Super Energy Efficient Design (S.E.E.D.) Home Evaluation

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Alliance for Residential Building Innovation (ARBI)

December 2012

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Definitions

ACH_{50}	Air changes per hour at 50 Pascals
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ARBI	Alliance for Residential Building Innovation
AWHP	Air-to-water heat pump
Btu	British thermal unit
CARB	Consortium for Advanced Residential Buildings
COP	Coefficient of performance
DEG	Davis Energy Group
DHW	Domestic hot water
DX	Direct expansion
ECM	Electronically commutated motor
EER	Energy efficiency ratio
ERV	Energy recovery ventilator
HERS	Home Energy Rating System
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilation, and air conditioning
kWh	Kilowatt-hour
PSC	Permanent split capacitor (motor)
PV	Photovoltaic
RCS	Reverse cycle chiller
S.E.E.D.	Super Energy Efficient Design
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SIP	Structurally insulated panel

Foreword

The “Super Energy Efficient Design” (S.E.E.D) home being evaluated under this project is a 1,935 ft^2, single-story spec home located in Tucson, Arizona. This prototype design was developed with the goal of providing an exceptionally energy efficient yet affordable home. The design includes numerous aggressive energy features intended to significantly reduce heating and cooling loads, such as structurally insulation panel (SIP) walls and roof, high performance windows, an energy recovery ventilator (ERV), an air-to-water heat pump with mixed-mode radiant and forced air delivery, solar water heating, and rooftop photovoltaic (PV) system. Source energy savings are estimated at 45% over the Building America B10 Benchmark. This project provides an opportunity to evaluate the commercial viability of these aggressive energy measures in a hot-dry climate.

The Alliance for Residential Building Innovation (ARBI) team used system commissioning, short term testing, long term monitoring and detailed analysis of results to identify the performance attributes and cost effectiveness of the whole house measure package. System monitoring was initiated in the summer of 2011 and the home was occupied in August, 2011. Results are presented from nine months of data collection. Actual post construction costs were obtained from the builder, and a cost effectiveness analysis was completed to evaluate commercial viability. Energy use was compared to BEopt model estimations, and annual cost benefits are determined relative to the builder standard.

Acknowledgements

Davis Energy Group would like to acknowledge the U.S. Department of Energy Building America program for their funding and support of development of this technical report as well as research that informed it. In addition, we would like to thank builder Michael Ginsburg of La Mirada Homes for his ongoing cooperation throughout the design, construction, and monitoring stages of this project.

1 Introduction

1.1 Background and Motivation

The "Super Energy Efficient Designed" (S.E.E.D.)[1] home being evaluated under this project is a 1,935 ft^2, single-story spec home located in Tucson, Arizona. The builder, Michael Ginsburg of La Mirada Homes, developed this prototype design with the goal of providing exceptionally energy efficient yet affordable homes and to determine which technologies and strategies will cost effectively accomplish this goal. The numerous aggressive energy efficiency measures that are incorporated into the S.E.E.D House contribute significantly to source energy reductions with an estimated 45% savings over the Building America B10 Benchmark (Hendron et al, 2010). Envelope measures significantly reduce the heating and cooling load and include structurally insulated panel (SIP) walls with added exterior foam, SIP roof panels, high performance low-E vinyl framed windows with a low solar heat gain coefficient (SHGC), appropriate shading by overhangs and exterior screens, and a fully insulated slab floor. The mechanical system consists of an air-to-water heat pump (AWHP) with a mixed-mode delivery system that delivers hot water through radiant floor tubing embedded in the slab, and chilled water through a combination of a small fan coil and the floor tubing. An energy recovery ventilator (ERV) is installed to provide filtered fresh air while minimizing the associated heating and cooling penalties of bringing in outside air. A solar water heating system with electric backup provides water heating and a rooftop photovoltaic (PV) system offsets utility electricity use. These measures, and specifically the package of measures, have the potential to lead to market-ready solutions that cost effectively provide comfort in homes with efficient, healthy, safe, and durable operation. Through detailed monitoring, this project affords the opportunity to evaluate the commercial viability of these energy measures in a hot-dry climate with an acute focus on the mixed-mode chilled water cooling delivery.

While the focus is on evaluation of measures specific to new construction single family residences in hot-dry climates, many of the energy efficiency measures are appropriate for various climate regions and in multifamily construction. The Building America Standing Technical Committees on Enclosures, Space Conditioning, and Analysis Methods have identified several gaps and barriers related to high performance building envelopes and HVAC and delivery systems. These outline the need for:

- Effective air tightness strategies
- Low cost space conditioning distribution strategies for low load homes
- Availability and documented performance of high efficiency, small capacity heating and cooling equipment for low load situations
- Better evaluation of alternative space conditioning systems (i.e. hydronic delivery).

Following on favorable results from a 2007 Building America study in Borrego Springs, California (Springer et al, 2008), the Davis Energy Group (DEG) was interested in using this house for further evaluation of mixed-mode chilled water cooling delivery. In the Borrego Springs test, two nearly identical homes were equipped with the same model 13 SEER condensing unit, one connected to a conventional DX evaporator coil and ducted distribution

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[1] http://lamiradahomes.net/lamirada_homes_seed.htm

system, and the other to a refrigerant-to-water heat exchanger with mixed-mode distribution. During the test period from July through September 2007, energy efficiency ratios (EERs) of 5.1 and 10.3 were measured for the standard system and the chilled water system, respectively. It was theorized that the reduced "thermal lift" resulting from the relatively high evaporator temperature of the chilled water system was responsible for the substantial reduction in compressor power.

For heating and cooling, the S.E.E.D. home incorporates an Aqua Products AWPH ("reverse cycle chiller") connected to a distribution system that consists of a small fan coil piped in series with the radiant floor (see Figure 1). The fan coil is included primarily to provide latent cooling during humid conditions. This system design is being evaluated in detail under ARBI Task 2, Project 1: Air-to-Water Heat Pumps with Mixed-Mode Delivery.

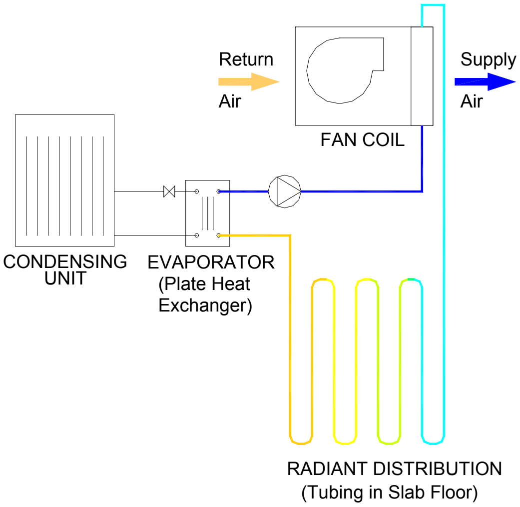

Figure 1. Schematic of mixed mode cooling system

1.2 Objectives and Research Questions

The primary objective of this study is to determine how well the high performance envelope and innovative cooling system interact to cost effectively reduce cooling energy use in this hot-dry climate. Efforts are made to answer the following research questions in this report.

1. Does the house meet the design expectations for energy efficiency, cost effectiveness, and marketability?
2. How effective is the combination of the high performance envelope, ERV, and other measures at minimizing the heating and cooling load, and what are the energy savings?

2 Project Description

The 1,935ft^2 S.E.E.D. house is located in Tucson, Arizona, which is in a hot-dry climate (IECC Climate Zone 2), at 2,400 ft elevation. The heating and cooling degree days for Tucson are 1,578 and 3,017, respectively (65° base). While the early summer is characteristically hot and dry, the monsoon season of late summer brings frequent rain and associated higher humidity. Figure 2 shows a picture of the completed house. See Appendix A and Figure A - 1 for a schematic floor plan.

Figure 2. Completed S.E.E.D house

During 2009 and 2010, DEG worked with La Mirada to provide HVAC and radiant design assistance, assist in selection of the energy efficiency measures, and model the house using EnergyGauge for evaluation relative to Building America Benchmark goals. DEG also assisted the builder in properly evaluating heating and cooling loads and duct sizing using ACCA Manual J and D methodologies so that equipment oversizing was avoided and proper system airflow was assured. The builder made the decision to use SIP walls and roof panels early in the design process. The SIP wall and roof panels are highly compatible with flat-roof Southwest architecture, simplify construction, and can potentially have a lower finished cost than frame walls and trusses.

As the builder wanted to pursue the idea of including solar space heating, TRNSYS simulations were conducted to estimate the feasibility and energy use implications of options, including solar water heating, and solar water heating plus space heating. This analysis showed that the space heating component was not cost effective. The resulting report convinced the builder to provide a solar water heater that would only serve domestic water heating loads. This report is included as an appendix in the Building America Test Plan (ARBI 2011).

