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Evaluation of Affordable Prototype Houses at Two Levels of Energy Efficiency

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R. Hendron
National Renewable Energy Laboratory

E. Hancock and G. Barker
Mountain Energy Partnership

P. Reeves
The Partnership for Resource Conservation

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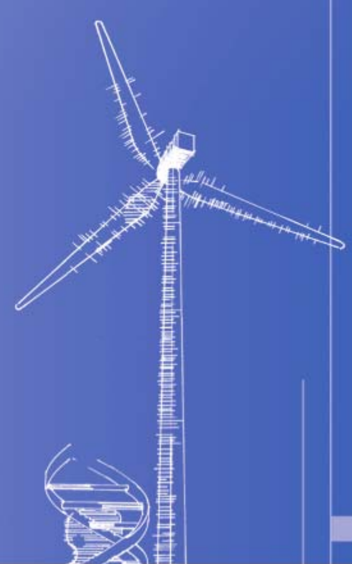

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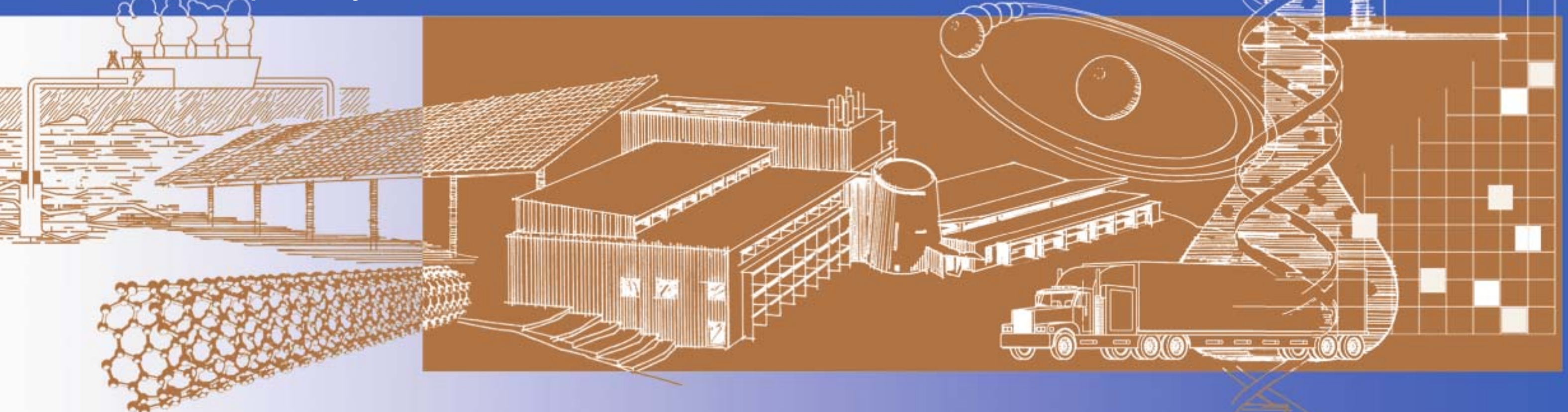

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An Evaluation of Affordable Prototype Houses at Two Levels of Energy Efficiency

Robert Hendron, Associate Member, ASHRAE; Ed Hancock; Greg Barker; Paul Reeves

KEY WORDS

Building envelope
Heat recovery units
Radiant heating equipment
Residential buildings
Solar equipment

ABSTRACT

Two high-performance prototype houses were built in Carbondale, Colorado, as part of the U.S. Department of Energy's Building America (BA) Program. Each prototype was a 1256 ft^2 (117 m^2), one-story, three-bedroom house and met the local requirements for affordable housing. The authors, representing the National Renewable Energy Laboratory, performed short-term field testing and DOE-2.2 simulations in support of this project at the end of December 2004. We also installed long-term monitoring equipment in one of the houses and are currently tracking the performance of key building systems under occupied conditions. One of the houses (designated H1) included a package of cost-effective energy-efficiency features that placed it well above the Energy Star level, targeting a Home Energy Rating System (HERS) score of 88-89. The other (designated H2) was a BA research house, targeting a HERS score of 94-95 and 45% whole-house energy savings compared to the BA Benchmark. The floor plans and other basic characteristics of the two houses were nearly identical except for the extended package of energy efficiency measures in the H2, including a 1.6 kW (5500 Btu/hr) photovoltaic system, a combination solar hot water and radiant space heating system, heat recovery ventilation, and orientation specific glazing. Preliminary results from the field evaluation indicate that the energy savings for both houses will exceed the design targets established for the project, although the performance of certain building systems, including the ventilation and foundation systems, leave some room for improvement.

INTRODUCTION

Two high-performance prototype houses were constructed in Carbondale, Colorado, in December 2004 as part of the U.S. Department of Energy's Building America (BA) Program. Both houses were 1256 ft^2 (117 m^2), one-story, three-bedroom designs, and each one met the local requirements for affordable housing, which limited the sales price to about $220,000, an amount affordable to a family earning less than 80% of the median income in Garfield County.

One of the prototype houses (designated H1) was treated as the "base case" for the purpose of side-by-side testing, even though its energy efficiency was well above the Energy Star level, with an estimated Home Energy Rating System (HERS) score of 88-89. The other (designated H2) was the BA prototype house, targeting a HERS score of 94-95, and 45% whole-house energy savings compared to the BA benchmark (Hendron 2005). The floor plans and other basic characteristics of the two houses were nearly identical except for the expanded package of energy efficiency measures in the H2. A list of key specifications for both houses is provided in Table 1. Figure 1 shows both prototypes as viewed from the southwest. More detailed design specifications and trade-off analysis can be found in the BSC deliverable report about this project (BSC 2004).

The authors, representing the National Renewable Energy Laboratory (NREL), visited the site in late December 2004 and performed a series of short-term field tests. The test results were used as inputs to hourly simulation models of each house for the purpose of calculating annual energy savings. The authors also installed long-term monitoring equipment in one of the houses in order to track the performance of certain key building systems over the course of one year.

