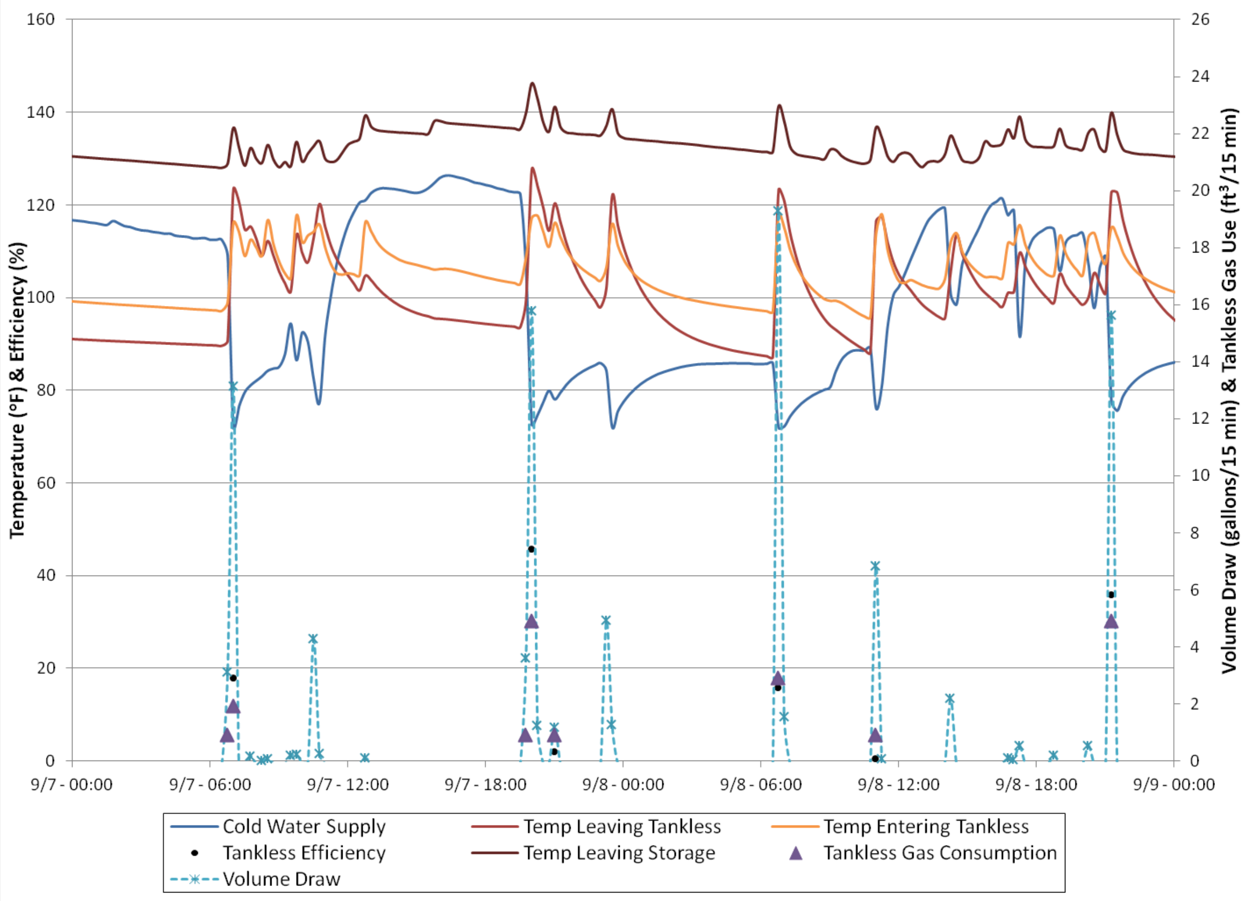

Figure 13. Summer water heater system operation

Despite the low efficiencies, it should be acknowledged that overall annual gas usage of the tankless water heater is relatively low. Annual consumption based on 2011 data is 30 therms. This is less than the 40 therms that storage gas water heaters use on average annually in storage losses alone[6]. While system issues have resulted in lower than ideal operational efficiencies, the overall impact is minimal.

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[6] Based on results of field research conducted by Davis Energy Group as reported in a preliminary project report titled “California Field Performance of Advanced Residential Gas Water Heating Technologies”. The final project report will be published in the end of 2012.

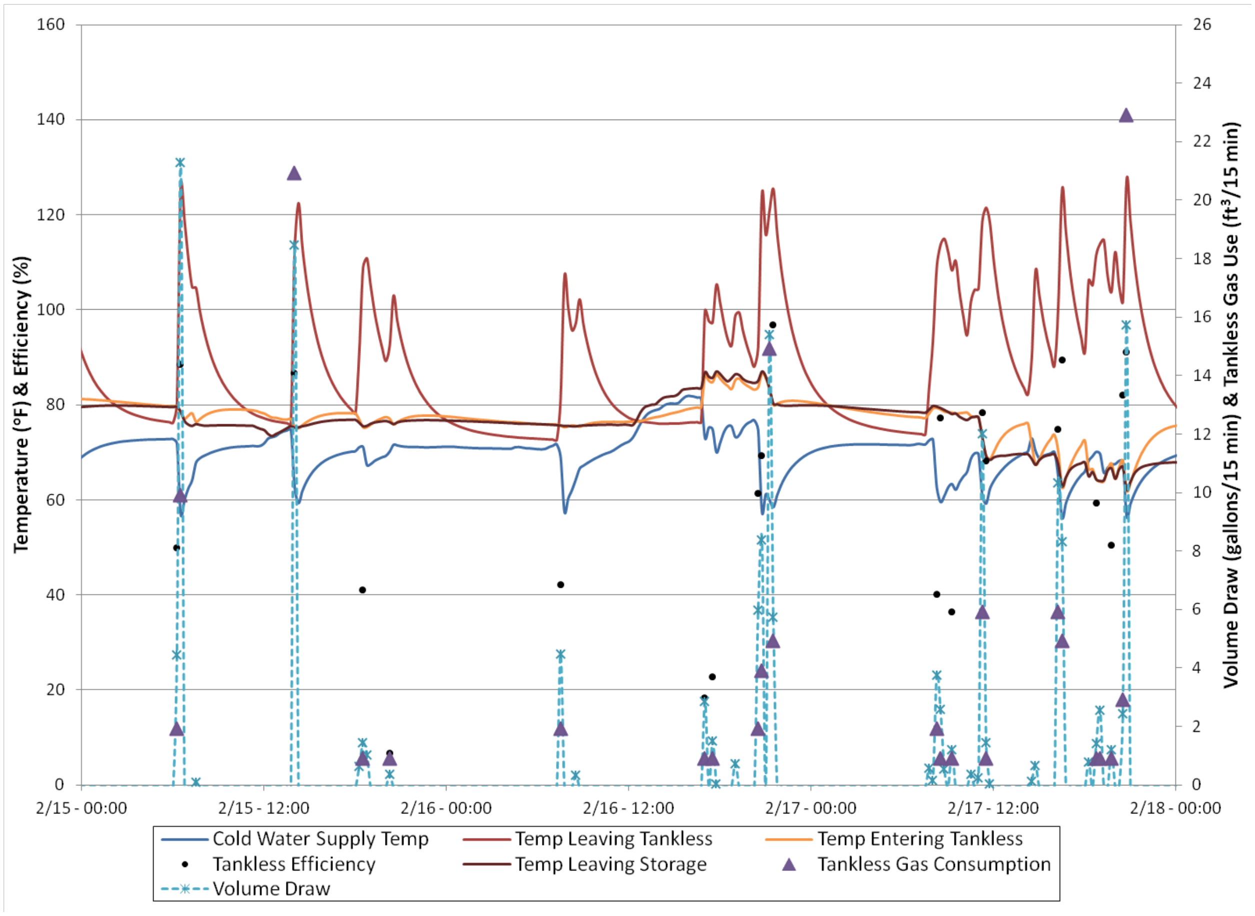

Figure 14. Winter water heater system operation

Total heating and cooling loads were not available from monitoring. Due to the difficulties in measuring airflow, detailed system monitoring of the mini-split was not conducted and therefore operational system efficiencies and capacities are unknown. Based on published data by Mitsubishi, heating efficiency at rated conditions (47°F outdoor air temperature) is 3.4 COP. This value was applied as an average operating efficiency to monitored heat pump power to estimate delivered heating energy. This is shown in Figure 15 along with energy supplied by the solar system to the hydronic heating coil (calculated from water side monitoring).

