

# Imagine Homes New Construction Occupied Test House

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July 2013

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## **Imagine Homes New Construction Occupied Test House**

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*Unless otherwise noted, all tables were created by IBACOS.*

## Definitions

ACH	Air changes per hour
AFUE	Annual fuel utilization efficiency
AHU	Air handling unit
AMY	Actual Meteorological Year
BA	Building America
BEopt	Building Energy Optimization (software)
CFIS	Central fan integrated supply
CFM	Cubic feet per minute
DHW	Domestic hot water
EF	Energy factor
HSP	House Simulation Protocols
HVAC	Heating, ventilation, and air conditioning
LAMEL	Lighting, appliances, and miscellaneous electric load
MEL	Miscellaneous electric load
PEX	Cross-linked polyethylene
PV	Photovoltaic
RH	Relative humidity
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
TMY	Typical Meteorological Year
XPS	Extruded polystyrene



## Executive Summary

This report discusses IBACOS' long-term monitoring plan completed to evaluate the performance of an energy-efficient home constructed in San Antonio, Texas, by builder-partner Imagine Homes in 2010. The home achieves a source energy savings of 32% without the installed photovoltaic (PV) system and 44% savings with the PV system contribution relative to the Building America (BA) House Simulation Protocols (HSP) (Hendron and Engebrecht 2010). Monitoring of the energy use, energy generation, and temperature conditions related to this high performance residential project took place between July 2010 and October 2011. This report summarizes the research findings related to heating, ventilation, and air conditioning (HVAC) system performance, estimated and actual energy use of key subsystems, electricity generation by the PV system, and performance of the solar thermal domestic hot water (DHW) system.

Changes in the insulation strategy that eliminated the use of spray foam in wall cavities raised concerns from the builder about occupant comfort complaints due to increased air leakage and necessitated additional air sealing measures to alleviate some of these concerns. Despite the builder's concerns about occupant comfort, measured air leakage was below the specified target. Furthermore, the HVAC system effectively maintained acceptable temperatures and humidity levels inside the house during peak cooling and heating and nonpeak operating periods. As a result, occupants are likely to be comfortable in the home year round (ASHRAE 2008). System runtime closely tracked outdoor temperature fluctuations during peak and nonpeak periods, indicating acceptable sizing of the system to design loads.

There were discrepancies between modeled and actual energy use values. After adjusting the model for actual weather conditions and indoor set points, actual space cooling energy use was the closest of all end uses to the corresponding modeled value. The energy consumption predicted for lighting, appliances, and miscellaneous electrical loads (LAMELs) was significantly higher than the measured amounts, and the energy consumption predicted for heating was significantly higher than the measured amounts.

The model predicted lower energy consumption for the solar thermal DHW system than was actually measured; however, despite performing less efficiently than predicted by the model, the solar thermal system was the main source of hot water for most of the year, and it performed well in that function. During the summer months, electricity use by the backup system was rare.

Energy modeling portrayed the performance of the PV system much more favorably than determined by measurements; based on modeling, the PV system was predicted to generate more energy and to offset more energy consumption than it actually did. One issue discovered was that, due to the usage characteristics of the house, the PV system was directly used by the house only 46.8% of the time. This time of production versus time of demand issue was not incorporated into the models used in the design of this house (e.g., Building Energy Optimization [BEopt™] software) but would indicate that a greater capacity PV system is not warranted unless electrical utilities offer generous feed-in-tariff rates.

## 1 Introduction and Background

Imagine Homes constructed a test house in San Antonio, Texas, under BA activities with the intention of achieving a source energy savings of 50% relative to the BA HSP (Hendron and Engebrecht 2010). The test house, shown in Figure 1, faces predominantly east, has a slab-on-grade foundation, and has 3,856 ft<sup>2</sup> of living area on two stories with five bedrooms. In collaboration with IBACOS, the builder selected the specifications for the test house on the basis of improved energy performance and cost effectiveness. In the case of the solar thermal water heater, the system selection was based on the product currently being installed by the plumber that included electric resistance as backup to the solar heat exchanger system. The HVAC contractor sized and selected the HVAC system based on the results of Air Conditioning Contractors of America Manual J load calculations (Rutkowski 2006). The as-built house utilized 2 × 6, 24-in. on center wall construction with stacked framing, three-stud corners, and ladder blocking at exterior walls, exterior foam sheathing, a cathedralized attic assembly with spray foam insulation underneath the roof deck, a high efficiency mechanical system, a solar thermal hot water system, and a 2-kW PV system. The house was predicted to achieve a 32% level of source energy savings without the PV system and 44% savings with the PV system contribution, relative to the BA HSP. Appendix A shows the house floor plans.