Table 1. Specifications for H1 and H2 Prototype Houses*

	H1 (88-89 HERS Rating)	H2 (94-95 HERS Rating)
Building Envelope		
Attic	R-53 hr·ft²·°F/Btu (R-9.3 m²·K/W) blown cellulose, 14 in. (0.36 m) minimum, some cathedral ceilings	R-53 hr·ft²·°F/Btu (R-9.3 m²·K/W) blown cellulose, 14 in. (0.36 m) minimum, some cathedral ceilings
Walls	R-20.8 hr·ft²·°F/Btu (R-3.7 m²·K/W), 2 x 6, 24 in. on-center (o.c.) optimum value engineered (OVE) with damp-spray cellulose; R-5 hr·ft²·°F/Btu (R-0.9 m²·K/W) extruded polystyrene (XPS) foam sheathing	R-20.8 hr·ft²·°F/Btu (R-3.7 m²·K/W); 2 x 6 24-in. o.c. OVE with damp-spray cellulose; R-5 hr·ft²·°F/Btu (R-0.9 m²·K/W) XPS foam sheathing
Rim joist	Spray foam cavity insulation, R-10 hr·ft²·°F/Btu (R-1.8 m²·K/W) 2-in. XPS on outside	Spray foam cavity insulation, R-10 hr·ft²·°F/Btu (R-1.8 m²·K/W) 2-in. XPS on outside
Foundation	Sealed conditioned crawl space, R-10 hr·ft²·°F/Btu (R-1.8 m²·K/W) 2-in. XPS on interior walls, concrete floor, supply registers to crawlspace with transfer grilles for return path	Sealed conditioned crawl space, R-10 hr·ft²·°F/Btu (R-1.8 m²·K/W) 2-in. XPS on interior walls, *lightweight gypcrete slab on framed floor,* transfer grilles from crawlspace to first floor
Windows	Low-E with high solar gain on south side, U = 0.36 Btu/hr·ft²·°F (2.0 W/m²·K), solar heat gain coefficient (SHGC) = 0.48; low-e spectrally selective on north and east sides, U = 0.33 Btu/hr·ft²·°F (1.9 W/m²·K), SHGC = 0.28; triple glazed on west side, U = 0.26 Btu/hr·ft²·°F (1.5 W/m²·K), SHGC = 0.24	Low-e with high solar gain on south side, U = 0.36 Btu/hr·ft²·°F (2.0 W/m²·K), SHGC = 0.48; *triple glazed on north, east, and west sides*, U = 0.26 Btu/hr·ft²·°F (1.5 W/m²·K), SHGC = 0.24
Infiltration	2.5 in² (0.0016 m²) leakage area per 100 ft² (9.3 m²) envelope area	2.5 in² (0.0016 m²) leakage area per 100 ft² (9.3 m²) envelope area
Mechanical Systems		
Heat	92.1% annual fuel utilization efficiency (AFUE) sealed-combustion furnace, ducts in conditioned crawlspace, single control zone	*92% AFUE gas boiler, 80,000 Btu/hr (23 kW) capacity, radiant floor in lightweight slab, three control zones, solar assisted*
Cooling	Alternate cooling strategies: ceiling fans, natural ventilation, one motorized window	Alternate cooling strategies: ceiling fans, natural ventilation, one motorized window
Ventilation	Intermittent central fan integrated supply ventilation with motorized damper, 33% duty cycle	*Continuous heat recovery ventilator (HRV)*
Domestic hot water (DHW)	Direct vent water heater, 0.62 energy factor (EF)	*Gas boiler (with storage tank connection), EF estimated at 0.75-0.80 (not rated by the Gas Appliance Manufacturers Association, GAMA), solar assisted*
Solar hot water	None	*Two 26.8 ft² (2.49 m²) panels on south awning, glycol loop, 105 gal (397 L) tank*
Photovoltaics	None	*1.625 kW (5540 Btu/hr) array on roof, 13 modules,1.8 kW (6140 Btu/hr) inverter*
Lighting and appliances	Compact fluorescent lighting (CFL) package, Energy Star appliances	CFL package, Energy Star appliances

** Items changed between H1 and H2 are shown in italics*

SHORT-TERM TESTING

Air Infiltration and Ventilation

A local HERS rater performed blower door tests on both prototype houses on December 17, 2004. A motorized window was partially open during the H1 test and could not be easily closed because the location was high and the motor was not yet operational. The measured envelope leakage was 475 cubic feet per minute at 50 Pascal (cfm50) (224 L/s @ 50 Pa) for the H2 and 625 cfm at 50 Pa (295 L/s @ 50 Pa) for the H1. Both houses easily met the design target of 1200 cfm at 50 Pa (566 L/s @ 50 Pa), even with the partially open window in the H1. After taking altitude into account, the measured values of cubic feet per minute at 50 pascals converted to annual average infiltration rates of approximately 0.12 ach for H2 and 0.15 ach for H1.

A tracer gas monitoring system was installed in each house from Friday afternoon (December 24) until Monday morning (December 27) to measure the net air exchange rates with and without ventilation. By the time the tracer gas test started, the motorized window in the H1 had been closed. Figure 2 shows the measured hourly average air exchange rate expressed as air changes per hour (ach). During the test period, the winds were calm (0-3 mph) (0-1.3 m/s), but outdoor temperatures were frequently in the single digits ºF (-18ºC to -12ºC). The occasional data gaps in Figure 2 occurred when tracer gas was being injected into the houses to maintain minimum concentration levels. During these periods, the ACH could not be calculated.

From hour 0000 until hour 2200 on Saturday, the ventilation systems were operated in both houses. The air exchange rate in H1 with the intermittent supply ventilation system running at a 33% duty cycle was usually between 0.20 and 0.25 ACH. The air exchange rate in H2 with the heat recovery ventilator (HRV) operating was generally between 0.27 and 0.33 ACH. At 2200 on Saturday, both ventilation systems were turned off. Natural infiltration was typically between 0.05 ACH and 0.12 ACH for both houses, even when the inside-outside temperature difference was as high as 60ºF (33ºC).

The ventilation rate recommended by ASHRAE Standard 62.2 (ASHRAE 2004) was 42 cfm (20 L/s) continuously or 84 cfm (40 L/s) at 50% duty cycle in the case of an intermittent system like the one in H2. Tracer gas measurements indicated that the increase in air exchange rate due to operation of the ventilation system in H1 was about 0.13 ach, or 29 cfm (14 L/s) based on an estimated conditioned volume of 13,400 ft^3 (379 m^3), including the conditioned crawlspace. The net ventilation rate of the HRV in the H2 prototype was about 0.21 ACH, or 47 cfm (22 L/s). Based on these measurements, it appeared that the H2 ventilation rate was consistent with ASHRAE 62.2, while the H1 was ventilated at a lower rate by design.

Temperature Stability and Uniformity

Comparisons of the thermal comfort in H1 and H2 were made from Friday afternoon through Monday morning. Of special interest was the difference in mean radiant temperature for the forced air heating system compared to the radiant slab heating system. Shielded and black globe temperature sensors were temporarily installed in the living room, master bedroom, and west bedroom of each house. Figure 3 shows a typical installation of the shielded and black globe sensors. The sensors were located 4 ft (1.2 m) above floor level near the center of the room. The shielded sensors represented the temperature of the air in the room without the influence of radiant heat transfer. The black globe sensors responded to both the room air temperature by convective heat transfer and the mean radiant temperature by exchanging heat through radiation with all surfaces in the room. The black globe temperature was meant to approximate the thermal comfort of a person in the room. It is important to note that black globe temperatures can vary significantly within a single room because the view factors to hot and cold surfaces sensors change depending on location.

Figures 4 and 5 show the 5-minute average shielded air temperatures from December 26 (Sunday) through December 27 (Monday) for both houses. The temperatures in H1 (Figure 4) exhibited short-term variations as the forced air furnace cycled on and off in response to the thermostat. The short-term variation in shielded air temperature for each location in H1 ranged from 2ºF to 4ºF (1.1ºC to 2.2ºC), depending on the time of day and the room. The room-to-room temperature variation in H1 was as high as

6ºF (3.3ºC). This room-to-room non-uniformity was likely a result of the single thermostat attempting to satisfy disparate and dynamic thermal zones, and to insufficient air balancing and mixing among the rooms.

The five-minute average shielded air temperatures in H2 (Figure 5) were significantly different from those in H1. H2 temperatures exhibited almost none of the short-term and room-to-room variation observed in H1. Three separate thermostats controlled the hydronic system in H2 and, as a result, much more uniform temperatures were achieved compared to H1. However, the H2 exhibited a more pronounced long-term temperature increase in response to late afternoon passive solar gains. The temperatures in rooms with high solar gains rose from 3ºF to 5ºF (1.7ºC to 2.8ºC) above their nominal set points. This was an interesting contrast to H1, which had nearly identical passive solar gains. It appeared that the concrete floor in H2 was less able to store the solar gains and moderate the air temperatures because it was already warm from hydronic heating. In other words, a greater fraction of incoming solar radiation may have reflected off the warm slab, instead heating the walls, ceiling, and indoor air.