Based on this estimate of total building heating load, solar thermal contributed 20% of the total load on an annual basis. Actual contribution may be greater or even lower due to a number of factors. The average operating efficiency of the heat pump is an estimate only and could be off substantially. If performance curves for the system were available, a better estimate could be obtained by applying the rated efficiency to the 15-minute data based on outdoor temperature. Additionally, due to the location of the mini-split (in a narrow hallway) and the lack of a distribution system, it may not have efficiently satisfied the house heating demands. During periods when solar was unable to satisfy a call for heating, the heat pump may have operated additional hours resulting in temperature stratifications within the home.

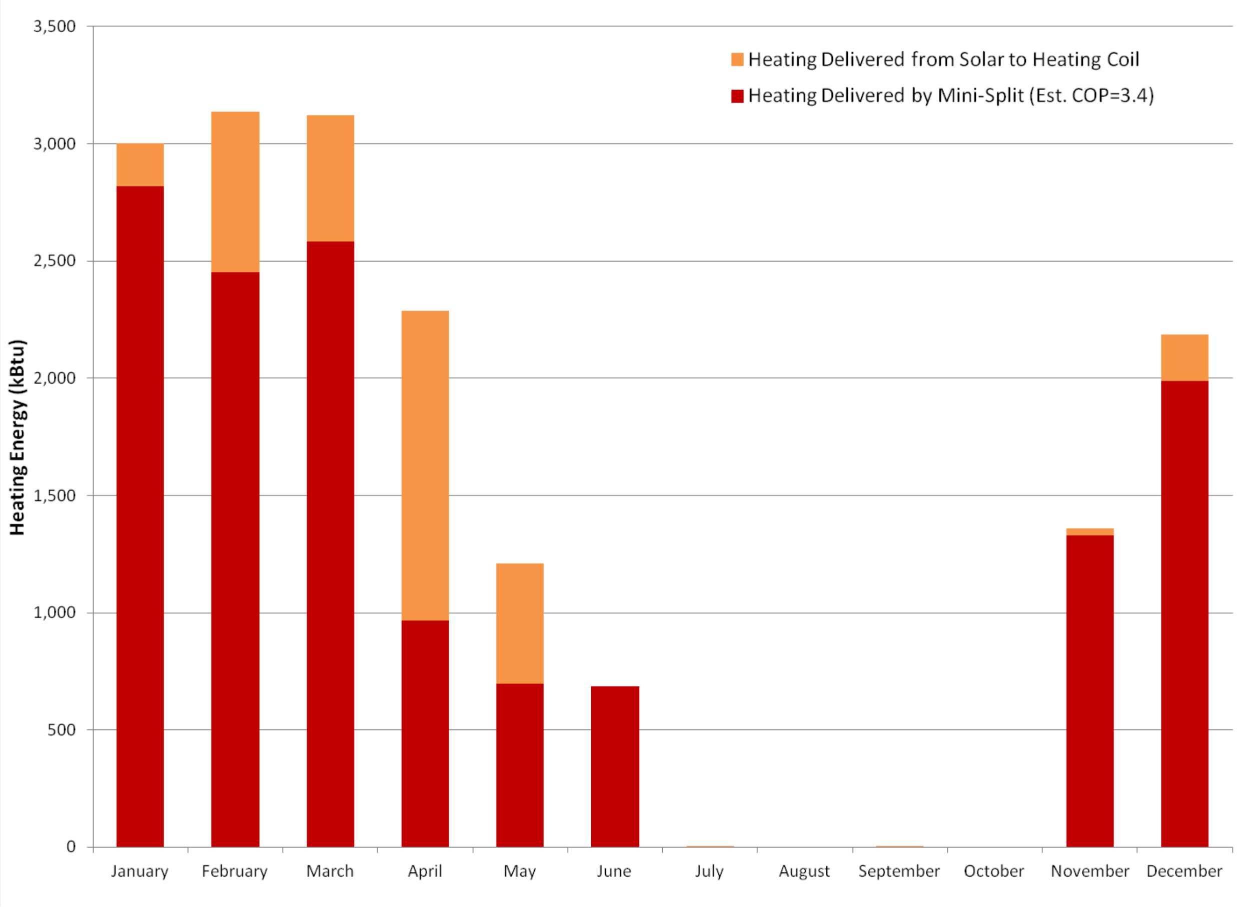

Figure 15. Contribution of solar thermal and mini-split to space heating and comparison to BEopt heating loads

Heating system operation during a March winter week is shown in Figure 16 showing mini-split heat pump and hydronic heating coil operation and relevant temperatures. The mini-split picks up most of the load during the nighttime when solar storage tank temperatures drop below an adequate supply temperature and the heat pump ramps down during the day to supplement the heating load not provided by the solar system. Because the mini-split is a variable capacity system with inverter compressor technology, it is able to throttle the output capacity and meet the required load more efficiently than constant speed systems with higher power draws and greater cycle degradation.