The builder was also interested in eliminating ducting and planned to use radiant floor heating, but was unsure how best to deliver cooling. DEG recommended the use of an AWHP with a mixed-mode delivery system that utilizes a small fan coil and a radiant floor cooling system for distribution for the following reasons:

- The flat roof design and lack of an attic allows little room for ducting; the small fan coil allowed use of small ducts that could fit within framing and soffits.
- Heat pump heating is the logical choice in an all-electric house.
- The exposed concrete floor facilitates the use of radiant cooling and improves the efficiency of radiant heating due to the lower resistance to upward heat flow and more moderate water temperatures.
- The water-based system with buffer tank and thermal energy storage in the floor slab can accommodate very low heating and cooling capacity without resulting in equipment short-cycling.
- The hydronic fan coil provides insurance against indoor humidity build-up and consequent floor condensation, and helps return higher temperature water to the evaporator in summer and lower water temperature in winter, resulting in improved heat pump performance.

Construction of the house began in March 2010. Walls were raised in July and the house was completed in April 2011. Monitoring of the house and the building mechanical systems has been initiated and will continue for a period of at least one year.

2.1 Energy Efficiency Measure Details

Table 1 summarizes the energy efficiency measures incorporated in the S.E.E.D. House.

Table 1. Building Energy Efficiency Measures

Measure	Specification
Basic Building Characteristics	
Building Type / Stories	Single Family, 1 story
Conditioned Floor Area	1935
Number of Bedrooms	4
Envelope	
Exterior Wall Construction	4.5 in. SIP Walls
Exterior Wall Insulation	4.5 in. SIP Panels (R-27) + R5 exterior foam insulation
Foundation Type & Insulation	Slab-on-grade w/ R-10 below slab and R-7 at edge
Roofing Material & Color	3-ply built-up roof with CRCC Rated Cool Roof
Ceiling Insulation	6.5 in. R-41 SIP Panels
Roof Deck Insulation	R-41
Radiant Barrier	No
House Infiltration - Blower Door Test	2.4 ACH_{50}
Thermal Bypass Inspection - QII	Yes
Thermal Mass	5 in. thick exposed concrete floor
Glass Properties: U-Value / SHGC	
All Windows	2-Pane Low-E, Low SHGC Vinyl 0.29 / 0.21
HVAC Equipment	
Heating Type & Efficiency	Heat Pump, 9 HSPF
AC Type & Efficiency	HP, 13 SEER, 11 EER
Heating & Cooling Distribution	Radiant floor & ducted
Duct Location & Insulation	In Conditioned Space, R-6
Verify Duct Leakage	Yes, <6%
Verify Cooling Right Sizing	Yes
Ventilation Cooling	n/a
Mechanical Ventilation	ERV, Ducted
Water Heating Equipment	
Water Heater Type & Efficiency	Electric Storage, RE 0.96
Tank Capacity/Gallons	80 gallon
HW Distribution	Time, Temp Recirculation, Master bath only
Solar Water Heater Type & Solar Fraction	Active / Closed Loop / 58% SF
Appliances & Lighting	
EnergyStar Appliances	Dishwasher/Fridge/Washer
Dryer Fuel	Electric
Oven / Range Fuel	Electric
Fluorescent Lighting Package	100% Flourescent
PV System	
PV Solar System Type & Capacity	3.4 kW DC system

Following is detailed information on individual measures that were selected, with discussion of their tradeoffs as appropriate.

Thermal Envelope

Walls/Roof: Polyurethane foam core SIPs are used for both the exterior wall and the roof. The SIPs construction was chosen for its thin profile and high R-value and to minimize thermal bridging, reduce the amount of wood used for framing, and reduce infiltration. The walls consist of 4.5 in. panels at R-27 plus 1 in. of R-5 exterior foam sheathing and 2 × 2 interior furring for electrical wiring. The roof is 6.5 in. SIP panel roof at R-41 with a 3-ply built up cool roof. The SIP roof panels have structural beam support resulting in solid foam panel-to-panel connection. While SIPs are currently more expensive than traditional wall framing, they require significantly less labor to install and reduce the risk of onsite installation defects. Additionally, they increase occupant comfort due to reduced infiltration and thermal bridging. Figure 3 shows the installation process for the walls.

Figure 3. SIP wall installation

Slab Foundation: The finished concrete floor surface reduces cost, facilitates the use of the thermal properties of the slab, and also matches the Southwest décor. R-10 rigid insulation is installed continuously below the slab and R-7 at the slab edge to reduce losses through the radiant heating and cooling (see Figure 4).

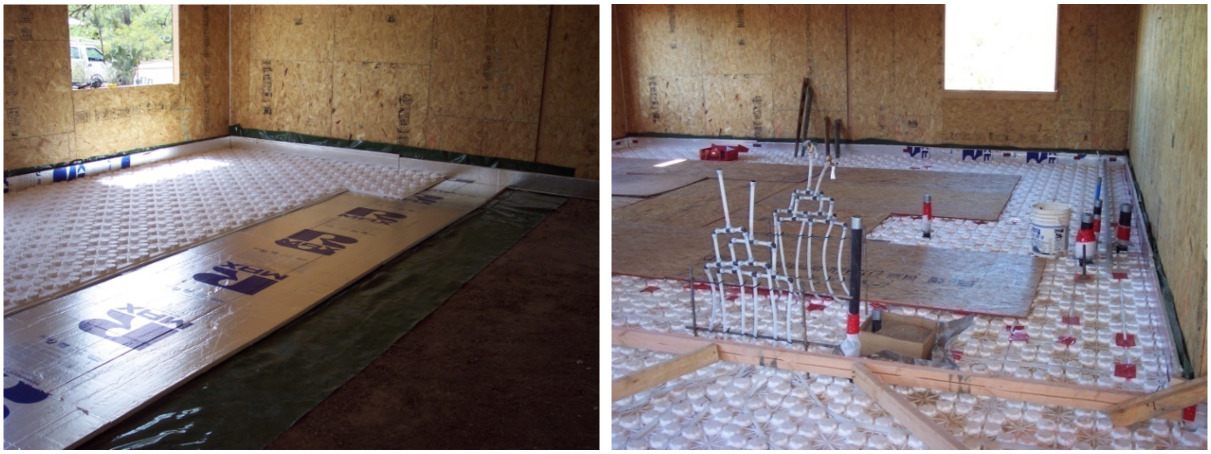

Figure 4. Insulation installed below slab (left) and PEX tubing laid out for radiant heating and cooling delivery (right)

Windows: High performance, vinyl-framed, argon gas-filled dual pane windows with a U-Factor of 0.29 Btu/hr-ft^2-°F and a solar heat gain coefficient (SHGC) of 0.21 were specified and installed. The house design also includes porches, screens, and overhangs to minimize direct solar gains through the windows year round (see Figure 5).

Air Tightness: The builder's intention was to attain a leakage rate of 5.0 ACH_{50} or lower by carefully caulking plates and other leakage points and by furring out exterior walls to create a chase for wiring and piping that are within the thermal and air barrier envelope. The tested ACH_{50} was 2.4. Extremely tight houses can present indoor air quality concerns if adequate mechanical ventilation is not provided; mechanical ventilation compliant with ASHRAE 62.2 (ASHRAE 2010) is provided via an ERV delivering filtered outdoor air throughout the house.

Figure 5. West elevation showing sun screen over window and air-to-water heat pump.

Mechanical Systems

Heating and Cooling: Both space heating and cooling are provided by the AWHP. Heating is delivered through the radiant floor while cooling is delivered via both the fan coil and radiant floor. The fan coil is sized to provide about half the required cooling capacity. The AWHP, manufactured by Aqua Products, consists of a 13 SEER Ruud heat pump perched on a module that contains the evaporator coil and temperature controls. Because the Ruud is installed with a non-matched heat exchanger coil it is not AHRI rated. Average rated efficiencies for this unit with a matched standard indoor evaporator coil are 11 EER and 9 HSPF. Figure 5 shows a picture of the installed unit. Chilled or hot water is piped first to a small fan coil to provide latent and sensible cooling (the fan is designed to only operate in the summer; however, an installed valve allows for fan coil bypass in any mode). The water is then delivered to the radiant floor tubing, which will provide the bulk of the sensible cooling and all of the heating. Piping chilled water to the fan coil first warms the water entering the slab and removes moisture in the supply airstream, reducing the risk of condensation on the floor surfaces. The fan coil is located in an insulated closet and all ductwork is in conditioned space. Figure 6 shows the installed hydronic equipment and piping. The small tank on the far right is the buffer tank for space conditioning. The large storage tank in the middle, with the drainback tank above it is for the solar domestic hot water (DHW). The hydronic fan coil can be seen on the far left in the closet.

Figure 6. Hydronic equipment and piping installed in the garage

Fresh Air Ventilation: An UltimateAir RecoupAerator ERV provides mechanical ventilation. The ERV exhausts air from the bathrooms, laundry and main room and supplies filtered outdoor air through the central heating and cooling duct system.

Water Heating: An 80-gallon storage tank is heated by a drainback solar water heater connected to an internal coil, and is supplemented by a 4500 W element located in the top of the tank. The solar water heating system includes one 4 ft × 10 ft flat plate collectors mounted at a 45 degree slope facing south, and the drainback tank is located above the storage tank (see Figure 6). Based on TRNSYS analysis, the solar heater should be able to provide nearly all of the hot water needs.

Lighting and Appliances

The S.E.E.D. house uses hard-wired fluorescent linear fixtures and CFLs for all hard-wired lighting. The dishwasher and builder-supplied clothes washer are ENERGY STAR® rated. The builder is also providing a central switch to disable non-critical consumer electronics throughout the house when not in use.