We next examined the difference between the shielded temperatures and the black globe temperatures during the time period shown in Figures 4 and 5. The black globe temperatures were typically less than the shielded temperatures at night and slightly greater than the shielded temperatures during daytime hours when passive solar gains were present. In the H1, the difference between black globe and shielded temperature was frequently greater than 1.5ºF (0.8ºC). In the H2, the difference was rarely greater than 0.5ºF (0.3ºC), suggesting a potentially noticeable improvement in thermal comfort attributable to the radiant floor heating system. These results also suggested that the H2 thermostat could be set about 1ºF (0.6ºC) lower than the H1 during the heating season yet achieve approximately the same comfort level based on mean radiant temperature. Such a thermostat adjustment would translate to approximately 1% whole-house energy savings if acted upon by the occupants.

Solar Water Heating Performance

The solar collector heat flows were calculated by measuring the flow rate and temperature difference of the glycol mixture entering and leaving the collector. The collector efficiency at noon on sunny days during the test period was about 40%, which was fairly consistent with our expectations.

However, there appeared to be significant reverse thermo-siphoning in the collector loop at night. There was a potential for this flow to establish itself at night because the hot storage tank was at a lower elevation than the cold solar collector. A check valve to prevent reverse flow was specified and installed but did not appear to be functioning correctly. This thermo-siphoning effect resulted in the loss of a substantial portion of the thermal energy collected during the day.

A second check valve was installed in the system on Friday, March 25, to prevent reverse thermosiphoning. Figure 6 shows the subsequent change in hourly average collector inlet and outlet temperature. Before Friday, the collector inlet temperature dropped to around 50ºF (10ºC) at night while the collector outlet temperature rose to around 86ºF (30ºC). After Friday, the collector inlet and outlet temperatures stayed around 77ºF (25ºC), which was the temperature in the mechanical closet. It therefore appears that the thermosiphon problem was resolved.

Space Heating Performance

Figure 7 shows a graph of hourly average thermal energy flows for space heating in the H2 measured using the long-term monitoring system. The boiler and radiant space heating energy flows were nearly identical because there was no DHW use during the short-term test period, and the solar hot water system did not provide a significant contribution toward the space-heating load. Very little active heating was required on Saturday and Sunday afternoons, indicating that the passive solar design virtually eliminated the heating load during sunny periods even when the outside temperature was below 40ºF (4ºC). The maximum space heating occurred at about 2100 even though the maximum indoor-outdoor temperature difference was typically at about 0600. This behavior was probably due to the thermal capacitance of the radiant floor heating system, which could have been slow to respond to rapidly changing heating loads.

PV System Performance

The H2 prototype was equipped with a nominal 1.6 kW (5540 Btu/hr) grid-tied photovoltaic system mounted on a south-facing roof surface at an angle of 45 degrees from horizontal. On December 23–24, 2004, we ran 18 i-V (current-voltage) traces over a range of solar and temperature conditions. Key parameters at Standard Test Conditions (STC) calculated using the calibrated model were compared to those provided by the manufacturer (BP Solar 2003). Figure 8 shows a single i-V curve measured near STC compared to the curve from the manufacturer. At the maximum power point, the measured power output at STC was 11% lower than predicted using the manufacturer's data. However, it is not surprising that the measured performance of the PV array was on the order of 10% below manufacturer's specifications because the manufacturer only guarantees 90% of the rated performance for the first 12 years of operation (BP Solar 2003).

Based on the measured AC output of the inverter, and applying the manufacturer's inverter efficiency curve, the hourly PV array efficiency (η) was calculated. The hourly back-of-module temperature was calculated based on measurements at the lower left corner of the arrays, adjusted by 18ºF (10ºC) to better reflect the temperature near the middle of the array. This adjustment was determined by examining the front-of-module temperatures under near-constant solar and temperature conditions using a small infrared sensor attached to an extension pole held over the front of each module. Although the infrared sensor readings were biased because of radiation reflected from the surface of the array, the relative temperature distribution was probably accurate enough for our purposes.

Using the measured array efficiencies (η) and effective back-of-module temperatures (T_{mod}), the efficiency at STC (η_0) and the temperature coefficient of efficiency (γ) were calculated by performing linear regression analysis using Equation 1, which is a simple model of PV array efficiency as a function of the effective back-of-module temperature (T_{mod}) for the array:

$$\eta = \eta_0 * (1 + \gamma * [T_{mod} - T_0]) \tag{1}$$

where

η = PV array efficiency

η_0 = PV array efficiency at $T_{mod} = T_0$

γ = temperature coefficient of efficiency

T_{mod} = effective back-of-module temperature for the array (ºC)

T_0 = 23ºC (corresponding to a cell temperature of about 25ºC)

A significant amount of shading of the PV array was observed in the morning, caused by the roof on the east of the array. The effect of this shading on PV power for a typical sunny winter day is evident in Figure 9, which compares the measured AC output from the inverter to the unshaded irradiance on a clear day in January.

BUILDING SIMULATIONS

PV Simulations

Using the short-term measurements discussed in the previous section and the procedure described by Barker (2003), a calibrated model for use in TRNSYS (Klein 2000) was developed. The efficiency of the inverter was modeled using the efficiency curve published by the manufacturer. To account for shading effects from the east roof, a correlation was developed to calculate the effective beam shading fraction as a function of time of day and time of year.

The calibrated TRNSYS model predicts an annual energy production of 2320 kWh (7.92 MBtu) based on TMY2 data. This result is about 82% of what would be predicted using the manufacturer's specifications. If the PV array had been installed in a location with no shading, the predicted annual energy production would be about 10% higher, or 2558 kWh (8.73 MBtu) per year.

Solar Hot Water and Space Heating Simulations

Based on the final configuration and measured performance of the solar hot water system, we developed a TRNSYS model to estimate annual energy savings and solar fraction. Space heating loads were taken from DOE-2.2 whole-house simulations (which will be discussed in the next section), and hot water demand profiles were based on the BA benchmark. Because of the configuration of the system, it was not possible to differentiate between solar energy used for water heating and solar energy used for space heating. Therefore, the combined load for space and water heating was used in the analysis of the solar system.

Figure 10 shows the predicted monthly energy provided by the solar system compared to the combined space and water-heating load. It is evident that the solar system will meet a large fraction of the DHW load during the summer months but is not likely to make a noticeable contribution toward the space-heating load, especially during the coldest months when even less useable solar energy is collected. Over the course of a typical year, the TRNSYS model predicts that a solar fraction of about 34.6% of the combined water and space heating load can be achieved. This is consistent with 94 therms (2800 kWh) of energy savings, or about $73/year based on an estimated natural gas cost of $0.78/therm for Carbondale. This does not account for the small increase in electricity cost (~$4) associated with the pump and controls.

Whole-House Energy Simulations

DOE-2.2 simulations were performed for both the H1 and H2 using the detailed design specifications, combined with measurements from short-term field-testing. Three zones were used in the model, corresponding to the three heating control zones in the H2 test house. Because the H1 had only one control zone, it was modeled using three zones held at the same temperature. In keeping with the standard BA performance analysis procedures (Hendron et al. 2004), the whole-house energy use of each test house was compared to the Building America Benchmark, Regional Standard Practice (RSP), and Builder Standard Practice (BSP). Key specifications for each of these base cases are listed in Table 2.