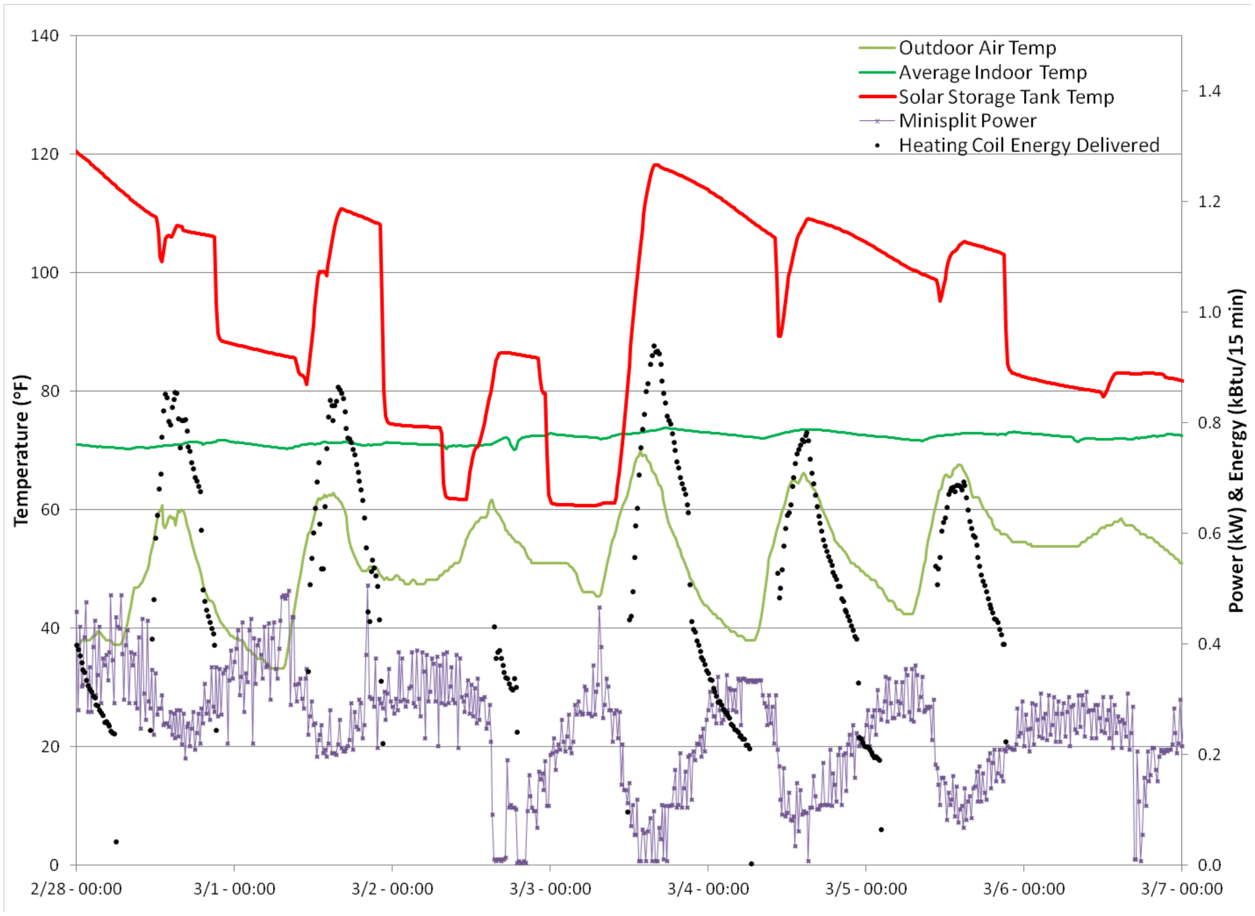

Figure 16. Winter heating operation of solar hydronic heating coil and mini-split heat pump

Load Reduction and HVAC Strategies

The Sonoma House incorporates a number of EEMs designed to significantly reduce the heating and cooling load on the building, consequently reducing energy use and allowing for equipment downsizing. These measures include high performance wall and roof assemblies, triple pane high performance windows, slab insulation, air sealing, and an ERV. BEopt was used to investigate the benefits of these various measures by estimating source energy use percent reductions. The base case used for comparison purposes was the pre-retrofit house specifications (Table 1) with the geometry, orientation and window area of the post-retrofit house. Since the pre-retrofit house did not have a cooling system, a standard efficiency air conditioner (SEER 13) was added for the purpose of this analysis. A 78 AFUE gas furnace was used in the model to represent the standard efficiency combined hydronic fan coil used for heating in the pre-retrofit case. The R-4.2 ductwork was located in the attic with an estimated 30% leakage. Table 7 summarizes the energy savings of the load reduction measures.

Upgrading the windows from single pane metal frame (1.28 U-value/0.8 SHGC) to the triple pane windows (0.105 U-value/0.52 SHGC) (Parametric Run #6) had the largest total source energy savings of all the envelope measures based on the BEopt analysis. Second to this is converting the vented attic to an unvented attic with R-52 insulation.

The option of upgrading the HVAC system in place of the envelope measures was also evaluated for comparison. Since mini-split heat pumps cannot be modeled in BEopt, a high efficiency single-speed heat pump was selected from the standard BEopt library for evaluation with a 12.7 EER and 8.8 HSPF. Replacing the HVAC system with a high efficiency heat pump provides greater savings than any individual load reduction strategy (Parametric Run #8), resulting in 29% source energy reduction. A portion of these savings can be attributed to the ductless distribution. Parametric run #10 combines all the envelope measures together (runs 2-7) resulting in 59% total source energy savings, which is twice the savings as upgrading HVAC alone. If the HVAC system has reached the end of its useful life and is to be replaced anyway, there are capital cost savings associated with load reduction measures through HVAC system downsizing, helping offset incremental costs for the envelope measures. The useful measure life of all of the envelope measures is significantly longer than the useful life of the HVAC equipment, which has an estimated useful life of 20 years.

BEopt modeling does not predict any energy benefit for the ERV compared to the base case which assumed exhaust ventilation only. Monitoring data confirms high fan energy use (12% of total source energy) and minimal load reduction benefit based on the mild climate. High electrical usage is due partly to the filter clogging and partly to the high fresh air ventilation rate. Heat exchanger effectiveness is reduced because of the small temperature differential across the heat exchanger due to the mild climate.

Table 7. Energy Savings Comparison of Load Reduction and HVAC Measures

Parametric Run #	Description	Total Source Energy (kBtu/yr)	% Total Energy Savings	Heating Source Energy (kBtu/yr)	% Heating Energy Savings	Cooling Source Energy (kBtu/yr)	% Cooling Energy Savings
1	Pre Retrofit Base Case (BC)	284	-	166	-	16.9	-
2	BC + New Walls (R-31+Radiant Wall)	262	8%	147	11%	14.3	15%
3	BC + White Metal Roof (Cool Roof)	281	1%	169	-2%	11.8	30%
4	BC + Unvented Attic (R-53+Radiant Barrier)	223	21%	113	32%	9.3	45%
5	BC + Slab insulation	255	10%	134	19%	19.8	-17%
6	BC + Triple Pane Low-e windows	208	27%	99	40%	8.0	52%
7	BC + Reduced infiltration (0.40 ACH_{50})	256	10%	139	16%	16.5	2%
8	BC + Mini-Split HP	202	29%	91	45%	10.2	40%
9	BC + ERV	293	-3%	171	-3%	17.1	-1%
10	BC + Envelope Package (Runs 2-7)	115	59%	13	92%	2.1	87%

4.4 Annual Energy Use

Total building energy use, net electricity use, and energy by end use for heating, cooling, ventilation, and DHW were calculated annually from monitored data for comparison with BEopt estimates. Utility bills from PG&E were provided by LBNL to inform total building gas usage. Building electrical metering was managed by LBNL. Due to system difficulties, LBNL data was unavailable from December, 2010 through the second week in February, 2011. Consequently, gross and net building energy use data was only available for 39 weeks in 2011. This data was extrapolated to estimate annual totals. While more granular monitoring of individual electrical panels was conducted by LBNL, due to the difficulties of isolating end uses, specifically lighting, further disaggregation of appliance, lighting, and miscellaneous electric load (MEL) electricity use was not possible. The BEopt model was calibrated to reflect actual blower door infiltration measurements, average seasonal interior temperature during the summer and winter, which were 76^{o}F and 73^{o}F, respectively, and actual airflow and fan efficiency of the ERV. The annual energy figures are presented in Table 8.