Photovoltaic System

A grid-connected 3.4 kW PV (DC) solar electric system is installed and is expected to produce most of the electrical energy used by the house on a net annual basis. While the PV system costs more than any one of the efficiency measures alone, it is a critical feature for the builder to determine the PV sizing required to achieve net zero energy and to help sell the home in the target market.

Figure 7. The 3kW photovoltaic system

2.2 Preliminary Savings and Cost Estimation

An evaluation was completed using BEopt v1.1 that predicts source energy savings for the S.E.E.D. House of 45% and 73% over the BA B10 Benchmark without and with PV, respectively. Savings over the regional standard are similar at 42% and 71% without and with PV, respectively. Arizona does not enforce a statewide energy code but allows individual municipalities to adopt and implement local codes. The city of Tucson enforces the 2006 International Energy Conservation Code (IECC) with certain local amendments. The "Regional Standard" energy savings reflect this baseline.

The building was modeled in BEopt using the specifications listed in Table 1; however, limitations due to BEopt capabilities and unknown operational efficiencies include the following:

- The AWHP seasonal efficiency is unknown. BEopt is only able to model air-to-air heat pumps. For modeling purposes, the rated efficiency of the Ruud heat pump was used.[2]
- The efficiency of the mixed-mode heating and cooling delivery system is unknown. Ducted distribution was modeled in BEopt with ducts located in conditioned space (per design).

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[2] Performance of the air-to-water heat pump is being calibrated using monitoring data and TRNSYS under ARBI Task 2, Project 1: Air-to-Water Heat Pumps with Mixed-Mode Delivery.

3 Methodology

3.1 General Technical Approach

The general approach of this research plan 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. Due to funding constraints, system level analysis was not conducted under this project. HVAC system design is being evaluated in detail under ARBI Task 2, Project 1: Air-to-Water Heat Pumps with Mixed-Mode Delivery.

The team verified control settings for the heating, cooling, and ventilation systems, and checked the operation of the heat pump, controls, zone valves, fan, and other components. Long-term monitoring is used to provide “continuous commissioning” and to identify failure of any components. DEG also verified that the builder has complete documentation on all systems, including installation, maintenance, and operation manuals, ready for conveyance to the owner.

Monitoring data is 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. Actual post-construction costs are obtained from the builder, and a cost effectiveness analysis is completed to evaluate commercial viability. Monitored energy use is compared to BEopt model estimations and annual cost benefits are determined relative to the builder standard. Nine months of occupied data are collected and evaluated for this analysis.

3.2 Measurements

The site is equipped with a data logger and modem for continuously collecting, storing, and transferring data via telephone lines or cellular communications. Sensors are scanned every 15 seconds, and data is summed or averaged (as appropriate) and stored in data logger memory every 15 minutes.

Monitoring Data Points

Table 2 lists all the measurement points that are monitored on a continuous basis. Key water side data points are shown in the piping diagram in Figure 8.

Short Term Tests

The DEG team and the HERS Rater collected additional data from the following short-term tests to support the calculations described in this test plan and facilitate answering the research questions. The tests are outlined below:

- A blower door test using standard protocols.
- A duct blast test to measure duct leakage (all ducts are in conditioned space).
- A water flow test to measure flows with different zone valves operating and with the fan coil bypassed.
- The air handler was tested to measure airflow, verify correct tap settings, and measure blower power.

- Heat pump circulation, solar loop, and hot water recirculation pumps measured to quantify power consumption.

Table 2. Monitoring Points List

Abbrev.	Description	Location	Sensor Type	Sensor Mfg./Model
TAO	Temp, air, outdoor	Northwest side of covered rear patio, in shade, on under side of patio roof	RTD, 4-20ma	RMYoung 41372LF
RHO	RH, air, outdoor		RH, 4-20ma	
TAI1	Temp, air, indoor, East	West Wing, next to T1, outside Bath 2, mount approx. 4 ft 6 in. high	RTD, 4-20ma	Vaisala HMW60
RHI1	RH, air, indoor, East		RH, 4-20ma	
TAI2	Temp, air, indoor, Living	Great Room, next to T2, on west wall of Dining area, mount approx. 4 ft 6 in. high	RTD, 4-20ma	Vaisala HMW60
RHI2	RH, air, indoor, Living		RH, 4-20ma	
TAI3	Temp, air, indoor, Master Bed	Master Bedroom, next to T3, on south wall, mount approx. 4 ft 6 in. high	RTD, 4-20ma	Vaisala HMW60
RHI3	RH, air, indoor, Master Bed		RH, 4-20ma	
TAS	Temp, air, AH Supply	Supply Plenum, Mech Rm	RTD, 4-20ma	Vaisala HMD60
RHS	RH air, AH Supply		RH, 4-20ma	
TAR	Temp, air, AH Return	Return Plenum, Mech Rm	RTD, 4-20ma	Vaisala HMD60
RHR	RH air, AH Return		RH, 4-20ma	
TWHL	Temp, Water, Heat Pump Leaving	Air Handler, Mech Rm	Immersion TT	Thermex
TWFS	Temp, Water, Floor Supply	Air Handler, Mech Rm	Immersion TT	Thermex
TWHE	Temp, Water, Heat Pump Return	Mechanical Room	Immersion TT	Thermex
TWCS	Temp, Water, Cold Water Supply	Mechanical Room	Immersion TT	Thermex
TWHO	Temp, Water, DHW Supply	Mechanical Room	Immersion TT	Thermex
TSF1	Slab bottom temp - zone 2	Living - floor surf near Tstat	Contact TT	Omega
TSF2	Floor surface temp - zone 2	Above insulation near Tstat	Contact TT	Omega
TSF3	Below slab insulation temp - zone 2	Below insulation near Tstat	Contact TT	Omega
TAERVS	Temp, air, ERV Supply	ERV Closet	RTD, 4-20ma	Vaisala HMD60\
RHERVS	RH, air, ERV Supply		RH, 4-20ma	
TAERVO	Temp air ERV Entering (Outdoors)	ERV Closet	RTD, 4-20ma	Vaisala HMD60
RHERVO	RH, air, ERV Entering (Outdoors)		RH, 4-20ma	
EHP	Energy, Heat Pump	At Outdoor Unit	Power Meter	Wattnode/WNB-3D-240-P
EHSE	Energy, Total House	Main Service Panel	Power Meter	Wattnode/WNA-1P-240P-PV
EWH	Energy, WH Electric Element	Mechanical Room	Power Meter	Wattnode/WNA-1-P-240P
EFAN	Energy, Air Handler Fan	Air Handler, Laundry	Power Meter	Wattnode/WNA-1-P-240P
EERV	Energy, ERV	ERV Closet	Power Meter	Wattnode/WNA-1-P-240P
EPV	Energy, PV System	Main Service Panel	Power Meter	Wattnode/WNA-1P-240P-PV
FWS	Flow, Heat Pump System	Mechanical Room	Flow meter	Onicon F-1300
EGEN	Energy, House to Grid	Main Service Panel	Power Meter	Wattnode/WNA-1P-240P-PV
SPC	Status, HW Recirc Pump	Mechanical Room	Current Status Mtr	Hawkeye
FWC	Condensate Flow	Mechanical Room	RainGauge	
SZ1	Zone 1 Status	Mechanical Room	Current Status Mtr	Hawkeye
SZ2	Zone 2 Status	Mechanical Room	Current Status Mtr	Hawkeye
SZ3	Zone 3 Status	Mechanical Room	Current Status Mtr	Hawkeye
FWD	Flow, Domestic Hot Water	Mechanical Room	Flow meter	Dwyer