**Figure 1. Front elevation of the test house**

This home achieved certification under the Build San Antonio Green and ENERGY STAR<sup>®</sup> programs. It also was awarded the 2011 Energy Value Housing Award Silver Award for a production home and the National Association of Home Builders National Green Building Award for single-family production home Green Project of the Year.

Table 1 shows the general building specifications for the test house and for the builder's standard product.

**Table 1. Technical Specifications for the San Antonio, Texas, Test House and Standard House**

<b>Component</b>	<b>Test House Specification</b>	<b>Standard House Specification</b>
<b>Concrete Slab</b>	Slab on grade, uninsulated	Slab on grade, uninsulated
<b>Exterior Walls</b>	2 × 6 framing, 24 in. on center, with sprayed-in cellulose (R-20) and ½-in. XPS insulating sheathing (R-3), for R-23 nominal thermal performance	2 × 4 framing, 16 in. on center, with low-density spray foam (R-13), for R-19 nominal thermal performance
<b>Roof</b>	Open-cell spray foam on roof deck, R-19 nominal thermal performance	Open-cell spray foam on roof deck, R-19 nominal thermal performance
<b>Exterior Doors</b>	U-value = 0.2	U-value = 0.2
<b>Windows</b>	U-value = 0.35, SHGC = 0.22	U-value = 0.36, SHGC = 0.29
<b>Building Airtightness</b>	1.3 ACH @ 50 Pascals (Pa) tested	2.58 ACH @ 50 Pa, average
<b>Mechanical Ventilation</b>	CFIS, AirCycler, 50% runtime, 40 CFM, filter and damper	CFIS, AirCycler, 50% runtime, 40 CFM, filter and damper
<b>Heating</b>	93.7% AFUE condensing furnace	92% AFUE furnace
<b>Cooling</b>	17 SEER condensing unit	15 SEER unit
<b>Ductwork</b>	In conditioned space, R-6 insulation; no duct leakage to outside	In conditioned space, R-6 insulation; no duct leakage to outside
<b>Water Heater</b>	115-gal electric backup tank, 0.84 EF, with 55-ft <sup>2</sup> collector solar thermal system	0.82 EF tankless, natural gas
<b>DHW Distribution</b>	PEX “homerun” manifold system, no pipe insulation	PEX “homerun” manifold system, no pipe insulation
<b>Appliances</b>	Gas range, all ENERGY STAR	Gas range, all ENERGY STAR
<b>Fluorescent Lighting</b>	100% fluorescent lighting	80% fluorescent lighting
<b>PV System</b>	2.0-kW PV array, grid-tied	PV not used
<b>% Better than BA HSP (Hendron and Engebrecht 2010)</b>	<b>32% (44% with PV)</b>	<b>14%</b>

ACH is air changes per hour; AFUE is annual fuel utilization efficiency; CFIS is central fan integrated supply; CFM is cubic feet per minute; EF is energy factor; PEX is cross-linked polyethylene; SEER is seasonal energy efficiency ratio; SHGC is solar heat gain coefficient; XPS is extruded polystyrene.

## 2 Research Questions

The test house served as an excellent opportunity for IBACOS to capture energy consumption information and to measure the performance of systems unique to the project. Short-term testing and long-term monitoring were conducted from July 2010 through October 2011 to answer the following research questions:

- How did the total actual energy use and the actual energy use of key subsystems (e.g., furnace, water heater, central air conditioning compressor, air handling unit [AHU], LAMELs) under occupied conditions compare to BEopt energy simulations when actual weather and operating conditions were used? Were differences due to weather, occupant behavior, modeling errors, or system performance issues?
- In what circumstances was the solar thermal DHW system used? How did energy consumption of the solar thermal DHW system vary during different times of the year? Were the delivered temperature and the capacity of DHW adequate?
- How effective was the HVAC system in maintaining acceptable temperatures and humidity levels during peak and nonpeak operating periods? Does the equipment appear to be properly sized? Would occupants likely be comfortable in the home?