BEopt is limited in its ability to evaluate a number of features in the Sonoma House including vented wall cavities with reflective airspaces, solar thermal space heating, and mini-split heat pumps. However, total gross annual electricity use aligns reasonably well between monitored and expected, within 14%. Annual PV production was underestimated by BEopt by 17%, resulting in a difference in net energy use of 40%. While pre-retrofit energy data is unavailable because the residence was purchased as a foreclosure, given the overestimate by BEopt of total energy use, it is reasonable to assume that at the building level this project has achieved its energy savings goals. Given the deep energy savings (56% source) that were estimated, at a minimum, the PMM goal for existing homes have been met.

The most significant discrepancies between monitored and estimated energy exist in space cooling and mechanical ventilation. As previously described, the ERV was set to deliver 70 CFM of outdoor air continuously, approximately 30% greater than the minimum required by ASHRAE 62.2 of 54 CFM. The increase in electricity use is primarily a result of increased fan power draw due to a clogged inlet vent. During the 2011 summer, review of monitoring data revealed that the ERV power was substantially higher than the expected baseline and had been increasing over time. A site visit confirmed that the ERV outdoor intake grille was severely clogged with debris, primarily plant matter. Once the grille was cleaned, the power measurement immediately dropped back down to its previous value. After another few months, the power began to creep up as the grille became clogged once again. This occurrence resulted in a substantial increase in system annual electricity use as well as efficiency decrease due to performance degradation. Unfortunately, the outdoor grille was not designed to be removed and cleaned; however, regular maintenance will need to be performed to ensure continued proper ERV operation. Systems that are designed with outdoor filters that are easy to be replaced or cleaned would help simplify this problem. Also, care should be taken to properly locate the outdoor air intake away from any obvious source of debris; however, it wasn’t clear that this was the problem at the Sonoma House.

The appliance and miscellaneous gas consumption is attributed solely to gas range use. Due to occupant use patterns, actual gas cooking use is much lower than estimated by BEopt.

Table 8. Annual Energy Use Comparison of Monitored and Modeling Estimates – Site Electricity and Gas

	Annual Site Energy			
	Monitored Data		BEopt Modeling Estimates	
End Use	kWh	Therms	kWh	Therms
Space Heating	1,310	-	1,619	-
Space Cooling	369	-	207	-
Domestic Hot Water	78	28	97	19
Appliances, Lighting + MELs	4,626	4	5,738	24
OA Ventilation (ERV)	922	-	638	-
Total Usage	7,305	32	8,299	43
Site Generation	(3,419)	-	(2,844)	-
Net Energy Use	3,886	32	5,455	43

Estimated space cooling energy from BEopt is 44% less than actual, while estimated heating energy use is 24% more than actual. A calibrated BEopt run was not completed using actual weather data, but heating degree days (HDDs) and cooling degree days (CDDs) from the monitored period were compared to the weather file[7]. Figure 17 compares heating and cooling degree days for the TMY3 weather file used in the BEopt model (Santa Rosa - AWOS) and monitored weather data at the Sonoma House. Monthly and annual heating degree days align fairly well. However, annual cooling degree days from the monitoring period are twice that of those based on the TMY3 data. This is especially true in July, which saw the highest cooling energy use of the season. The differences in cooling energy use could easily be explained by the differences between last summer's cooling weather and the weather file. Differences in heating energy use are not as significant and monitored heating energy use is expected to be lower than modeled values because the solar heating contribution through the fan coil in the ERV was not able to be modeled in BEopt.

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[7] Daily HDDs and CDDs were calculated using daily mean temperatures estimated as the average between the daily maximum and minimum temperatures.

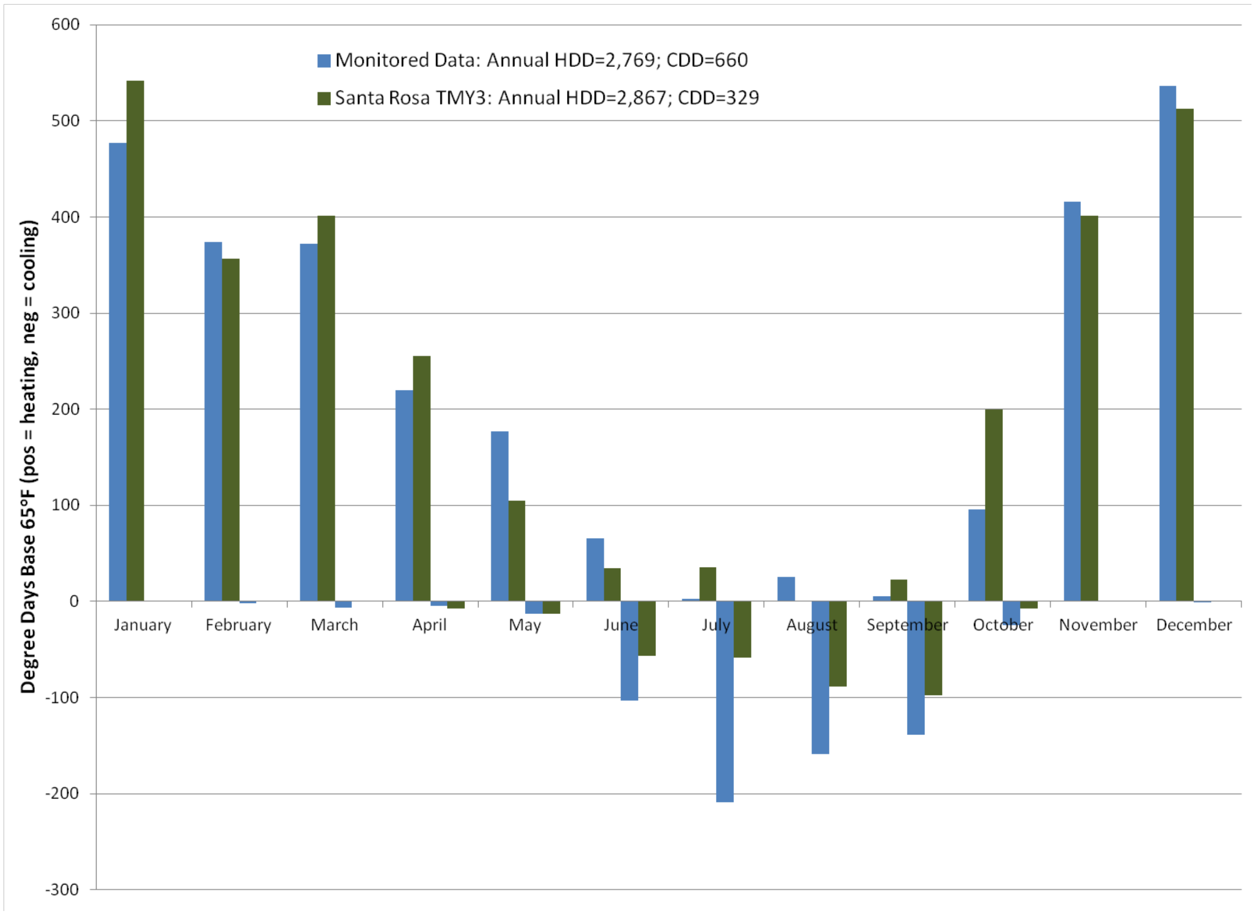

Figure 17. Degree day comparison

Monitored energy use by end use was converted to source energy using national average figures for energy consumption and is shown in Figure 18. Over 60% of total source energy is attributed to appliances, lighting, and miscellaneous energy use. In this mild marine climate, space heating and space cooling only represent 17% and 5% of total energy, respectively. The miscellaneous category also includes loads such as irrigation and a pump for an outdoor water fountain. Water heating energy use is significantly reduced due to the solar water heating system.