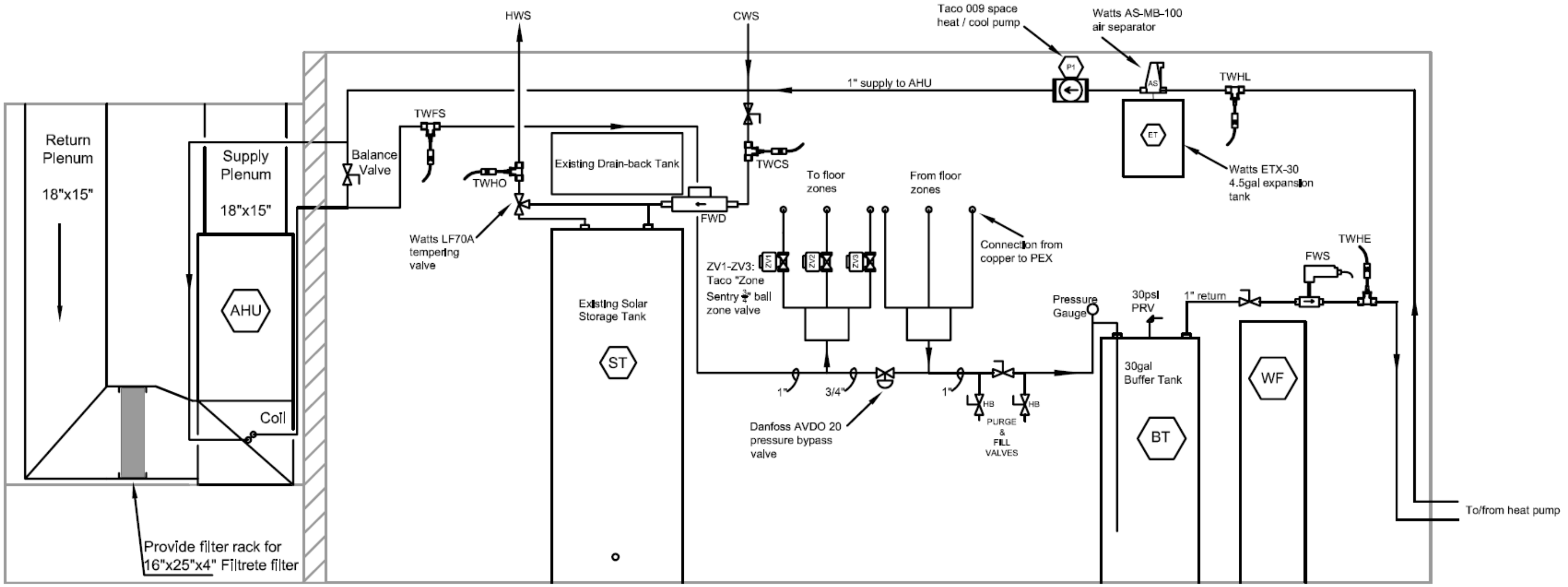

Figure 8. Monitoring sensor location schematic

3.3 Equipment

Data logger Specifications

Data Electronics data loggers are used to collect and store monitoring data. A Model DT-800 is used for this site. Analog inputs are single-ended type (all referenced to ground). Digital inputs are used for power monitors and status signals; high speed counter inputs are 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

Modem Specifications

The Datataker RS232 port is connected to a Hayes compatible modem. Modem settings are established using the following commands:

E0	Commands not echoed
M0	Quiet mode
L0	Low ring volume
&D0	DTR ignored
&R0	CTS tracks RTS when modem is on-line
&N6	Communication at 9600 Baud Rate
&S0	Forces DSR signal high
S0=1	Auto answer mode, one ring
\N2	Reliable mode only
&W0	Saves active profile 0

A 9-to-25 pin RS232 cable (modem - DCE) with connections as shown on Page 13 of the Datataker Manual (Version 3.1) is used to connect the modem to the Datataker.

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	RM Young 41372LF	4-20 mA	14 - 140°F	±0.5F
				0 – 100%	±2%RH
RTD	Indoor / Duct temperature / RH	Vaisala HM*60	4-20 mA	23 - 131°F	±1.5%
				0 – 100%	±2%RH
Type T Thermocouple	Immersion Water temperatures	Gordon Watlow Type T special limits	~11mV @ 500ºF	Range = -328 to 662ºF	0.4%
	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 WNA-1-P-240-P	pulse	CTA/40	±0.5%
Large power monitor	Total house power, PV production	Watt Node WNB-3D-240-P	pulse	CTA/60 CTA/120	±0.5%
Flow meter	Water flow	Onicon F-1300	pulse	varies by meter	±0.5%
Pyranometer	Insolation	LiCor	Analog	varies by sensor	±5%

3.4 Computation of Monitoring Variables

Whole house electricity use and PV electricity production: Energy supplied to the house and energy produced by the PV system are measured by two power meters and used to identify total house electric use.

End-use electricity use: Electric use of the water heating system includes the electric water heater, hot water recirculation pump, and solar collector pump. Recirculation pump energy use (E_{recirc}) is calculated based on pump status and a one-time measurement of pump power as in Equation 1. The solar collector pump power was not monitored but is estimated based on PV array operation and rated pump power. PV power production was used as an indicator of when the pump would be available to operate based on collector temperatures. Based on the relatively low system recovery loads, a factor of 50% was applied to the available hours to account for times when the tank setpoint was met. Total DHW electricity use is calculated using Equation 2.

Equation 1: $E_{recirc} = SPC * P_{recirc} / 1000 * 15\text{ min} * 1\text{ hour} / 60\text{ min}\ (kWh)$

Equation 2: $E_{dwh} = EWH + E_{recirc} + E_{solar\ pump}\ (kWh)$

Where:
SPC = recirculation pump status (% run time of 15 min monitoring period)
P_{recirc} = recirculation pump power (W) = 38 W
EWH = electric use of water heater heating element and solar pump (kWh)

Total power input to the heating and cooling system is the sum of that of the outdoor compressor unit, the circulation pump, and the indoor fan. Circulation pump energy use (EPUMP) is calculated based on heat pump status and a one-time measurement of pump power as in Equation

3. Heat pump status is calculated as a part load factor within the data logger program by filtering on heat pump system flow, FWS. Total heat pump electricity use is calculated using Equation 4.

Equation 3: $\text{EPUMP} = \text{PLEHP} * P_{circ} / 1000 * 15 \text{ min} * 1 \text{ hour} / 60 \text{ min}$ *(kWh)*

Equation 4: $E_{hp} = \text{EHP} + \text{EFAN} + \text{EPUMP}$ *(kWh)*

Where:
PLEHP = heat pump part load factor (% run time of 15 min monitoring period)
P_{circ} = heat pump circulation pump power (W) = 150 W
EHP = heat pump energy (kWh)
EFAN = air handler fan energy (kWh)

ERV energy use is continuously monitored and is used to further disaggregate building electricity use. E_{misc}, which includes appliance, lighting and miscellaneous electric load (MEL) energy use, is calculated as the difference between total building electricity use and DHW, HVAC, and ERV electricity according to Equation 5.

Equation 5: $E_{misc} = \text{EHSE} - E_{dhw} - E_{hp} - \text{EERV}$ *(kWh)*

Where:
EHSE = total house electricity use (kWh)
EERV = ERV electricity use (kWh)

<u>Additional data</u>: Outdoor temperature and relative humidity are monitored on site.

4 Results

The following results are from evaluation of the S.E.E.D. house, with a focus on whole building performance and cost effectiveness.

4.1 System Commissioning

Major commissioning tasks were conducted over two days in April, 2011. The focus of the trip was to verify correct operation of the mechanical systems, specifically the heat pump, verify correct operation of the monitoring equipment including sensors and communications, and take one-time measurements of pertinent data points.

Integrating the zoning, the hydronic and air systems, and heat pump in both heating and cooling required some creative on-site revisions to the original design as well as troubleshooting. Although efforts were made to use off-the-shelf components, this was not possible in all instances. A custom control box was constructed to communicate between the zone thermostats, the zone valve controller, the heat pump, and the fan coil. The TACO zone controller is designed for heating-only systems; it is not capable of controlling heating and cooling. A residential zone control may have worked, but the defrost control may not have been compatible with the AWHP equipment. A relay was installed to open all floor zone valves when a defrost signal is received from the heat pump allowing the heat pump to absorb heat from the entire slab instead of from a single zone.

The Aqua Products controls require that a heating call be received from a single zone to activate the reversing valve in heating. Therefore, the living room zone was selected as the master zone and has to call for heating for either of the other two zones to receive heating. For cooling, the controls were able to be set up such that a call for cooling from any zone would initiate heat pump operation.

There was some difficulty wiring the pump into the Aqua Product controls. It was expected that if the pump relay output was wired directly to the unit it would operate whenever there was a call for heating or cooling; however, at start-up it was found that the pump was not operating at all. A second relay was installed between the zone controller and the heat pump. A control schematic can be found in Appendix B.

A zone bypass was installed on the radiant floor system to maintain a minimum flow rate through the heat pump when only one zone is calling. The monitoring equipment was used to verify both pump flow and power under different scenarios. Both flow and power remain relatively constant regardless of the number of zones calling.

One-time HERS tests, including duct and building envelope leakage testing, were completed by HERS raters contracted by the local utility (Tucson Electric Power). DEG also conducted testing to verify fan coil airflow, fan coil power, and pump power. Refer to Appendix C for testing and commissioning results.

Cooling operation began with using the floor only for delivery and the air handler turned off. The air handler was enabled later in the summer to test mixed-mode delivery performance for comparison. During the local monsoon season, the builder discovered that the condensate pan had been installed incorrectly at a slight slant, not allowing the condensate to drain and causing it to pool in the pan. This water then re-evaporated into the supply airstream, resulting in the re-introduction of humidity to the space. Once the issue with the condensate pan was identified, the builder fixed the problem by leveling the pan, which facilitated proper drainage, and indoor relative humidity decreased. However, relative humidity never exceeded 60% during this period, and the occupants did not express any discomfort.

4.2 Short Term Test Results

Following are results of short term tests conducted either by DEG or Tucson Electric Power. Test results showed alignment with design expectations.

Table 4. Results of Short Term Tests

Short Term Test	Results
Blower Door Infiltration	2.41 ACH$_{50}$ (1.48*10^{-4} SLA)
Duct Blaster Leakage	5.7% (46 cfm)
Cooling Airflow	831 cfm
Heat Pump Circulation Pump	150 W
DHW Recirculation Pump	38 W
Solar System Pump	137 W

4.3 Monitoring Results and Discussion

Whole Building Performance and Comparison

Nine months of monitoring data during occupied times was available for this report (August 2011 - April 2012). While the monitoring period began before August, the house was unoccupied and some of the systems were not operating. The data was analyzed to evaluate electricity use by end use, evaluate percent of total building electricity covered by the PV system, and compare monitored data to BEopt estimations. Figure 9 shows monthly electricity use by end-use including monthly PV system production. Electricity use in August is twice as high as most other months due to very high cooling loads. Daily average temperatures ranged from 84°F to 95°F during this month, much higher than other months in the monitoring period.