Table 2. Key features of the Building America Benchmark, RSP, and BSP

Same as Test House Except:	Benchmark	Regional Standard Practice (RSP)	Builder Standard Practice (BSP)
Building Shell:			
Wall	R-19.2 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-3.4 $m^2 \cdot K/W$)	R-13 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-2.3 $m^2 \cdot K/W$)	R-19 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-3.3 $m^2 \cdot K/W$)
Ceiling/roof	R-38.5 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-6.8 $m^2 \cdot K/W$)	R-27 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-4.8 $m^2 \cdot K/W$)	R-27 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-4.8 $m^2 \cdot K/W$)
Windows	U-Value = 0.36 $Btu/hr \cdot ft^2 \cdot {}^oF$ (2.0 $W/m^2 \cdot K$) SHGC = 0.32	Double pane, clear	Double pane, low-e
Crawlspace wall	R-16.7 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-2.9 $m^2 \cdot K/W$), unvented	Uninsulated, vented	R-10 $hr \cdot ft^2 \cdot {}^oF/Btu$ (R-1.8 $m^2 \cdot K/W$), unvented
Infiltration rate	0.39 ACH	0.39 ACH	0.35 ACH
HVAC:			
Air conditioner	SEER 10	SEER 10	SEER 10
Gas furnace (H1 only)	78 AFUE furnace	78 AFUE furnace	90 AFUE furnace
Gas boiler (H2 only)	80 AFUE boiler	80 AFUE boiler	90 AFUE furnace
Duct location	Crawlspace	Crawlspace	Crawlspace
Gas DHW	0.54 EF	0.54 EF	0.56 EF
Ventilation	Continuous exhaust fan	Continuous exhaust fan	Continuous exhaust fan
Lighting	90% incandescent	90% incandescent	90% incandescent

The predicted whole-house source energy savings compared to the benchmark are 20% for the H1 and 52% for the H2, as shown in Tables 3 and 4. In the H1 house, the space heating end-use was reduced the most, followed by lighting. The ventilation system showed negative savings because the large central furnace fan is used to draw in and distribute the ventilation air. For the H2 house, improvements in space heating, domestic hot water, lighting, and site generation (PV system) were the largest contributors to whole-house energy savings. There was again an energy penalty for the ventilation system, but in this case the HRV reduced the impact of ventilation on space conditioning energy, so the net effect was actually an overall reduction in energy use. It should be pointed out that the HRV had certain additional features that tended to increase the fan energy requirements, including HEPA filtration and air recirculation, resulting in approximately twice the energy consumption as the HRV that was originally specified. It should also be noted that Building America analysis requires the use of a SEER 10 air conditioner when modeling a prototype with no cooling system if there is any cooling load at all. This approach credits the energy savings associated with a reduced cooling load but does not credit energy savings resulting from the absence of an air conditioner.

Table 3. Predicted End-Use Energy Consumption of the H1 Prototype.

					Source Energy Savings for H1					
	Annual Source Energy				Percent of End-Use			Percent of Total		
	Bench	**RSP**	**BSP**	**H1**	**Bench**	**RSP**	**BSP**	**Bench**	**RSP**	**BSP**
End-Use	MBTU/yr	MBTU/yr	MBTU/yr	MBTU/yr	%	%	%	%	%	%
Space Heating	76	79	81	57	24%	28%	29%	11%	13%	14%
Space Cooling	4	7	2	1	65%	81%	28%	1%	3%	0%
DHW	24	24	24	21	13%	13%	13%	2%	2%	2%
Lighting	19	19	19	10	44%	44%	44%	5%	5%	5%
Appliances + Plug	42	42	42	37	12%	12%	12%	3%	3%	3%
OA Ventilation	2	2	2	6	-276%	-276%	-276%	-3%	-3%	-3%
Total Usage	166.7	173.3	170.1	134.1	20%	23%	21%	**20%**	23%	21%
Site Generation	0	0	0	0				**0%**	0%	0%
Net Energy Use	167	173	170	134	20%	23%	21%	**20%**	23%	21%

The "Percent of End-Use" columns show the change in each end-use category.

The "Percent of Total" columns show the overall energy savings associated with each end-use.

Table 4. Predicted End-Use Energy Consumption of the H2 Prototype

					Source Energy Savings for H2					
	Annual Source Energy				Percent of End-Use			Percent of Total		
	Bench	RSP	BSP	H2	Bench	RSP	BSP	Bench	RSP	BSP
End-Use	MBTU/yr	MBTU/yr	MBTU/yr	MBTU/yr	%	%	%	%	%	%
Space heating	75	79	81	35	54%	56%	57%	24%	26%	27%
Space cooling	4	7	2	2	60%	78%	18%	1%	3%	0%
DHW	24	24	24	12	53%	53%	53%	8%	7%	8%
Lighting	19	19	19	10	44%	44%	44%	5%	5%	5%
Appliances + plug	42	42	42	37	12%	12%	12%	3%	3%	3%
OA ventilation	2	2	2	8	-343%	-343%	-343%	-4%	-3%	-3%
Total usage	166	173	170	103	38%	40%	39%	**38%**	40%	39%
Site generation	0	0	0	-24				**14%**	14%	14%
Net energy use	166	173	170	79	52%	54%	53%	**52%**	54%	53%

The "Percent of End-Use" columns show the change in each end-use category.

The "Percent of Total" columns show the overall energy savings associated with each end-use.

The energy savings associated with specific packages of energy-efficiency measures in the H1 and H2 are summarized in Tables 5 and 6. These tables provide estimates of energy cost savings but do not include the first cost or maintenance cost of individual measures. Because such costs are very difficult to quantify in the context of a prototype house, we did not try to evaluate the overall cost effectiveness of the energy-saving measures. For the H1, the most important improvements were higher insulation levels, high-performance windows, very tight envelope, an efficient lighting and appliance package, and efficient space and water heating equipment. For the H2, there were obviously many key features that contributed to the 52% energy savings. The largest contributors were the PV system, efficient radiant heating, solar hot water, efficient lighting and appliances, orientation-specific glazing, and tight building envelope. It can also be seen that the HRV in the H2 is expected to provide a very significant whole-house source energy savings of about 7% compared to the central-fan integrated supply ventilation system used in the H1 and 3% energy savings compared to the simple exhaust ventilation fan assumed for the benchmark.

Table 5. Predicted Savings for Energy Efficiency Measures in the H1 Prototype

					National Average		Builder Standard (Local Costs)			
	Site Energy		Source Energy		Energy Cost		Energy Cost		Measure	Package
Increment	kWh	therms	MBTU	Savings %	$/yr	Savings %	$/yr	Savings %	Value ($/yr)	Savings ($/yr)
Base (BA)	6098	1021	166.7		$ 1,505		$ 1,291			
Base (RSP)	6562	1039	173.3	-4%	$ 1,563	-4%	$ 1,342			
Base (BSP)	5907	1074	170.1	-2%	$ 1,539	-2%	$ 1,316			
Base + imp. wall insulation	5857	1046	166.7	0%	$ 1,508	0%	$ 1,290	2%	$ 26	$ 26
Base + imp. ceiling ins	5784	1016	162.9	2%	$ 1,473	2%	$ 1,261	4%	$ 29	$ 55
Base ++ improved windows	5846	966	158.5	5%	$ 1,431	5%	$ 1,227	7%	$ 34	$ 89
Base ++ infiltration	5802	902	151.5	9%	$ 1,366	9%	$ 1,174	11%	$ 53	$ 142
Base ++ ventilation	6745	902	161.1	3%	$ 1,448	4%	$ 1,250	5%	$ (77)	$ 66
Base ++ improved EF DHW	6745	871	158.0	5%	$ 1,419	6%	$ 1,226	7%	$ 24	$ 90
Base ++ improved heating system	6159	793	144.0	14%	$ 1,293	14%	$ 1,118	15%	$ 108	$ 198
H1 Prototype lighting, appl., and plug	4819	830	134.1	**20%**	$ 1,211	20%	$ 1,038	21%	$ 80	$ 278

Notes:

"Source Energy Savings %" and "National Average Energy Cost Savings %" compared to the BA base case, whereas the "Energy Cost Savings %" and the "Package savings $/yr" are compared to the BSP case.