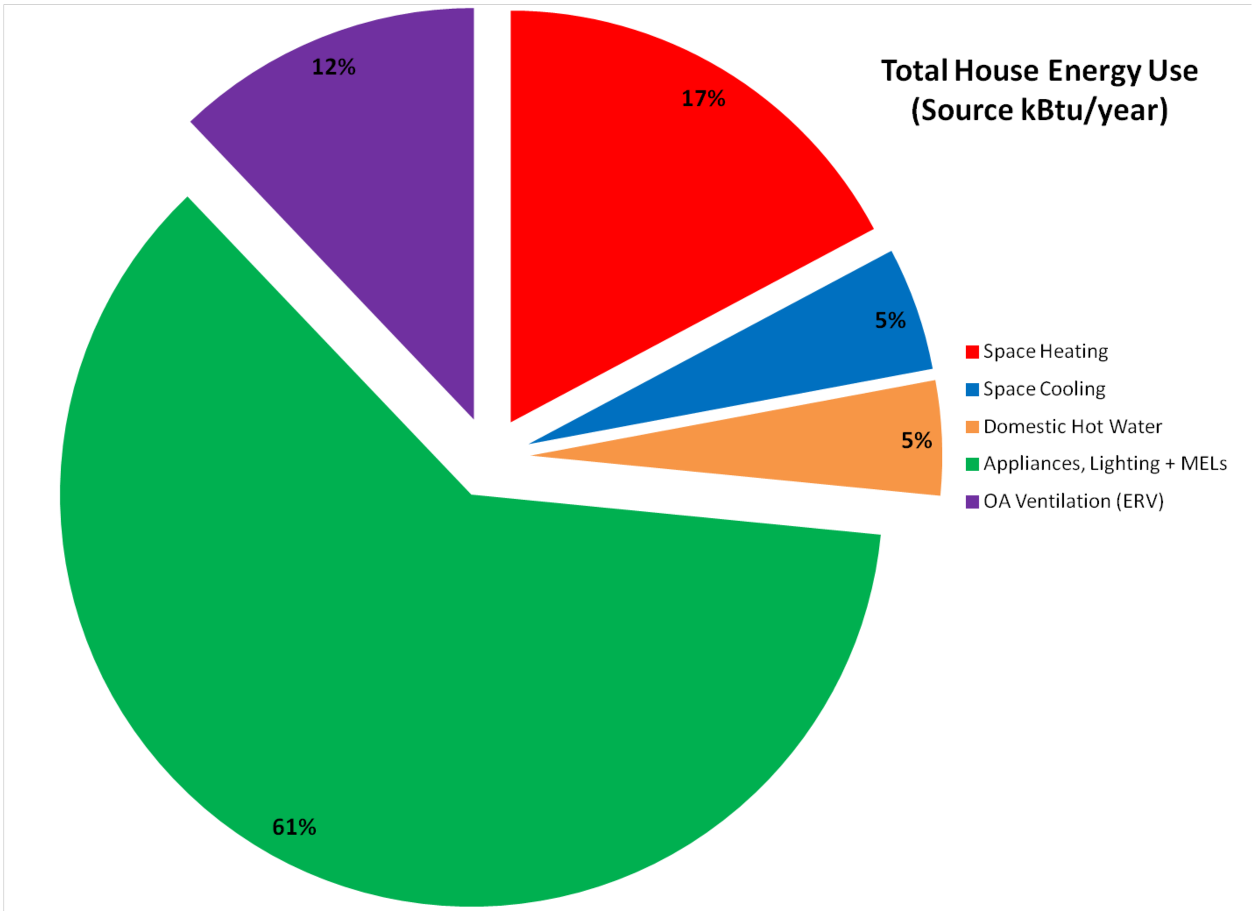

Figure 18. Breakdown of monitored energy use

Modeling was also conducted by other consultants for PH program participation. The PH program has maximum heating energy and maximum total source energy use requirements of 4.75 kBtu/ft^2/yr and 38.1 kBtu/ft^2/yr, respectively. Table 9 compares actual energy use to both the PH requirements and the design targets determined by the PH consultant. Annual heating energy use was taken from the full year of monitoring heating energy use. Total annual source energy use was extrapolated from the 39 weeks of data provided by LBNL. Actual energy use was significantly lower than the design target, especially for heating energy, and met the PH performance standards.

Table 9. Passive House Energy Target Comparison

	Annual Energy (kBtu/ft^2/yr)		
	PH Standard	Design Target	Actual
Space Heating (Site)	4.75	4.1	1.88
Total Energy (Source)	38.1	27.6	20.0

4.5 Project Costs and Builder Feedback

The builder provided total project costs and a breakdown for each of the major EEMs. Table 10 summarizes these costs, which are actual costs to the builder over the pre-retrofit base case and include both material and labor. All costs are gross costs and do not include any available incentives. Since this project incorporated an addition of almost 450 ft^2 of conditioned floor area, these project costs do not completely isolate the cost of the energy upgrade to the existing home with a portion of some of the costs attributed to the addition, such as the framing of new walls. Also, the costs for air sealing measures are difficult to isolate and potentially may be greater than the $1,600 listed below. Some of this incremental cost may be wrapped up in the wall and roof assembly costs.

The cost effectiveness of individual measures is difficult to quantify due to the interactive effects of combining EEMs in a building. Defining cost effectiveness for retrofit applications presents additional complexities due to all the non-energy benefits inherent to many upgrades in existing homes. Adding insulation, replacing windows and air sealing can turn a previously uncomfortable home into a comfortable, quiet, and enjoyable space.

Table 10. Energy Related Measure Project Costs

EEM Description	Measure Cost
Exterior walls: framing of new walls, R-15 or R-21 cavity insulation + R-16 EPS + radiant wall/air gap	$39,450
Unvented attic & roof insulation (R-53+Radiant Barrier)	$30,000
Slab insulation	$16,500
Triple pane low-e windows	$91,000
Reduced infiltration (0.40 ACH_{50})	$1,600
Mini-split heat pump	$12,000
Hydronic coil in ERV & integration of solar thermal for space heating	$2,100
ERV	$8,400
Tankless water heater	$6,500
Solar water heater	$13,650
ENERGY STAR appliances	$19,455
LED & fluorescent lighting	$62,000
PV solar system	$18,600
Total	$321,255

The “builder standard” for this project is a house built to qualify as LEED-Homes Silver. The builder specializes in “green” construction and retrofits. The area in which he builds (Sonoma County) includes a population that is environmentally conscientious and interested in reducing building energy use. The town of Sonoma requires that all construction perform at least 15% better than the 2008 California Title-24 energy code. The builder bid the project as both a PH retrofit and a standard “green” retrofit. According to the builder, a conventional “green” retrofit for this project would include the following measures:

- Dual pane low-e windows
- Existing walls: 2 × 4 16 in. oc with R-15 cavity insulation. New walls: 2 × 6 24 in. oc with R-21 cavity insulation
- Vented attic with a high level of blown attic insulation
- No slab insulation
- Air sealing to ~ 5 ACH_{50}
- Solar thermal DHW
- High efficiency ducted heat pump, no solar space heating
- Rooftop solar PV
- Similar lighting and appliances measures.