Throughout the nine-month period, the 3.4 kW PV offset 71% of total house electricity use. Over the course of a year, this percentage may increase since the nine-month period did not cover summer, during which time increased solar radiation is available. However, high cooling loads in June and July may dampen any gains from increased PV production.

The pie chart in Figure 10 breaks down the relative contribution of each end use over the nine-month monitoring period. Almost half of total electricity is attributed to lighting, appliances, and MELs. Cooling represents 25%, which is a substantial portion considering that most of the monitored months with cooling loads are in the swing season. Over half of the heat pump cooling energy was expended in August.

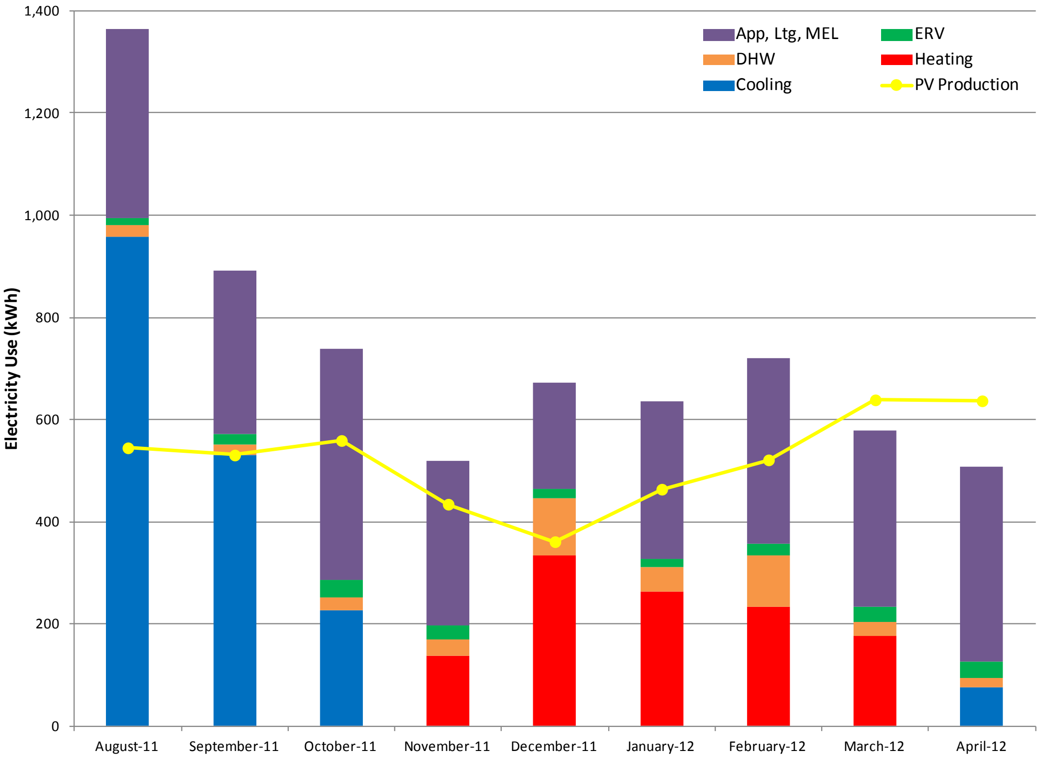

Figure 9. S.E.E.D. house 9-month electricity use by end-use

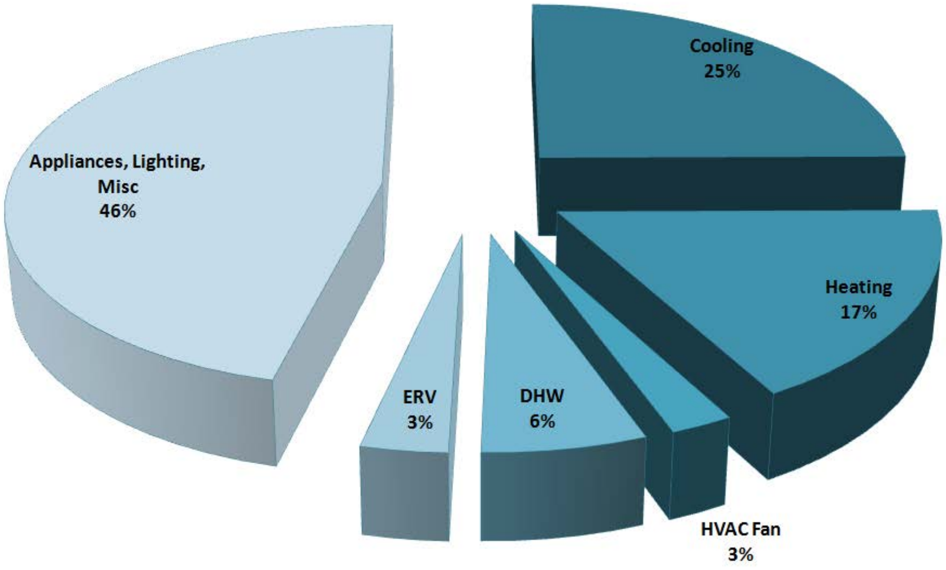

Figure 10. Pie chart showing percentage of total 9-month electricity use by end-use

Figure 11 provides a comparison of monitored energy use with estimates from BEopt. Heating and cooling energy use is removed for this comparison since BEopt limitations do not allow for accurate modeling of the strategy used in the S.E.E.D. house. While it is a 4-bedroom home, there were only one to two occupants for the majority of the monitoring period (two occupants during August through December; one occupant from January through April). The BEopt model was updated to reflect two bedrooms and similarly two occupants, based on occupancy calculations in the House Simulation Protocols (Hendron et al, 2010). After accounting for occupancy, monitored data shows about one third less electricity use for all non-HVAC/DHW loads than BEopt predicts. ERV use was 27% less than estimated and DHW use was three times greater. While the DHW solar collector pump was not monitored and therefore a portion of the 405 kWh is an estimate, the pump contribution was relatively minor next to the winter electric resistance heating. BEopt modeling predicted very little backup water heating. However, while monitoring data confirmed this was the case during the summer, fall, and spring, electric resistance DHW energy use increased during the winter months as the solar resource and output of the solar water heater is reduced. Total DHW electricity use in December was 100 kWh. Total monitored and BEopt electricity (including HVAC) were within 2% of one another.

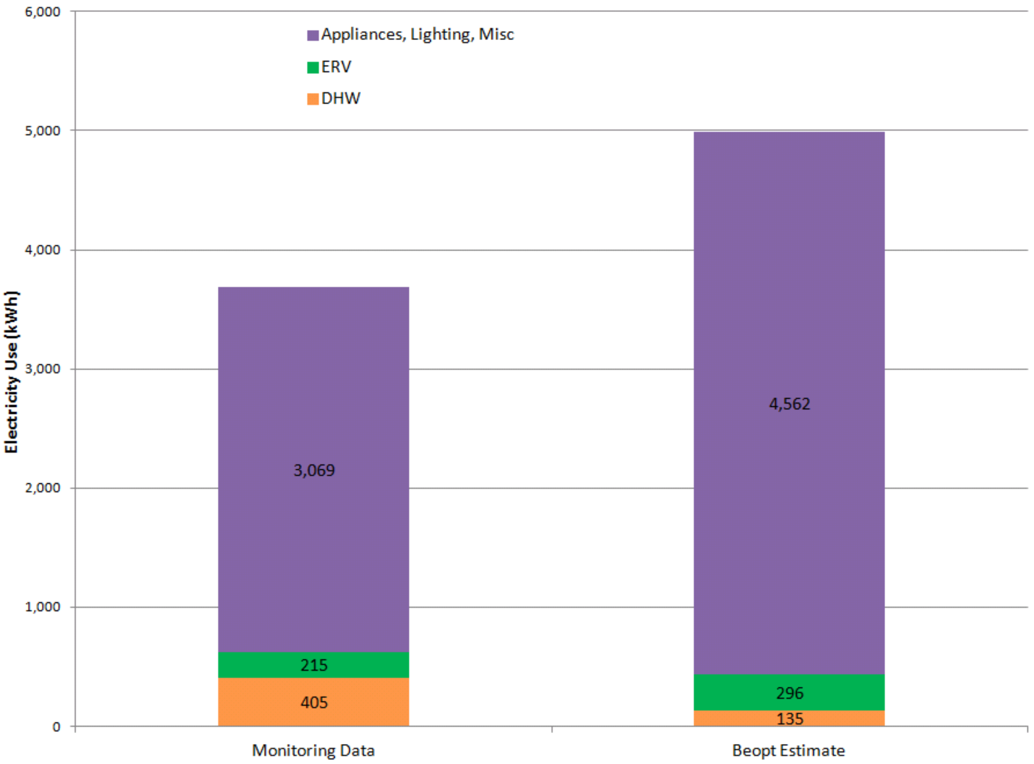

Figure 11. Comparison of 9-month monitored electricity use with BEopt estimate

Load Reduction Strategies

The S.E.E.D. house incorporates a number of energy efficiency measures 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 R-value SIP walls and roofs, high performance low-E windows, slab insulation, air sealing, ducts in conditioned space, and an ERV. BEopt was used to investigate the benefits of these various measures by estimating cooling and heating loads and total energy use percent reductions. The base case used for comparison purposes was the B10 Benchmark applied to a home with geometry, orientation, and window area of the S.E.E.D. house. Table 5 shows that the most considerable savings from an envelope measure are achieved through increasing wall performance from R-13 to almost R-34 through the use of SIP walls. However, moving ductwork to conditioned space provides even greater savings accompanied by significant building load reductions. Parametric run #8 packages all the envelope measures together (runs 2-6) resulting in 13% total source energy savings. Adding ductwork in conditioned space to the envelope package increases savings to 18% with an over 50% reduction in both heating and cooling loads. Instead of a 4-ton unit heat pump in the base case, a 2-ton unit can be used and was installed. Heat pump capital cost saving, estimated at approximately $925, helps offset incremental costs for the envelope measures. As a comparison, forgoing the load reduction measures and installing a high efficiency heat pump (12.5 EER and 9.0 HSPF) results in 4% source energy savings.