National average electric cost:	0.0874	$/kWh
National average gas cost:	0.952	$/therm
Colorado electric cost:	0.0814	$/kWh
Colorado gas cost:	0.778	$/therm

Table 6. Predicted Savings for Energy Efficiency Measures in the CORE H2 Prototype

					National Average		Builder Standard (Local Costs)			
	Site Energy		Source Energy		Energy Cost		Energy Cost		Measure	Package
Increment	kWh	therms	MBTU	Savings %	$/yr	Savings %	$/yr	Savings %	value ($/yr)	savings $/yr
Base (BA)	6098	1015.8	166.1		$1,500		$1,286			
Base (RSP)	6562	1034	172.7	-4%	$1,558	-4%	$1,338			
Base (BSP)	5907	1075	170.2	-2%	$1,540	-3%	$1,317			
Base + imp. wall insulation	5857	1045	166.6	0%	$1,507	0%	$1,289	2%	$27	$27
Base + imp. ceiling ins	5784	1015	162.8	2%	$1,472	2%	$1,260	4%	$29	$57
Base ++ improved windows	5822	953	156.9	6%	$1,416	6%	$1,215	8%	$45	$102
Base ++ infiltration	5780	890	150.0	10%	$1,352	10%	$1,163	12%	$52	$154
Base ++ ventilation (central fan)	6357	890	155.9	6%	$1,403	6%	$1,210	8%	$(47)	$107
Base ++ ventilation (HRV)	6299	788	145.0	13%	$1,301	13%	$1,126	15%	$84	$191
Base ++ improved EF DHW	6299	691	135.1	19%	$1,208	19%	$1,050	20%	$159	$267
Base ++ improved heating system	6345	569	123.1	26%	$1,096	27%	$959	27%	$91	$358
Base ++ solar hot water	6392	475	114.0	31%	$1,011	33%	$890	32%	$69	$427
Base ++ lighting, appl., and plug	5025	505	103.0	**38%**	$920	39%	$802	39%	$88	$515
H2 prototype including PV	2705	505	79.3	**52%**	$717	52%	$613	53%	$189	$704

Notes:

"Source Energy Savings %" and "National Average Energy Cost Savings %" compared to the BA base case, whereas the "Energy Cost Savings %" and the "Package savings $/yr" are compared to the BSP case.

National Average Electric Cost:	0.0874 $/kWh
National Average Gas Cost:	0.952 $/therm
Colorado Electric Cost:	0.0814 $/kWh
Colorado Gas Cost:	0.778 $/therm

LONG-TERM MONITORING OF THE H2 PROTOTYPE

During the short-term test period, we installed long-term monitoring equipment to collect energy consumption data in the H2 prototype for one year, beginning in January 2005. Our interest in long-term monitoring was to document the actual performance of the house after it became occupied and to evaluate the long-term performance of the PV and energy efficiency systems. It is particularly useful to have detailed performance data if the utility bills indicate that energy use is significantly different from initial expectations. The data can be used to determine whether the lighting, heating, cooling, and hot water systems are consuming more or less energy than expected and whether the PV and solar DHW systems are producing more or less than expected. About eight months of data have been collected at the present time, and we will continue collecting data until at least January 2006.

Solar Water Heating

Figure 11 shows a graph of the monthly average measurements of solar energy collected for each hour of the day for the period from January through August 2005. The reverse thermosiphoning described earlier in this paper caused the apparent positive (but actually negative) heat flow that occurred at night from January through March. The turbine in the flow meter was actually moving in the reverse direction from its intended flow direction, but the counting mechanism could not discriminate between forward and reverse turbine rotation.

Hourly measured collector efficiency values from January through August 2005 were compared to the corresponding rated efficiency curve derived from Solar Rating and Certification Corporation Document OG100 (SRCC 1995). The results of this comparison suggested that the measured efficiency was consistent with the rated efficiency within the accuracy of our instrumentation.

PV System

The measured average electricity output of the PV system through August 2005 is shown in Figure 12. The PV output is consistent with our expectations for a nominal 1.6 kW (5500 Btu/hr) system. Over the first eight months of 2005, an average of 64% of electrical energy use has been met by the PV system on a net-energy basis.

Other Monitored Results

The natural gas usage during the first few months of occupancy struck many observers as very high considering the level of energy savings that was anticipated. The measured space heating load was 20 million Btu for the time period from January through April. The DOE-2.2 simulations were repeated using the actual weather conditions and occupant behavior patterns (internal loads, thermostat settings, and hot water usage). Indeed, the simulations predicted that the space heating load should have only been about 14 million Btu (4100 kWh), or 30% less than the actual measured load. Heat losses to the ground were the most likely cause of the discrepancy, although we have not yet verified this as the cause because our current model cannot perform reliable analysis of interactions between the heated slab, the crawlspace, the ground, and the rest of the house. Because of limitations with DOE-2.2, certain effects are difficult to model accurately: (1) the radiative exchange between the heated slab and the crawlspace floor, (2) air movement between the crawlspace and the house, and (3) ground coupling effects over time. We decided that direct measurements of heat loss to the ground would be the best way to quantify losses through the crawlspace and subsequently installed two heat flux transducers in the ground to provide an estimate of this heat flow. The Community Office for Resource Efficiency (CORE) is planning to install rigid insulation above the crawlspace in January 2006, and we will monitor the effect on ground heat loss over the second half of the winter.

It was also noticed that the base level of electricity use was relatively high for the H2 prototype, remaining close to 400 W (1400 Btu/hr) throughout the night. The HRV selected by the builder was not the same unit originally specified, and it consumed a relatively large amount of electricity, approximately 170 W (580 Btu/hr) continuously. The high electricity use of the HRV was associated with functionality that may not be necessary for typical homes, including HEPA filtration and recirculation of indoor air. In addition, it was observed that the boiler pump was operating 24 hours/day, contributing approximately 80 W (270 Btu/hr) to the overnight electricity use. (This does not include the increased gas usage associated with transferring heat from the boiler to the solar tank during the night when there is no call for heating.)

The remaining 150 W (510 Btu/hr) could be attributed to fairly typical continuous loads from the refrigerator, clocks, electrical standby losses, and perhaps some lighting. Modifications to the pump controls were completed in late June 2005, and subsequent data indicated a significant decrease in base electricity load during summer nights. We also expect the HRV to be replaced with a less energy intensive model by the end of 2005.

SUMMARY AND DISCUSSION

We were able to draw several conclusions about the performance of the H1 and H2 prototype houses based on the short-term test results, whole-house and solar energy simulations, and preliminary data from long-term monitoring:

- Both the H1 and H2 prototypes met the design target of 1200 cfm at 50 Pa (566 L/s @ 50 Pa) with room to spare. Blower door testing indicated leakage rates of 475 cfm at 50 Pa (224 L/s @ 50 Pa) for the H1 and 625 cfm at 50 Pa (295 L/s @ 50 Pa) for the H2. The estimated annual average infiltration rate, adjusted for altitude, was 0.12 ACH for the H1 and 0.15 ACH for the H2.
- Despite very cold weather during the test period, the natural infiltration as measured by a tracer gas was between 0.05 ach and 0.12 ach for both prototypes.
- Based on tracer gas measurements, the ventilation rate provided by the HRV in the H2 prototype was about 0.21 ach, or 47 cfm (22 L/s), meeting the ASHRAE 62.2 recommendation of 42 cfm (20 L/s). The intermittent supply ventilation system operating at 33% duty cycle in the H1 prototype provided an average of about 0.13 ach, or 29 cfm (14 L/s), which was less than the recommended level in ASHRAE 62.2.
- Relatively large room-to-room temperature variations were measured in the H1 prototype, which had a forced air heating system with a single thermostat. In contrast, room-to-room temperatures were very uniform in the H2 prototype, which had a radiant floor heating system with three control zones.
- Short-term temperature fluctuations were evident in the H1 prototype due to the cycling of the forced air heating system. No such short-term fluctuations were present in the H2 prototype, but passive solar gains that could not be stored in the heated slab resulted in a relatively large temperature rise of about 4ºF (2.2ºC) on sunny afternoons.
- A comparison of temperatures measured by shielded sensors and black globe sensors indicated that an equivalent comfort level could be achieved by the radiant floor system in the H2 prototype with a thermostat setting about 1ºF (0.6ºC) lower than the forced air system in the H1.
- A reverse thermosiphoning phenomenon was observed in the H2 solar water heating system during short-term testing and subsequent monitoring. The problem was fixed on March 25 when a second check valve was added to the system.
- The predicted annual net solar contribution toward water heating and space heating in the H2 is 34.6%, saving about $73/year. This estimate is based on typical occupant behavior (as represented by the benchmark operating conditions) and TMY2 weather data and does not account for the small increase in electricity associated with the solar DHW system (~$4). The actual solar contribution will be evaluated after a year of measured data is collected.
- The current estimate of annual PV output is about 2320 kWh (7.92 MBtu) based on a TRNSYS model calibrated with field measurements. This represents about 46% of the predicted total electricity use based on typical occupants and TMY2 weather data. The actual fraction of the electricity load met by the PV system during the first few months of 2005 was even higher at 64%. The main reason the actual value was better than predicted was because the occupants used less electricity than a typical family in a three-bedroom house.
- Shading of the PV array on the H2 during the morning hours caused by the east section of the roof is predicted to have a noticeable effect (~10%) on annual PV output.

- Whole-house energy savings for the H2 is estimated to be 52% compared to the BA benchmark, exceeding the design goal of 45% by a significant margin. Whole-house energy savings for the H1 is expected to be about 20%.
- Because the H2 was intended to be a showcase for advanced energy efficiency technologies, the package would not be cost effective to a builder in a typical production environment without large subsidies and cost sharing. In contrast, the H1 included a well-established combination of measures that have proven to be cost effective in other BA projects. Unfortunately, we did not have access to sufficient builder cost data to substantiate cost-effectiveness in the context of this particular project.
- The expected reduction in CO_2 emissions over the estimated 30 year life of the energy efficiency measures is approximately 262,000 lb for the H1 and 697,000 lb for the H2.
- Preliminary monitoring of electricity and DHW consumption in the H2 did not indicate any major performance issues, with the exception of the boiler pump and the large HRV fan, both of which operated continuously and led to an unusually large base electric load. The pump controls have since been modified, and the pump now only operates when auxiliary heat is needed. The HRV may be replaced by a less energy intensive model in the near future.
- The actual measured space heating load is higher than our simulations predict. The most likely cause is that we have underestimated the winter energy loss through the crawlspace. Because this effect cannot be modeled with a high level of accuracy using our DOE-2.2 model, we will be performing some additional tests during the remainder of the monitoring period to help identify the cause of this issue with greater certainty.

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FIGURES

Figure 1. H1 (right) and H2 (left) prototype houses (viewed from the southwest).

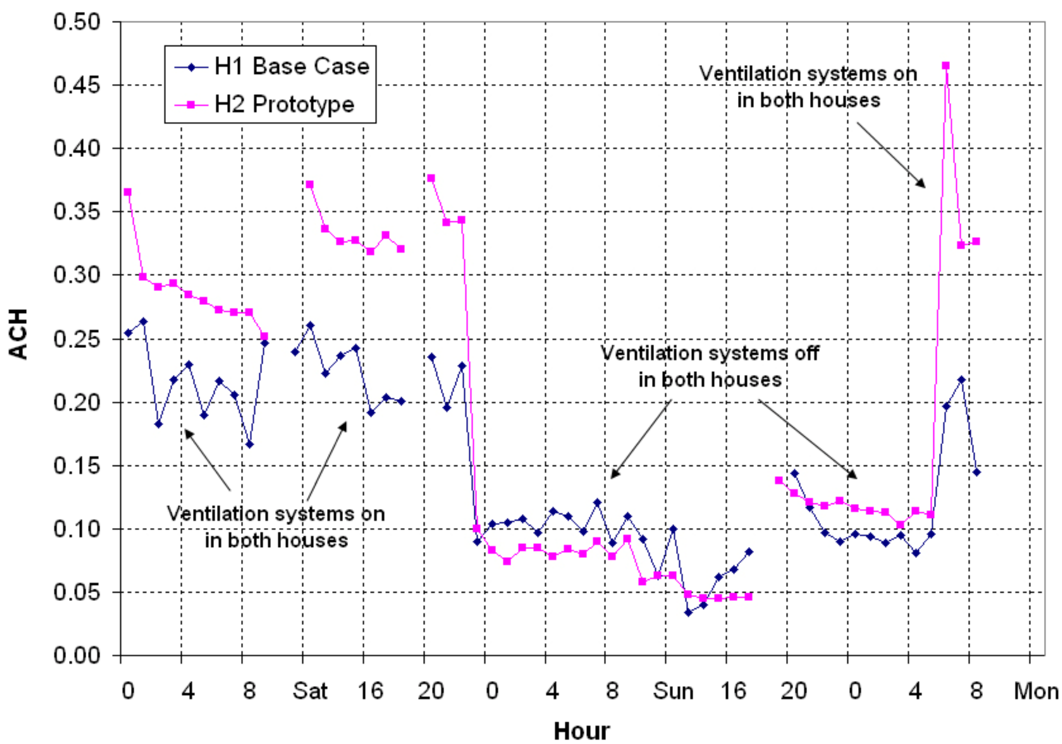

Figure 2. Measured air exchange rates during tracer gas tests.

Figure 3. Shielded air temperature sensor (left) and black globe temperature sensor (right) in master bedroom.

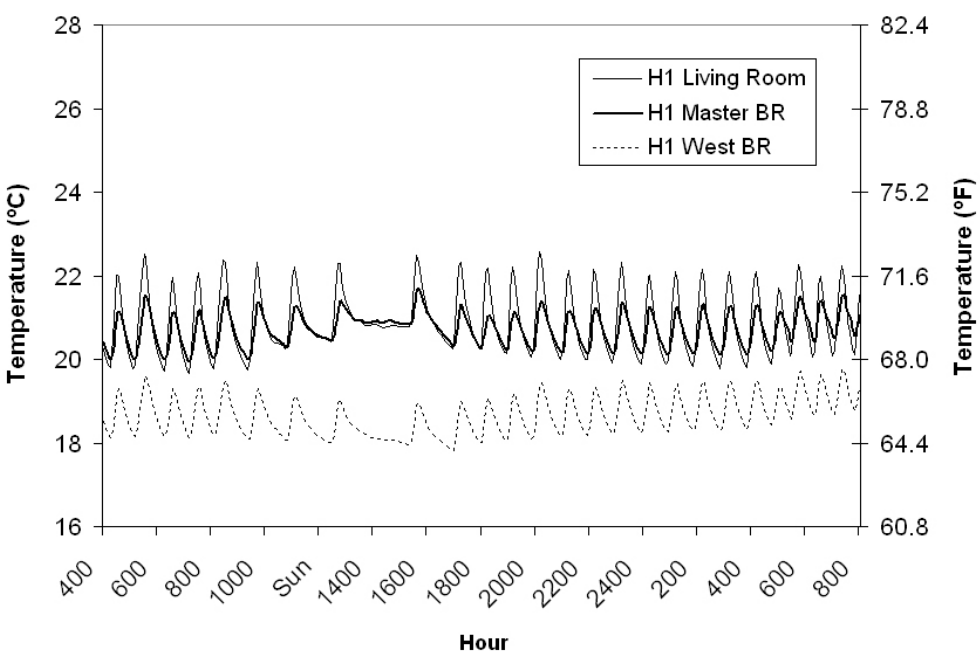

Figure 4. Average shielded air temperatures in the H1 at five-minute intervals (December 26-27, 2004).