The incremental cost for the Sonoma Deep Retrofit above a conventional "green" retrofit is an estimated $96,000, or a premium of 11% cost. Assuming a 5.5% interest rate on a 30-year mortgage, the monthly incremental cost would be approximately $545. Predicted savings based on BEopt for the Sonoma Deep Retrofit over the conventional "green" retrofit are estimated at 40% source energy[8], resulting in $61[9] monthly utility bill savings. While these savings are substantial, they do not justify this cost increase. Because of the relatively mild (marine) climate, heating and cooling energy costs are much lower than seen in more extreme climates. The PH concept originated in Germany, which is a cold climate with high heating loads and more expensive energy costs. Provided this is a test house and the builder's first PH project, it is expected that this price increase can be reduced based on builder feedback discussed below.

A majority of the incremental cost was spent on envelope measures, which provided a highly insulated and tightly constructed building. Wall, roof and foundation insulation and air sealing practices were both costly and labor intensive and involved education and training on the part of the builder and subcontractors. However, this strategy has the potential in similar marine climates to eliminate cooling altogether and in smaller homes, where internal gains dominate, perhaps even eliminate heating.

The triple pane windows, imported from Germany, were one of the most expensive elements of the project, and can't be justified by energy savings alone. Table 11 shows a cost and payback comparison for the triple pane windows that were installed and a standard dual glazed low-e window. The high SHGC of 0.52 is the same for both windows, so the energy savings reflect the difference in U-value only. Both incremental window costs are high, partly due to the portion of total cost attributed to non-energy characteristics. These non-energy benefits need to be taken into account when selecting windows; however, there is not a straightforward way to do this with standard cost effectiveness analyses. It also should be noted that total glazing area in the house is high at around 25% of total wall area, also increasing total costs.

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[8] Estimated savings for the conventional green retrofit over the pre-retrofit case are 26% source energy based on BEopt modeling.

[9] Based on a national average electricity rate of $0.1126. There are no gas savings.

Table 11. Window Incremental Performance Comparison

Base Case	Incremental Measure	Source Energy Savings (kBtu/yr)	Incremental Cost ($)	Annual Utility Savings ($/yr)	Simple Payback (yr)
Pre Retrofit Base Case (BC)	BC + Dual standard Low-e windows	42	$59,500	$1,320	45
Pre Retrofit Base Case (BC)	BC + Triple pane Low-e windows	76	$91,000	$1,631	55

While mini-split heat pumps are readily available, their market share remains low and incremental costs are high. Additionally, their benefits have yet to be completely quantified and performance over a range of operating conditions adequately understood. However, eliminating duct losses allows for system downsizing and, in homes where a single indoor unit sufficiently satisfies the loads, the savings achieved from eliminating a centrally ducted system may justify the costs. Also, previous lab and field studies by Ecotope have shown good agreement between lab, field and manufacturers' rated COPs (NEEA 2011).

Even with the high incremental costs, the builder is still committed to building to PH standards. This test house has allowed for identification of more cost-effective means of achieving similar deep energy savings. Based on his experience of installing the advanced building retrofit measures, the builder decided on the following changes for future projects.

- Simplified wall assemblies: Exterior foam insulation above a certain thickness requires unique means of properly securing the sheathing, such as furring strips. These methods were labor intensive and unfamiliar to the installers. The builder conveyed that he would use a staggered double stud assembly for future deep retrofits and new homes to reduce thermal bridging. This approach incorporates construction practices that are familiar to builders, reducing both labor and material costs. This practice may not be feasible for many existing homes where converting single stud walls to double stud walls would be complicated, expensive, and reduce indoor floor area. In these cases, reducing exterior foam insulation to 1 in. of EPS can reduce costs significantly and improve the cost effectiveness of exterior wall retrofits in mild climates.
- Standardized air sealing: The builder used a variety of air sealing tape products in the Sonoma House. While this allowed him to test the effectiveness and usability of a number of brands, it was costly and complicated. From this experience, he has identified a single brand that is both cost effective and performs well. In addition, substituting the use of tape around wire and plumbing penetrations with EPDM gaskets would further reduce cost. While building gaskets are more expensive than standard caulk and foam, many in the PH industry endorse their benefits because of superior sealing capabilities, longer lifetime, and ease of installation and verification of proper application. The Grace Ice & Water Shield® used on the Sonoma House as a waterproofing layer on the exterior walls added unnecessary cost, and the builder felt that standard house wraps would suffice for this application if they are properly taped, and are about one third of the cost.
- Solar thermal for DHW only: The complexity of integrating the solar thermal system with space heating (using the ERV fan) was not cost effective in the Sonoma House.

Higher heating loads would be required to improve cost effectiveness. Increased solar storage capacity would increase the solar contribution but would likely not improve the cost effectiveness in the mild climate.

This project also identified measures and techniques that the builder considered successful and will continue to incorporate in future projects.

- Windows: As previously discussed, windows were the single most costly component of the project. However, in the builder's opinion, the German-manufactured triple pane windows are unparalleled in performance, quality, and durability to any other products available in the United States. He has worked with products from many national manufacturers, including Serious Materials, and has not found a window with comparable glazing properties, both thermal performance and visible light transmittance, and longevity. Other benefits include superb air sealing. He will continue to import German windows in all future jobs that are able to support the costs.
- Unvented attic: The builder felt that converting the attic to a non-vented space for mechanical equipment provided substantial energy benefits that were justified by the cost. For retrofit applications, the builder's takeaway was that installing blown cellulose using netting in between the roof trusses and at knee walls was fairly simple. When the roof is being replaced anyway, adding rigid foam insulation is an easy modification. He would reduce the thickness of rigid to 1 in. for simplicity and cost savings. However, truss configuration and space constraints in some existing attics may complicate this process and it may be difficult to achieve an R-value equivalent to R-38 or R-49 at the roof, which is easily attained with a typical depth of blown-in cellulose or fiberglass at the ceiling level. Unless mechanical equipment and ducts are located in the attic, it may be more cost effective to seal the attic floor and blow in insulation.

The extreme building envelope and window features will not likely become cost effective in mild climates with low heating and cooling energy needs anytime soon without significant material and labor cost reductions or significant increases in energy costs. While the incremental costs of the measures implemented to meet PH standards are much higher than can be justified by current energy savings, there still seems to be a growing market for PH. The builder indicated he receives one or two inquiries per week from homeowners inquiring about PH projects and none for conventional construction. The current market seems to lie in high end custom homes and deep retrofits, where the incremental costs for the energy features may be small in comparison to other non-energy features included in the house. In the case of the Sonoma project, the $96,000 price tag for the energy features was only 10% of the overall cost of the deep retrofit. Regardless of the questionable cost effectiveness of homes built to PH standards, the program is having an impact on the general market for high performance homes, and is helping to educate builders on better building practices. Because of overlapping practices and standards, it is probable that the PH program may also yield benefits to other programs aimed at improving efficiency. The Sonoma project has received a lot of attention both nationally and locally, and the builder is currently working on a new construction PH project in Sonoma and is in the bid process for another PH deep retrofit. In this respect, the Sonoma House project was both marketable and commercially viable in selected markets.

5 Recommendations and Conclusions

Measured energy use of the Sonoma House matches reasonably well with expectations from BEopt modeling and confirms that the project has attained its energy savings goals. Savings over the pre-retrofit case, estimated from BEopt, are 56% of total source energy. Envelope measures including high R-value wall, floor, and ceiling assemblies and tight air sealing were effective at reducing building loads. Builder air sealing techniques were very successful and decreased infiltration to 0.40 ACH_{50}. The incremental costs to reduce building loads to this level were not insignificant. Retrofitting the house to the levels of insulation used is not currently cost effective in the mild climate where heating and cooling loads are relatively low. Through the process, methods were identified to achieve similar results more cost effectively, although additional test houses will also be valuable to contribute further to this knowledge set. Parametric modeling with BEopt showed that the installed package of envelope measures provides twice the source energy savings than simply upgrading the heating and cooling system to a high efficiency unit.