Table 5. Energy and Building Load Savings Comparison of Load Reduction Measures

Parametric Run	Description	Total Source Energy (kBtu/yr)	% Energy Savings	Heating Load (kBtu/h)	Cooling Load (Tons)	% Heating Load Savings	% Cooling Load Savings
1	BA B10 Benchmark (BC)	*201*	-	*55*	*3.7*	-	-
2	BC + SIP walls	188	6%	45	3.1	17%	16%
3	BC + SIP roof w/ single ply	197	2%	51	3.5	7%	7%
4	BC + underslab & edge insulation	199	1%	54	3.7	2%	2%
5	BC + Low-e windows	198	2%	53	3.6	4%	3%
6	BC + reduced infiltration (2.4 ACH_{50})	197	2%	51	3.5	6%	5%
7	BC + ducts in conditioned space	187	7%	41	2.7	25%	29%
8	Envelope Package	**175**	**13%**	**35**	**2.5**	**36%**	**33%**
9	Envelope Package + Ducts Inside	**164**	**18%**	**25**	**1.7**	**54%**	**55%**

BEopt modeling does not predict any energy benefit through use of an ERV compared to a standard exhaust mechanical ventilation system. While there is a decrease in heating energy use during the winter, the increased fan energy use results in a net increase in electricity. Monitored results of the ERV show average power consumption of 50 Watts when delivering 75 to 80 cfm and a sensible effectiveness approaching 80% as the temperature difference between indoors and outside increase with decreased effectiveness at lower temperature differences.

4.4 Cost Effectiveness and Marketability

The builder's cost-effective model was to offset the incremental cost of energy efficiency measures with cost savings by using basic instead of mid-range or high-end finish products. The money invested in tight, insulated enclosures and high efficiency mechanical systems is countered by savings from installing base model cabinets, no floor coverings, no tile work or granite, fewer accessories, reduced landscaping, etc. Additional detail on this can be found on the builder's website[3].

Table 6 summarizes as-built cost data provided by the builder for the energy efficiency measures incorporated in this project. Incremental costs are based on the builder's standard elements that would be included in a house that the builder normally would construct. Base case costs are estimated primarily from contractor bids and provided by the builder. In some cases where data was not available, costs were taken from the BEopt cost database.

Including the cost of the PV system and net utility incentives and tax credits, the total estimated incremental cost is around $38,000. Not including PV, the estimated incremental cost is just over $32,000. Through a combination of local utility incentives and available state and federal tax credits, the builder was able to offset most of the cost of the PV system. As discussed previously, the builder offset some of the incremental costs associated with the building efficiency measures by specifying basic finish products. The cost savings to the builder via this strategy are not presented in Table 6 except when the cost trade is within the same product. For example, cost savings for lighting and appliances were achieved by specifying lower cost lighting fixtures and base model appliances. Through the trade-off of features and reducing his profit margin from 9% to 5%, the builder was able to price the home at $5,000 over what he would normally sell a comparable house without any of the energy features.

While in a good housing market this should be an effective marketing strategy, the Tucson real estate market continues to suffer greatly since the market crash. Average sale prices of single family homes in Tucson are down 17% over the past year[4] with an average sale price in September, 2011 of $120,000. The trend is similar across low, medium, and high range homes. The builder placed the S.E.E.D. house on the market upon completion of construction. While his project has received a lot of interest and press within the community, he did not receive any serious offers. Because he reduced his profit margin to 5% to sell at almost the same price as a similar home without the energy features, he does not have as much flexibility to drop the price, which could help sell the home in the current market. After a couple of months he moved in himself and has been occupying the home since. As the market improves, the expectation is that energy efficiency, especially in middle income homes, will become a much stronger selling point.

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[3] http://www.lamiradahomes.net/lamirada_homes_cost_effective.htm

[4] http://www.zillow.com/local-info/AZ-Tucson-home-value/r_7481/. Accessed 12/08/11.

Table 6. S.E.E.D. Home Measure Costs

Component	Builder Standard Base Case	As Built	Base Cost	As-Built Cost	Incremental Cost
Exterior Walls	2 × 6 frame, R-19 batt	4.5 in. SIP + 1 in. ext. foam	$34,800	$48,219	$13,419
Roof	Truss, R-30 blown-in	6.5 in. SIP			
Slab	No insulation	Edge and underslab (Creatherm)		$2,675	$2,675
	4 in.SlabMonoPour w/ slab rebar	5 in.Slab/Ftg&Stm no slab rebar	$15,000	$16,345	$1,345
Windows	U-value/SHGC = 0.4/0.3	U-value/SHGC = 0.29/0.21	$3,800	$4,272	$472
Envelope Sealing	Standard caulking and sealing	Extra caulking and sealing			$0
HVAC	7.7 HSPF/13 SEER, 4-ton	Aqua Products RCS, 2-ton	$13,652	$25,026	$11,374
Reverse Cycle Chiller	n/a	13 SEER / 8.5 HSPF	included above	included above	included above
Air Handler	1600 cfm, Ruud or equal	MagicAire DUC08, 800 cfm			
Ducting	1600 cfm system, R-8 ducts	800 cfm system, R-6 ducts in conditioned space			
Radiant Floor/Manifolds	none	Per plan			
Zone Controls/Valves	none	Per plan			
Mechanical Ventilation	Exhaust fan, 50 cfm	ERV	$462	$2,441	$1,979
Water Heating	50 gal. electric, EF = 0.904	Electric, EF = 0.96	$610	N/A	-$610
Solar Water Heating	None	80 gallon drainback, single tank, 1-4x10 Eagle Sun AE-40 collector		$4,331	$4,331
Hot Water Recirculation	None	Pump, time/temp control		$400	$400
Lighting	66% incandescent	100% fluorescent	$2,350	$1,870	-$480
Appliances	Standard efficiency	ENERGYSTAR refrigerator, dishwasher, clothes washer	$6,000	$3,536	-$2,464
PV System	None	SunPower 3.4 kW DC		$24,045	$24,045
		Less Utility Incentives / Tax Credits		($18,236)	
Total Costs			**$76,674**	**$114,924**	**$38,250**

From a perspective of construction, performance and operation, the S.E.E.D. home has met the builder's expectations. He was very happy with the construction of the building envelope, and the performance of the building during the hot summer exceeded his expectations. Monitoring data shows favorable results in terms of system operation and overall energy use. He has been disappointed with the marketability of the home, but at this point attributes it to the current market conditions, not the features of the home.

Savings over the builder standard, as specified in Table 6, were evaluated using BEopt. Estimated annual source energy savings are 37% and 74% without and with PV, respectively. A cost effectiveness analyses was conducted assuming the costs in Table 6 and annual utility savings based on BEopt. This analysis assumes that the incremental cost of the energy efficiency measures will be wrapped up into a homeowner mortgage at an interest rate of 5.5% and a loan term of 30 years. Utility savings are estimated using average utility rates and escalation rates for electricity and natural gas of 4% in Arizona A real discount rate of 3% is used. Based on these assumptions, the $38,250 incremental cost is not justified and results in a negative average annual cash flow of $361. However, a positive average annual cash flow is achieved if the incremental cost can be reduced to around $30,000, which is reasonable based on a mature market cost analysis conducted for the AWHP strategy alone[5].

In another analysis, when the actual additional cost to the buyer of $5,000 is used, the average annual cash flow is positive at $1,120. If the builder were to increase his profit margin back to 9%, increasing the additional cost to the buyer up to $24,000, the annual cash flow to the homeowner would still be $265.

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[5] Savings are achieved through reductions in radiant floor costs primarily justified by labor savings and elimination of the ducted system. Preliminary analysis has shown that in a hot-dry climate the fan coil is not necessary for dehumidification purposes and that the radiant floor can deliver all necessary cooling without risk of floor condensation.

5 Conclusions and Recommendations

Whole building energy performance based on nine months of data is better than expected. Total electricity use (before PV generation) is within 1% of BEopt estimates and the 3.4 kW PV system offset 71% of total house electricity use; actual PV production was 14% greater than what BEopt estimated. Good building envelope design and distributed thermal mass all contribute to reducing the need for space cooling and providing superior indoor comfort.