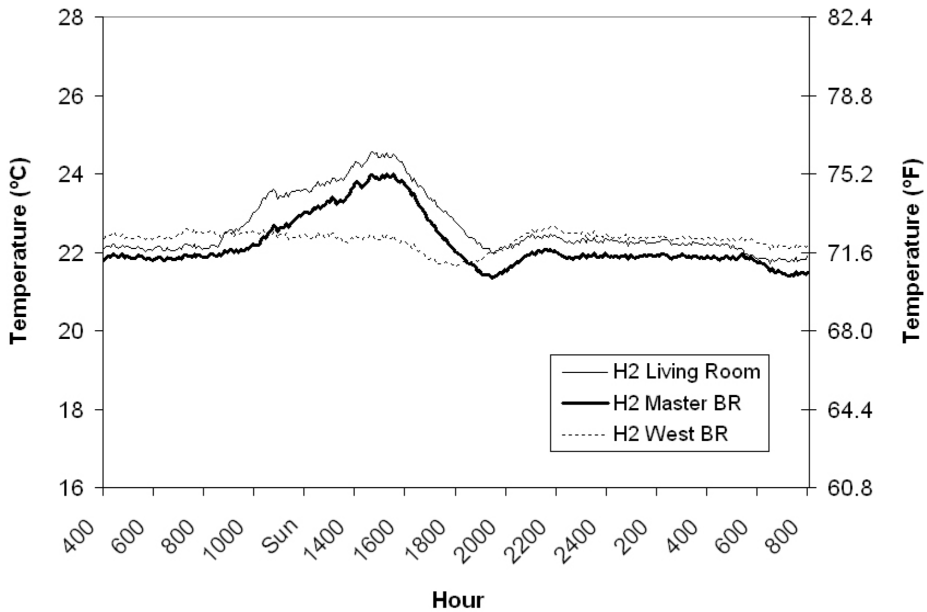

Figure 5. Average shielded air temperatures in the H2 at five-minute intervals (December 26-27, 2004).

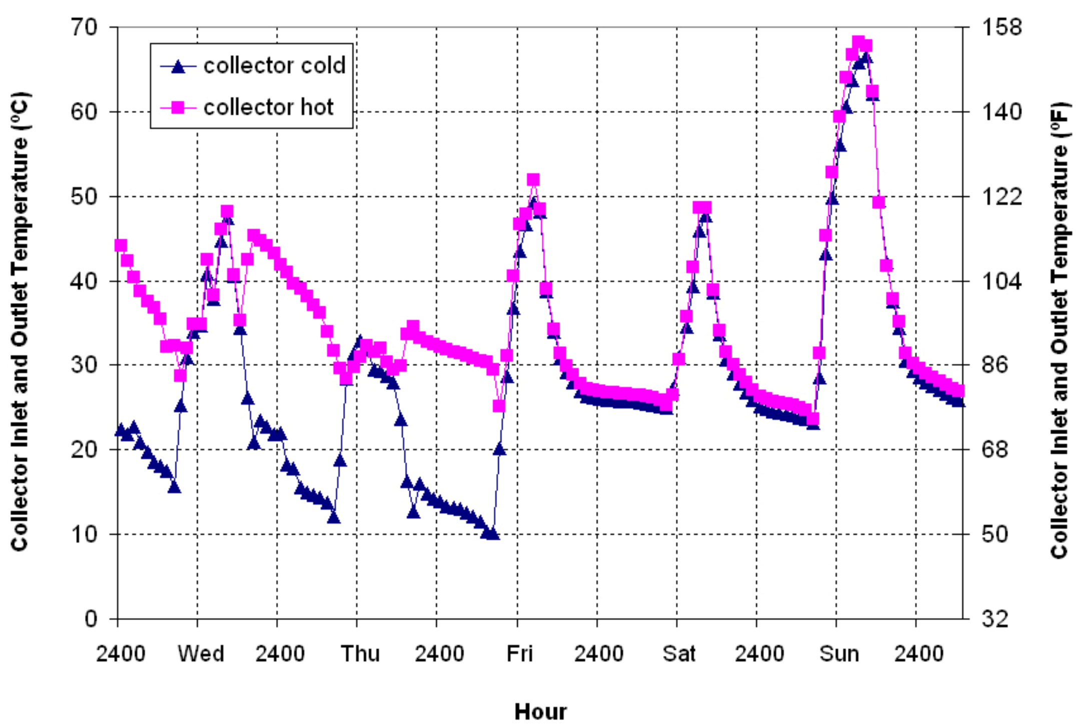

Figure 6. Collector inlet and outlet temperatures before and after the thermosiphoning issue was resolved.

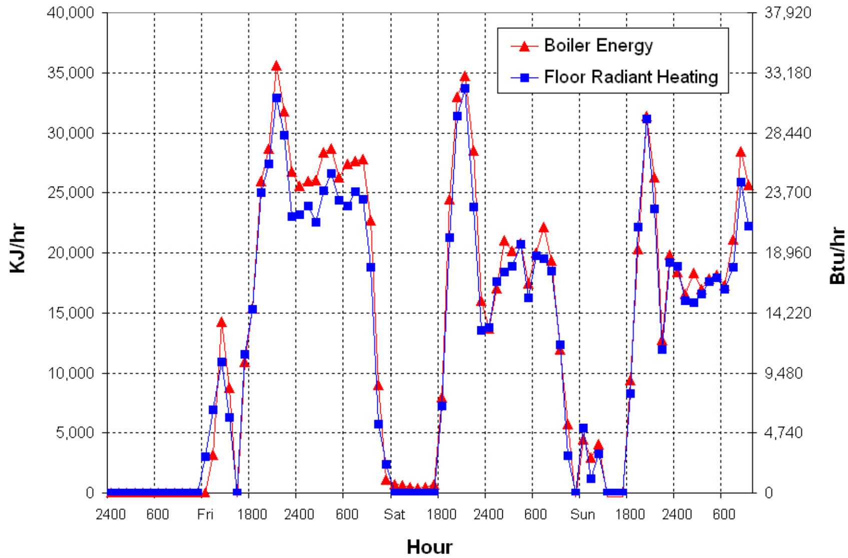

Figure 7. Space heating thermal energy flows during test period.

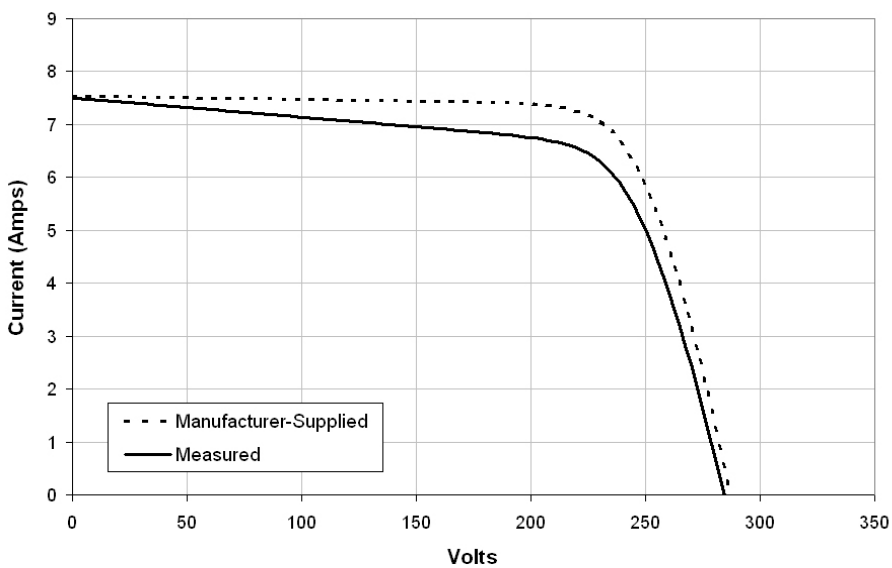

Figure 8. i-V curves comparing the manufacturer's curve to the measured curve and scaled to STC at 25ºC (77ºF) and 1000 W/m^2.