The solar water heating system performed very well and was able to support the majority of the domestic water heating load on an annual basis. The average annual solar fraction was 78% with solar fractions during the summer months exceeding 90%. Tankless efficiencies were lower than expected, due in part to unnecessary firing of the tankless water heater during the summer when the solar tank was capable of supplying the entire load for a hot water draw, and also due to low daily hot water use. Tankless performance, when paired with solar hot water systems, can be improved if proper controls are in place. At its simplest, the tankless water heater can be unplugged during the summer months since monitoring shows that tank temperatures remained above 120^{o}F most of the summer (June-September) and never dropped below 104^{o}F. A better solution would be to provide a bypass valve around the tankless water heater when storage tank temperatures are adequate for hot water loads. Additionally, mixing valve location can affect system performance. Some manufacturers recommend locating the mixing valve before the tankless to reduce the incoming temperature to a range so that the tankless may operate without cycling or thermally stressing the heat exchanger. However, this can cause unnecessary firing of the water heater, especially during the summer when entering temperatures may be sufficient to supply the water heating load. Controls developed by the manufacturers to better monitor entering conditions and only fire the water heater when necessary may also provide a solution.

The solar water heating system was not nearly as effective in offsetting space heating loads, only providing an estimated 20% of the annual heating load. Given the added complexity and cost, it does not make sense in mild climates. Additionally, Sonoma is relatively dry for a marine climate with fewer overcast days that other more humid marine locations, which may experience less solar radiation on an annual basis for conversion to useful thermal energy.

The installed windows do not qualify for the federal energy efficiency tax credit as an ENERGY STAR window because of the high SHGC. The ENERGY STAR window performance requirements are based on broad geographic regions that do not adequately reflect the sub-climates within, and particularly marine climates. Sonoma has a very minimal cooling load with annual (HDD six times greater than CDD. Sonoma is in the same ENERGY STAR climate region as Fresno, California, which has over three times the CDD as Sonoma. We recommend that ENERGY STAR consider relaxing the requirement for low SHGCs in these climates, as modeling shows they increase annual energy use.

This test house has provided valuable insight into the performance and cost effectiveness of PH strategies as a means of achieving deep energy retrofit savings in a marine climate. Builders, such as PassivWorks, who are willing to experiment with non-industry standard construction methods, as well as homeowners who are willing to fund such efforts, are invaluable to the process of identifying, defining, and refining cost effective practices for deep energy savings. The Sonoma House has made a valuable contribution in advancing research aimed towards zero net energy homes. Information gained from the construction process and detailed building monitoring has identified best practices, "lessons learned," and other practical recommendations that will contribute to future deep retrofit and new construction projects.