The builder's cost-effective model was to reduce the incremental cost of energy efficiency by using basic finish products and reducing his profit margin. These trade-offs allowed the builder to price the home at $5,000 over what he would normally sell a comparable house without any of the energy features. Using annual energy savings based on BEopt modeling, this incremental cost would result in a positive average annual cash flow to the homeowner of $1,120.

While this strategy has not yet been successful in the current Tucson real estate market, which has been hit hard by the market crash, the authors theorize that this strategy may be very effective in the future as utility costs increase, time-of-use pricing becomes more prevalent, and zero net energy homes are encouraged or mandated through regional and/or national energy policy. During difficult economic periods, buyers are very focused on price and, as a result, often do not consider the performance of the home.

Without considering the builder's cost tradeoffs, relatively small reductions in incremental cost are necessary to make the whole building energy efficiency package cost effective. Significant cost reductions in the AWHP are achievable if the technology can gain larger market penetration and acceptance. Further cost savings could be achieved with the elimination of ducted distribution for cooling. Due to the prototype nature of this project, the HVAC system costs were much higher than would be expected if installed by a contractor more familiar with this strategy. Contractor familiarity is expected to increase in the future as radiant systems gain greater market acceptance due to their comfort and efficiency benefits. Other potential cost savings may include: a) heat pump water heating or condensing gas technologies for water heating in place of solar water heating; b) less expensive heat recovery products and climate-specific evaluation to identify the most cost-effective mechanical ventilation strategies; and c) other methods of achieving high R-value walls and roof other than high cost SIP assemblies.

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Appendix A: Floor Plan and Construction Details