Although this was not specifically a research question, the builder was interested in the effectiveness of an alternative air sealing strategy to mitigate occupant comfort issues due to air leakage. The builder's standard practice of insulating wall cavities with low-density spray foam helped to consistently achieve air leakage rates below 3.0 ACH50, and the builder had high confidence in the performance of this air sealing system. The test house did not include spray foam as exterior wall insulation, but spray foam was used to seal around exterior penetrations, to insulate the band joist, and in other key air leakage locations (such as dormer transitions at exterior walls and hard-to-reach framing details). As an additional measure of air sealing, drywall was glued to the framing at the perimeter of the sheets (including around windows and doors), and ½ in. of XPS foam sheathing was installed on the exterior walls with the seams taped.

### 3 Experimental Methods

To answer the research questions, the research team collected measurements of energy use at key locations within the test house. Data were collected using remote sensing devices installed during construction and commissioned at the completion of the home.

To observe the performance of the test house in every season, IBACOS conducted long-term monitoring for more than one year—July 2010 through October 2011. Due to later startup of the solar thermal and PV systems, full data collection began in early September 2010. The research team measured temperature and relative humidity (RH) levels at the thermostat location on each floor and outdoors using thermocouples and RH sensors. Electrical power for the whole house, the outdoor condensing unit, the furnace fan, and the water heater (including pump) was measured using pulse output watt-hour meters and current transducers.

IBACOS used a gas meter to measure natural gas consumption for the furnace; the team did not measure gas usage for the whole house. Although the water heater was a solar thermal system with electrical backup, two other devices were using natural gas in the house: the fireplace and range. The gas consumption of the fireplace was extrapolated from the difference between measured furnace gas usage and modeled predictions of heating gas usage using actual meteorological year (AMY) weather files and measured indoor set point temperatures. The gas consumption of the range was not measured, but its contribution was determined according to the BA HSP (Hendron and Engebrecht 2010) and was included as 4.2 MBtu/yr. For the purpose of this research, the separate monitoring of the range and fireplace did not justify the additional expense and complexity of another meter. Measuring appliance gas usage is currently a gap identified in the working group of the BA Standing Technical Committee on Test Methods and Protocols.<sup>1</sup>

Water heater thermal energy output was measured using thermocouples and a high resolution flow meter (75.7 pulses/gal). This was accomplished by measuring the temperature of the hot water supply and the temperature and volume flow rate at the cold water return. All sensors were connected to a central data logger with a 10-s scan rate and data storage every minute or hour. IBACOS retrieved data by using a cellular modem connected to the logger. A family of five occupied the home during the monitoring period. Figure 2 through Figure 4 are representative images of the measurement devices installed in the test house. Sensor locations throughout the home can be seen on the test house floor plans shown in Figure 5 and Figure 6.

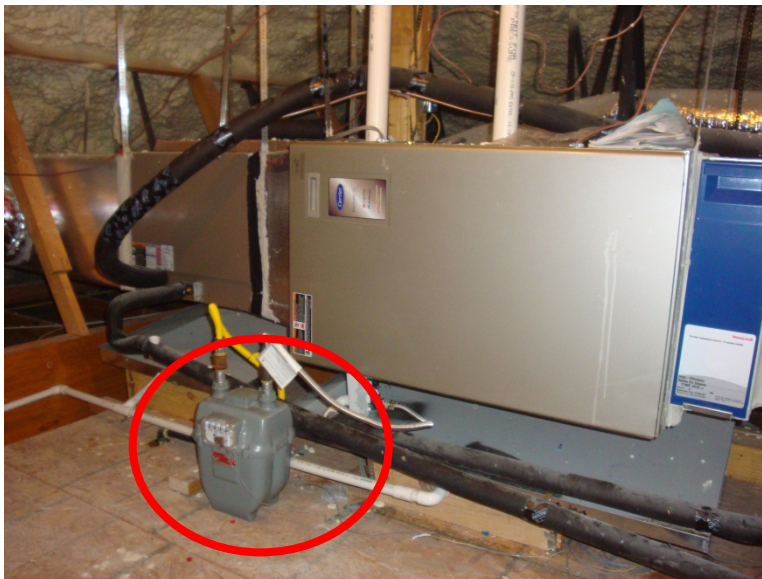
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<sup>1</sup> <https://sites.google.com/site/buildingamericasc/>.