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Appendix A: Building Plans

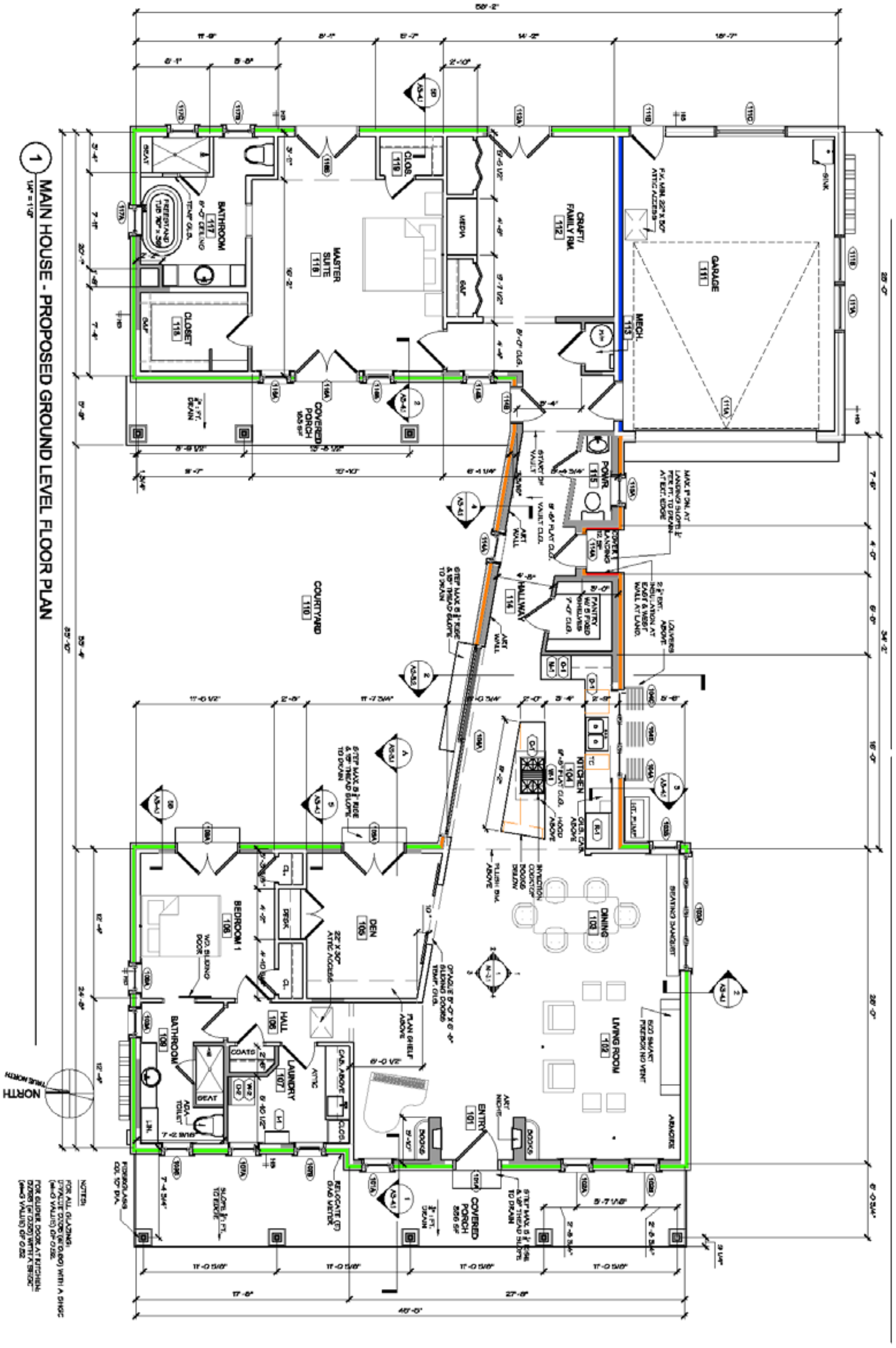

Figure 19. Floor plan with wall assembly descriptions

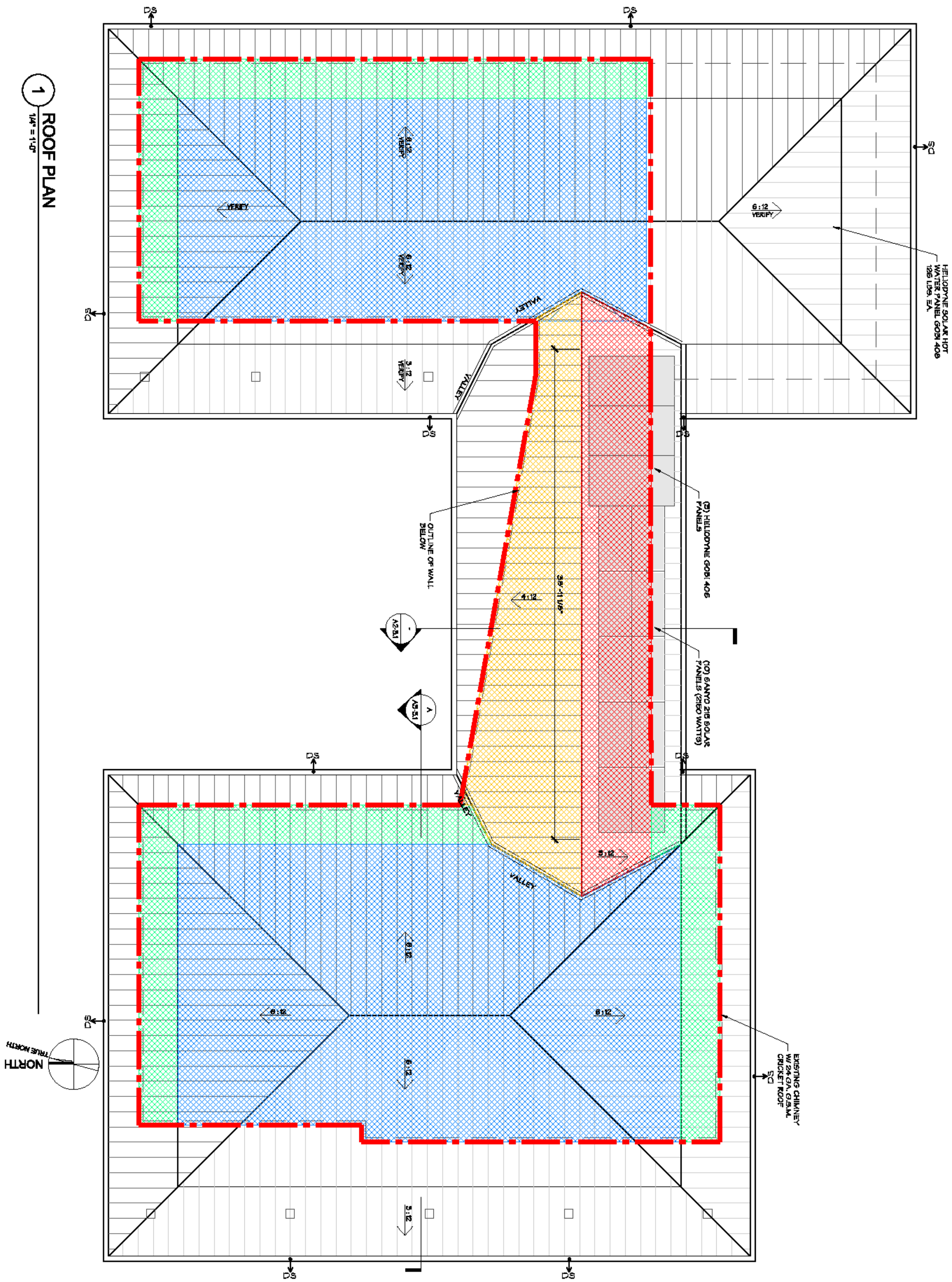

Figure 20. Roof plan with roof assembly descriptions

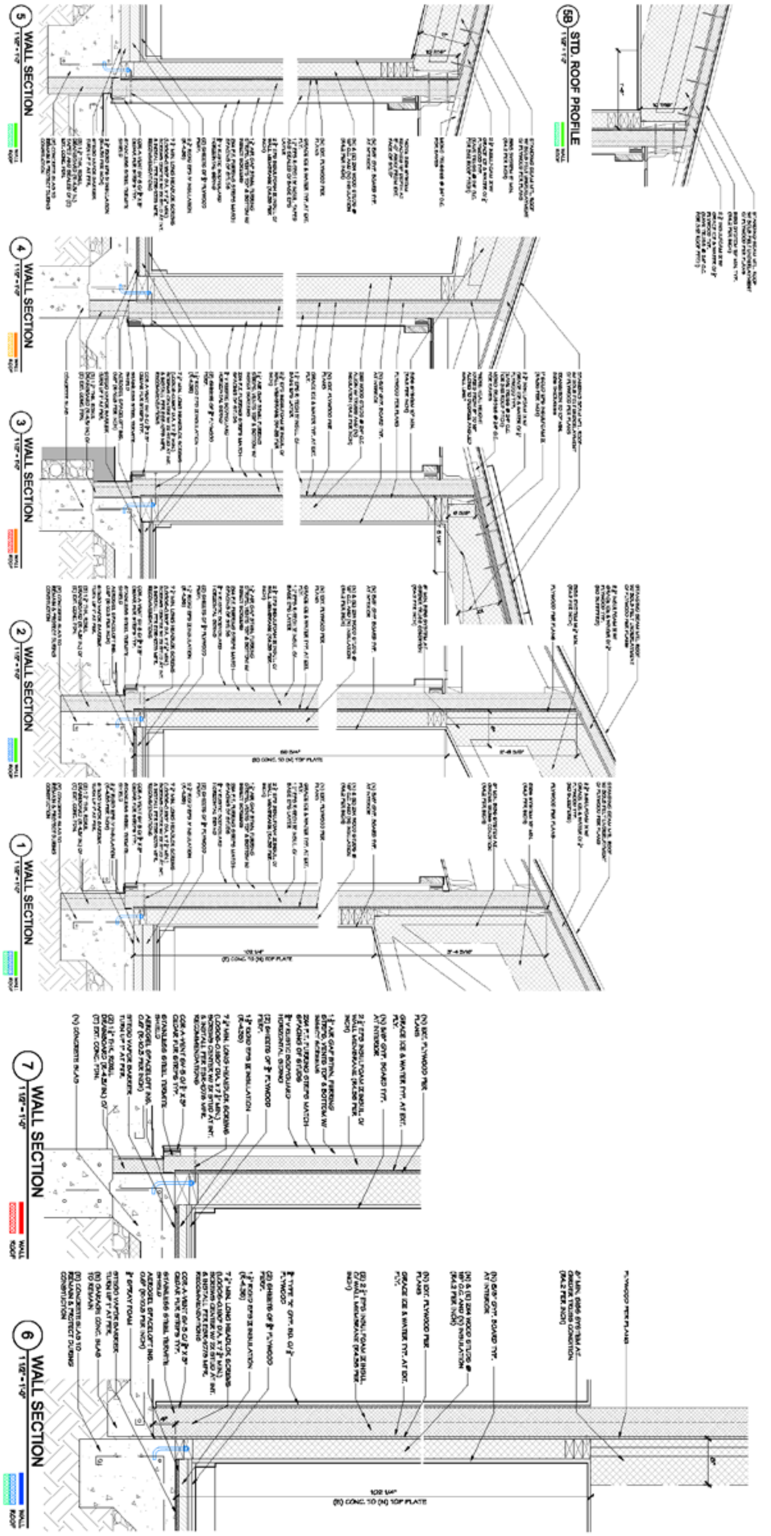

Figure 21. Wall and roof section details

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