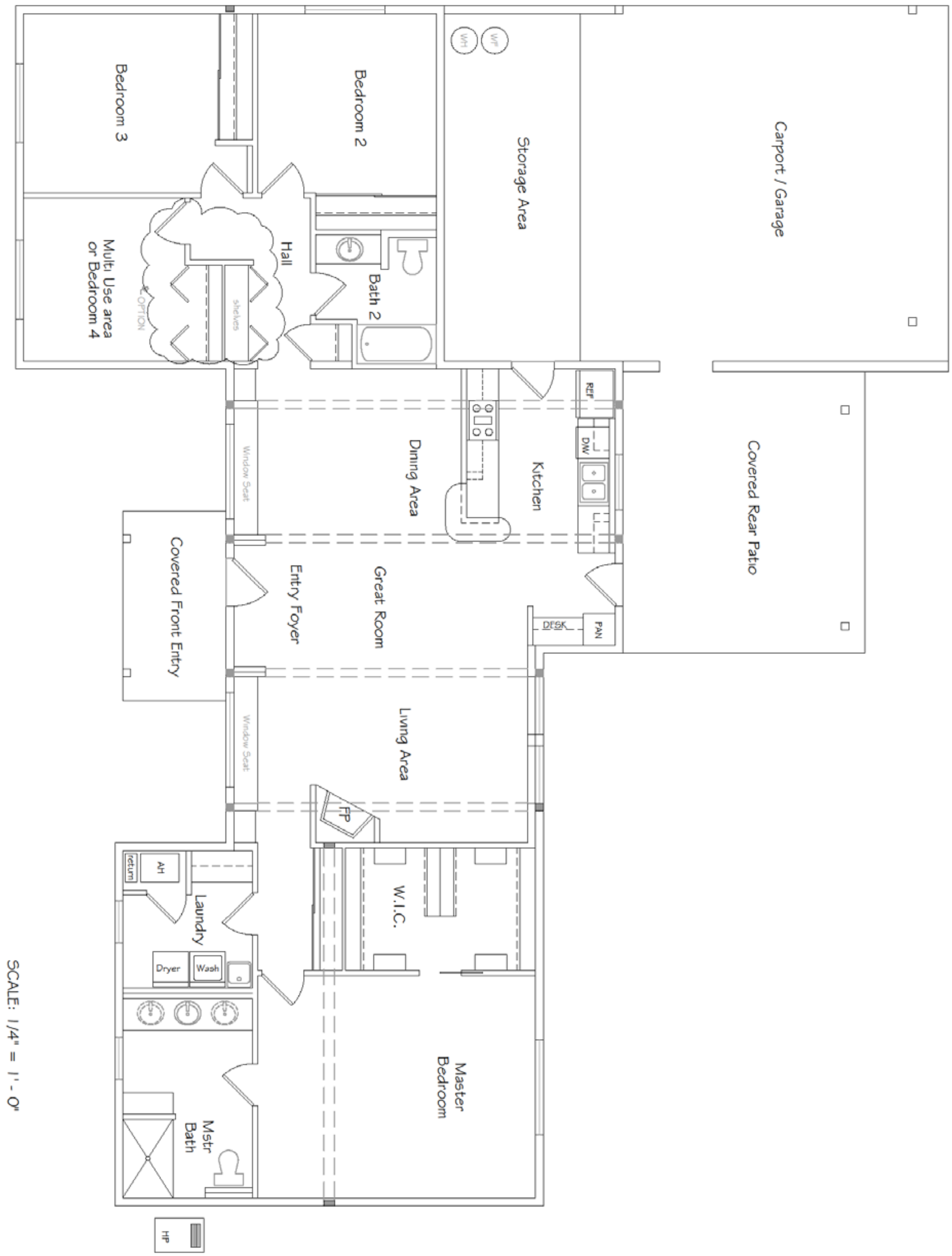


Figure A - 1. Floor plan

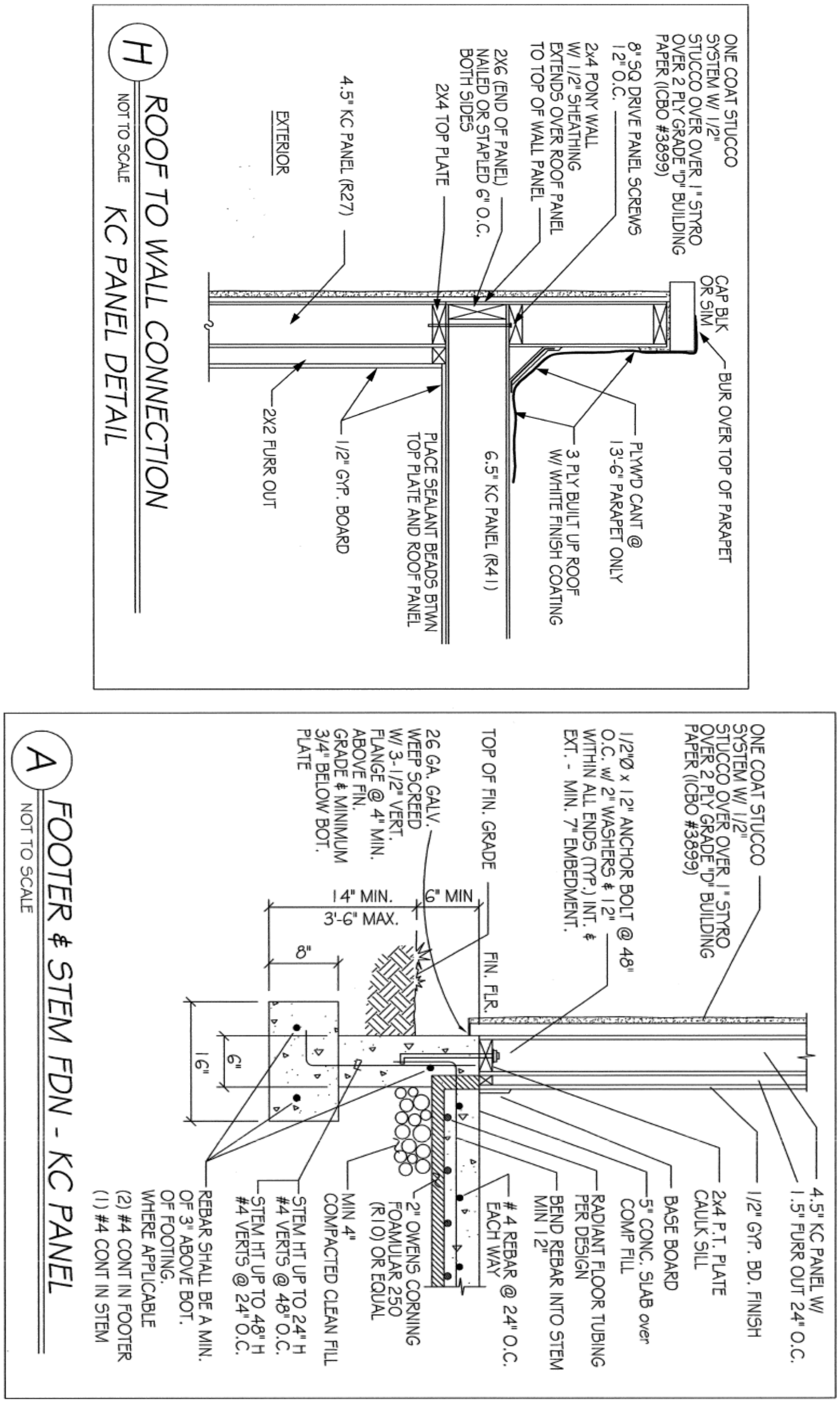
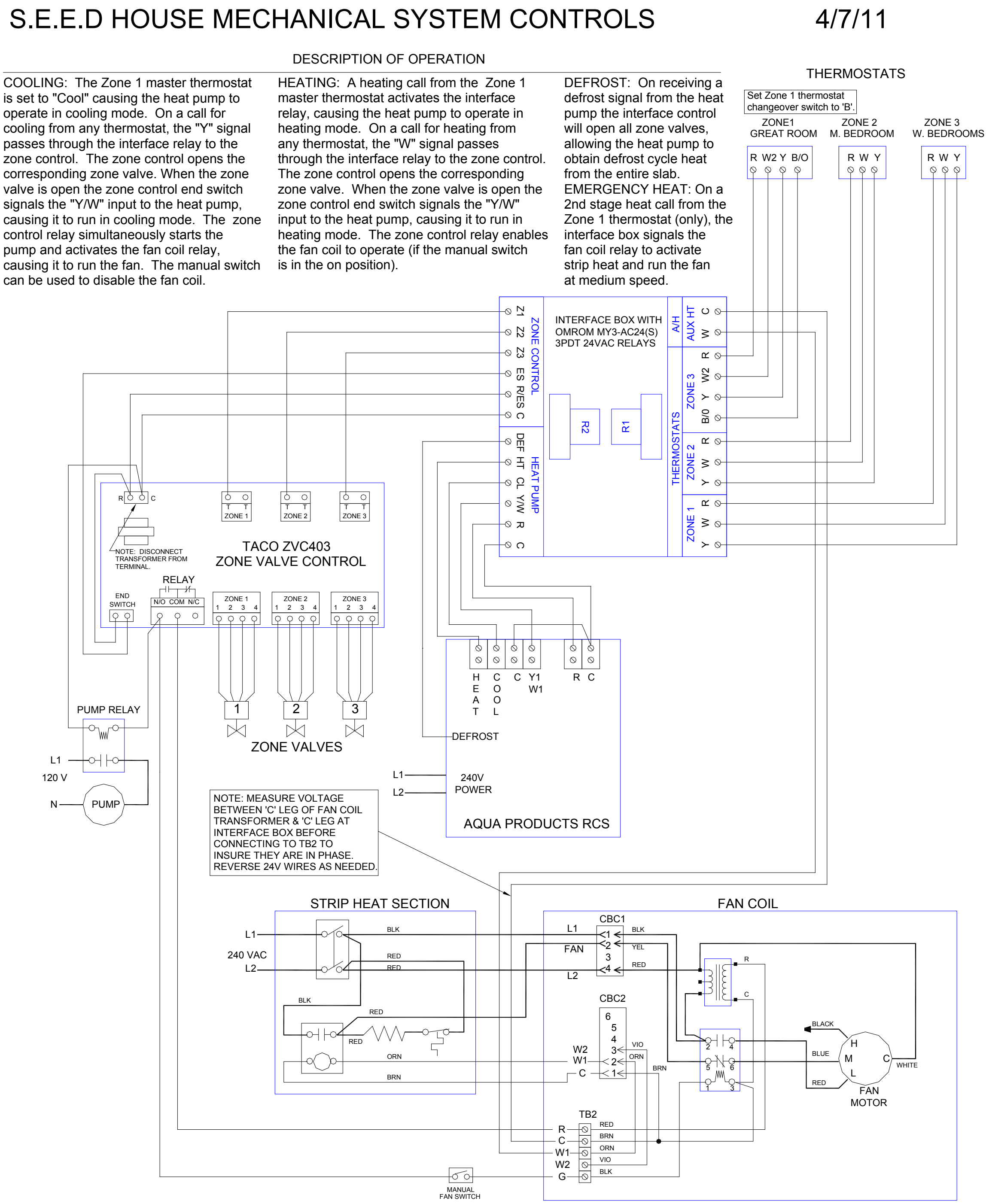


Figure A - 2. Wall, roof, and foundation details

Appendix B: Mechanical System Controls Schematic

The control diagram and associated description for the heat pump and zone control are shown in Figure A - 3.



S.E.E.D HOUSE MECHANICAL SYSTEM CONTROLS 4/7/11

DESCRIPTION OF OPERATION

COOLING: The Zone 1 master thermostat is set to "Cool" causing the heat pump to operate in cooling mode. On a call for cooling from any thermostat, the "Y" signal passes through the interface relay to the zone control. The zone control opens the corresponding zone valve. When the zone valve is open the zone control end switch signals the "Y/W" input to the heat pump, causing it to run in cooling mode. The zone control relay simultaneously starts the pump and activates the fan coil relay, causing it to run the fan. The manual switch can be used to disable the fan coil.

HEATING: A heating call from the Zone 1 master thermostat activates the interface relay, causing the heat pump to operate in heating mode. On a call for heating from any thermostat, the "W" signal passes through the interface relay to the zone control. The zone control opens the corresponding zone valve. When the zone valve is open the zone control end switch signals the "Y/W" input to the heat pump, causing it to run in heating mode. The zone control relay enables the fan coil to operate (if the manual switch is in the on position).

DEFROST: On receiving a defrost signal from the heat pump the interface control will open all zone valves, allowing the heat pump to obtain defrost cycle heat from the entire slab.

EMERGENCY HEAT: On a 2nd stage heat call from the Zone 1 thermostat (only), the interface box signals the fan coil relay to activate strip heat and run the fan at medium speed.

Set Zone 1 thermostat changeover switch to 'B'.

NOTE: DISCONNECT TRANSFORMER FROM TERMINAL.

NOTE: MEASURE VOLTAGE BETWEEN 'C' LEG OF FAN COIL TRANSFORMER & 'C' LEG AT INTERFACE BOX BEFORE CONNECTING TO TB2 TO INSURE THEY ARE IN PHASE. REVERSE 24V WIRES AS NEEDED.

Figure A - 3. Mechanical system controls schematic

Appendix C: Short Term Testing and Commissioning Results

SYSTEM/SENSOR COMMISSIONING

Preparation and Base Load Measurement

- ☒ Shut off breakers for water heater element, refrigerator, microwave, range, washing machine, and PV system.
- ☒ Run hot water tap (bathtub) to deplete solar storage (didn't do)
- ☒ Shut off the ERV.
- ☒ Unplug solar pump.
- ☒ Unplug recirc pump.
- ☒ Wait 5 minutes while base load is being measured.

Verify Hydronic System Operation

- ☒ Install flowmeters and recharge system
- ☒ Review control wiring, verify transformer in zone control is disconnected
- ☒ Disconnect heat pump compressor from contactor
- ☒ Unplug heating pump from switched outlet and plug into live outlet.
- ☒ Set all thermostats to cool and power up heat pump
- ☒ Verify pump operation
- ☒ Set up logger to read flow and set logger spans correctly
- ☒ Manually open Zone 1 (guest bedrooms) and wait 5 minutes while pump power and flow are recorded
- ☒ Manually open Zone 2 (living) and wait 5 minutes.
- ☒ Manually open Zone 3 (master bedroom) and wait 5 minutes.
- ☒ Adjust bypass valve to ensure a minimum flow of 5gpm in all zone calling scenarios

Table A - 1. Hydronic System Flow Rate with Various Zones Calling

Zones Calling	Flow Rate (gpm)
All open	6.21
Zone 1 only	5.72
Zone 2 only	5.69
Zone 3 only	5.69
Zone 1 & 2 only	5.74
All closed	5.65

DHW Pump Power Tests

Solar Pump (could not test – leak in solar collector)

- ☒ Plug in the solar pump.
- ☒ Wait 5 minutes (after pump starts running)

☒ Unplug and turn off water.

Recirc Pump

☒ Plug in recirc pump and set to "manual on."

☒ Wait 5 minutes while pump power is recorded.

Air Handler Airflow Tests

To check supply/return temperature calibration:

☒ Turn on switch at fan coil.

☒ Unplug the pump from live outlet.

☒ Close coil bypass valve (noting original position).

☒ Activate Living Room thermostat in cooling mode (verify fan operation)

☒ Wait 5 minutes while supply/return sensors are checked.

To measure airflow:

☒ Plug the pump into the switched outlet.

☒ Set Living Room thermostat to heat and raise temperature until it turns on the heat pump.

☒ Manually close the zone valve for the Living Room.

☒ Wait 15 minutes or until supply/return temperature difference stabilizes.

Restore System

☒ Set Living Room thermostat to 78 (cooling mode).

☒ Reset the position of the coil bypass valve.

☒ Turn on breakers that were turned off in Step 1, Preparation.

☒ Plug in the solar pump.

☒ Turn on the ERV.

☒ Set recirc pump to "timer."

HERS TESTS

Duct tightness test

☒ Test total duct leakage **24 supply/22 return: 46 cfm total leakage**

Blower door

☒ Test building leakage with blower door (CFM_{50} < 1935) **750 CFM_{50}**

One Time Measurements

☒ Verify fan coil airflow **831 cfm**

☒ Measure solar pump power **137 Watts**

☒ Measure heat pump circulation pump power **150 Watts**

☒ Measure DHW recirculation pump power **38 Watts**

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