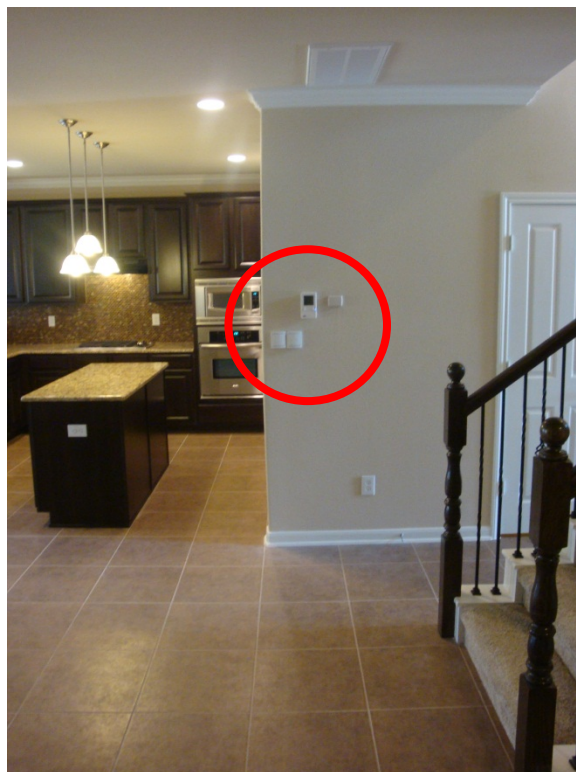




**Figure 2. Outdoor temperature and RH sensor mounted far enough from the home so it will not be influenced by it**



**Figure 3. Gas meter used to determine