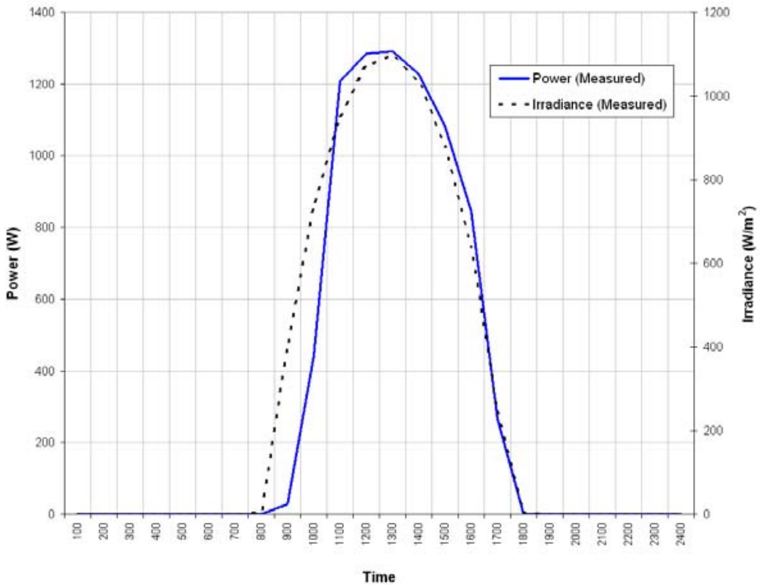

Figure 9. Comparison of AC output from the PV system to irradiance for a typical winter day, illustrating the effect of morning shading.

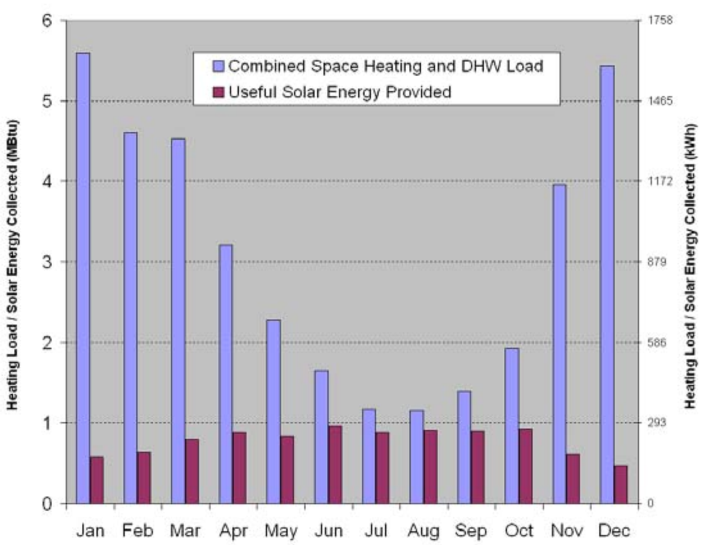

Figure 10. Predicted contribution of solar water heating system toward meeting the domestic hot water and space heating loads, calculated using a TRNSYS model and measured performance data.

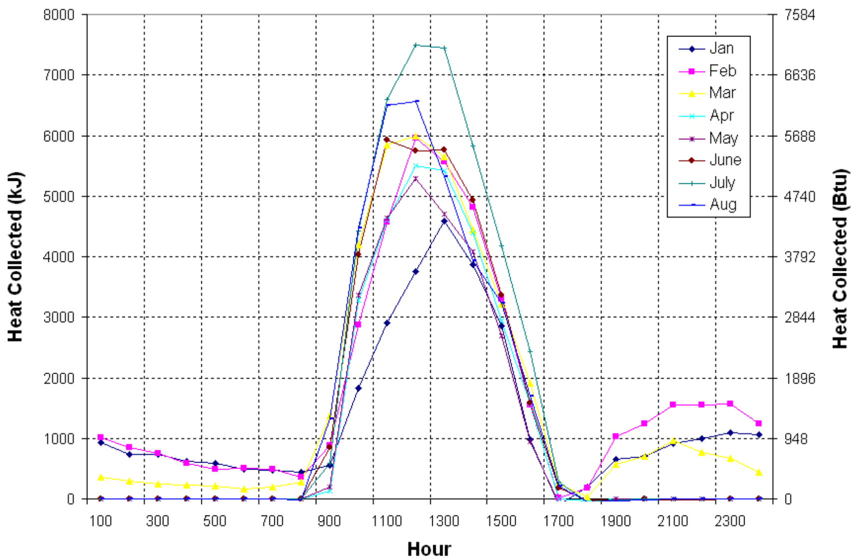

Figure 11. Monthly average solar thermal energy collected during the first eight months of 2005.

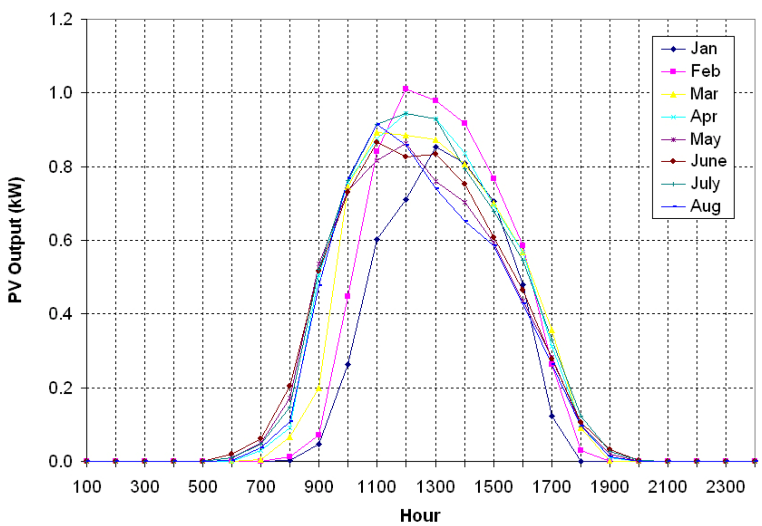

Figure 12. Average PV system output during the first eight months of 2005.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

Two high performance prototype houses were built in Carbondale, Colorado, as part of the U.S. Department of Energy's Building America (BA) Program. Each prototype was a 1256 ft2 (117 m2), 1-story, 3-bedroom house, and met the local requirements for affordable housing. The National Renewable Energy Laboratory (NREL) performed short-term field testing and DOE-2.2 simulations in support of this project at the end of December 2004. We also installed long-term monitoring equipment in one of the houses, and are currently tracking the performance of key building systems under occupied conditions. One of the houses (designated H1) included a package of cost-effective energy efficiency features that placed it well above the Energy Star level, targeting a Home Energy Rating System (HERS) score of 88-89. The other (designated H2) was a BA research house, targeting a HERS score of 94-95, and 45% whole-house energy savings compared to the BA Benchmark. Preliminary results from the field evaluation indicate that the energy savings for both houses will exceed the design targets established for the project, although the performance of certain building systems, including the ventilation and foundation systems, leave some room for improvement.

15. SUBJECT TERMS
Building envelope; heat recovery units; radiant heating equipment; residential buildings; solar equipment; Building America; U.S. Department of Energy

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