natural gas usage by the furnace**



**Figure 4. Temperature and RH sensor at the first-floor thermostat location**

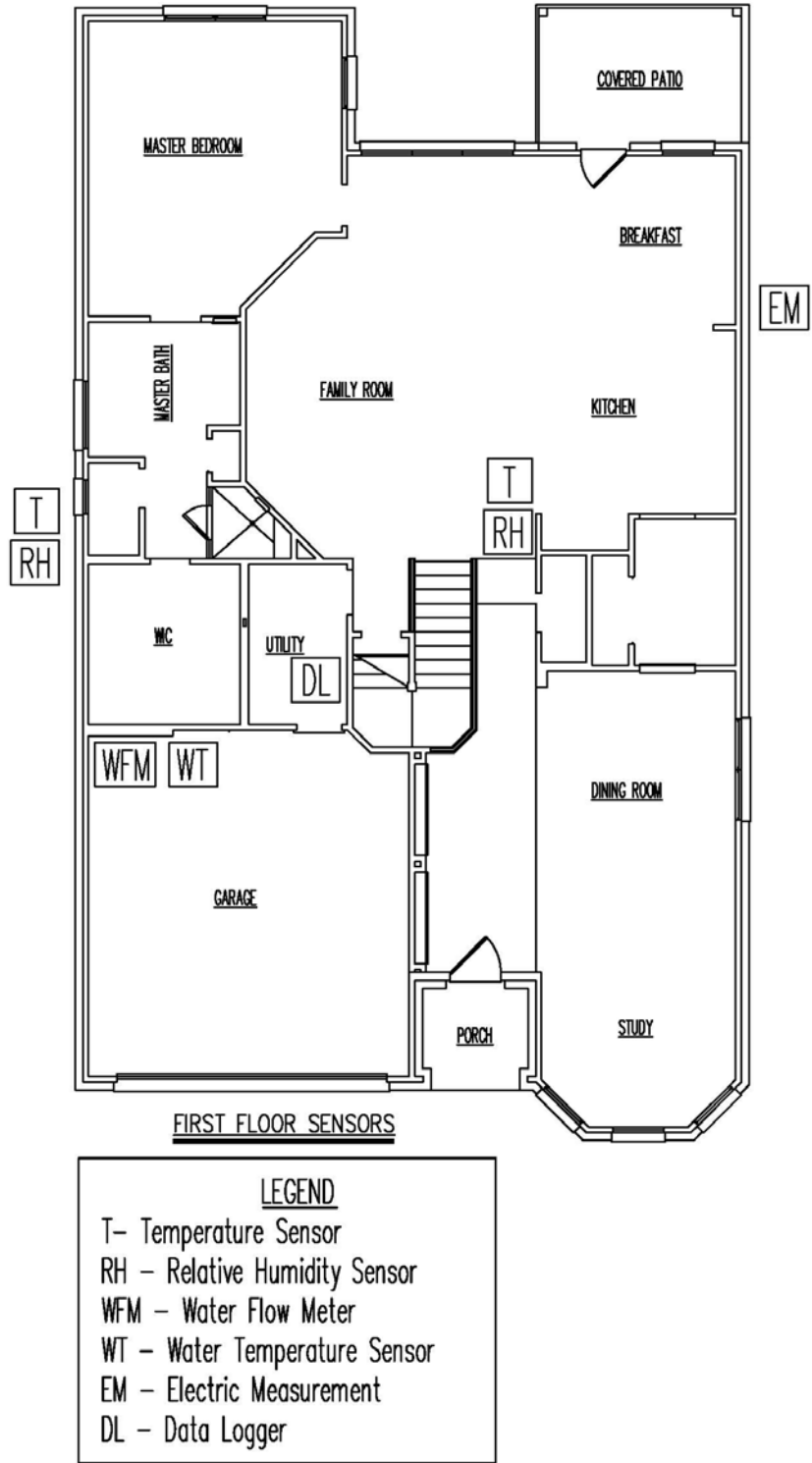
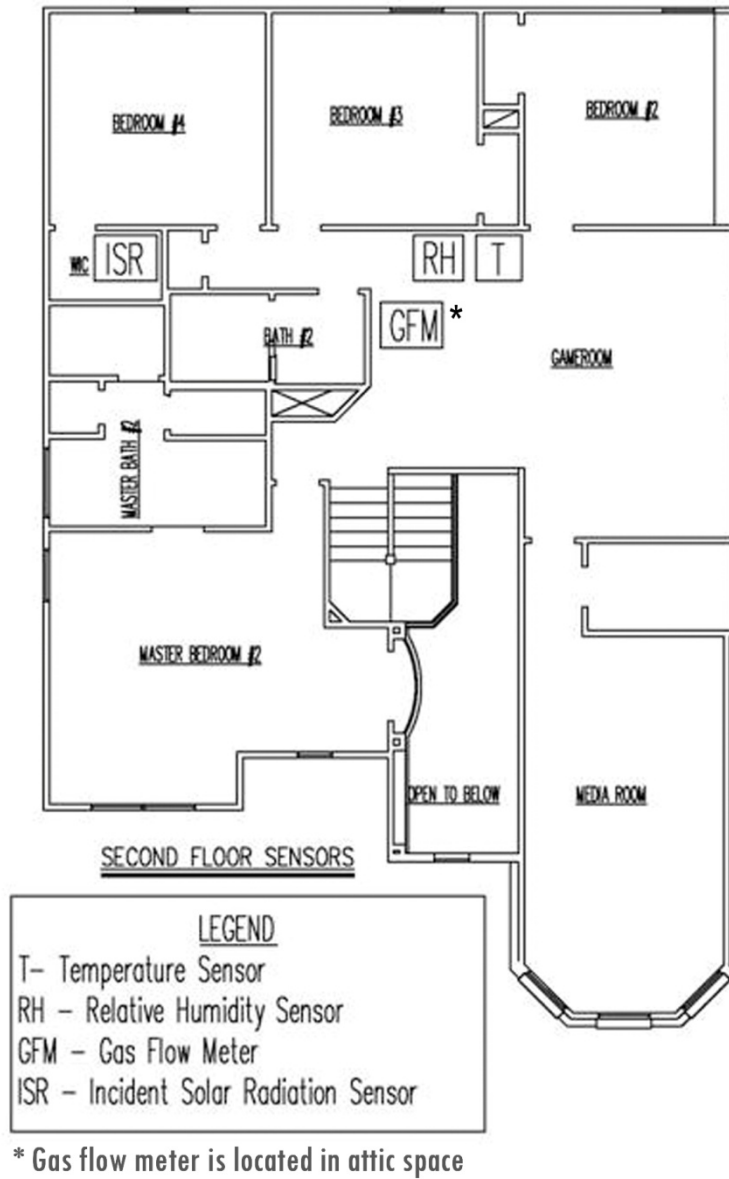


Figure 5. First-floor plan with sensor locations noted





**Figure 6. Second-floor plan with sensor locations noted**

## 4 Results

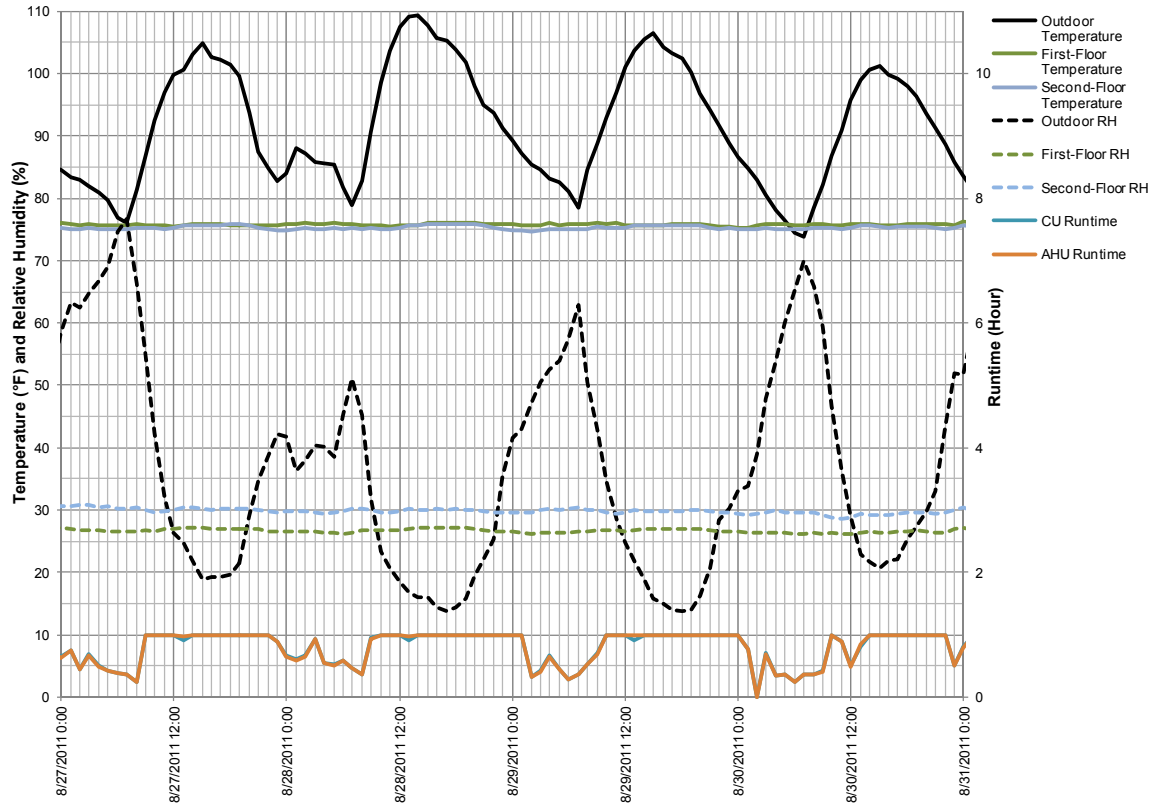
IBACOS collected data from the test home from mid-July 2010 through October 2011. The team's analysis of data determined that the 12-month period from October 1, 2010, to September 30, 2011, provided consistent data from all sources. Consequently, the data were used to represent the annual measurement period.

### 4.1 HVAC System Evaluation

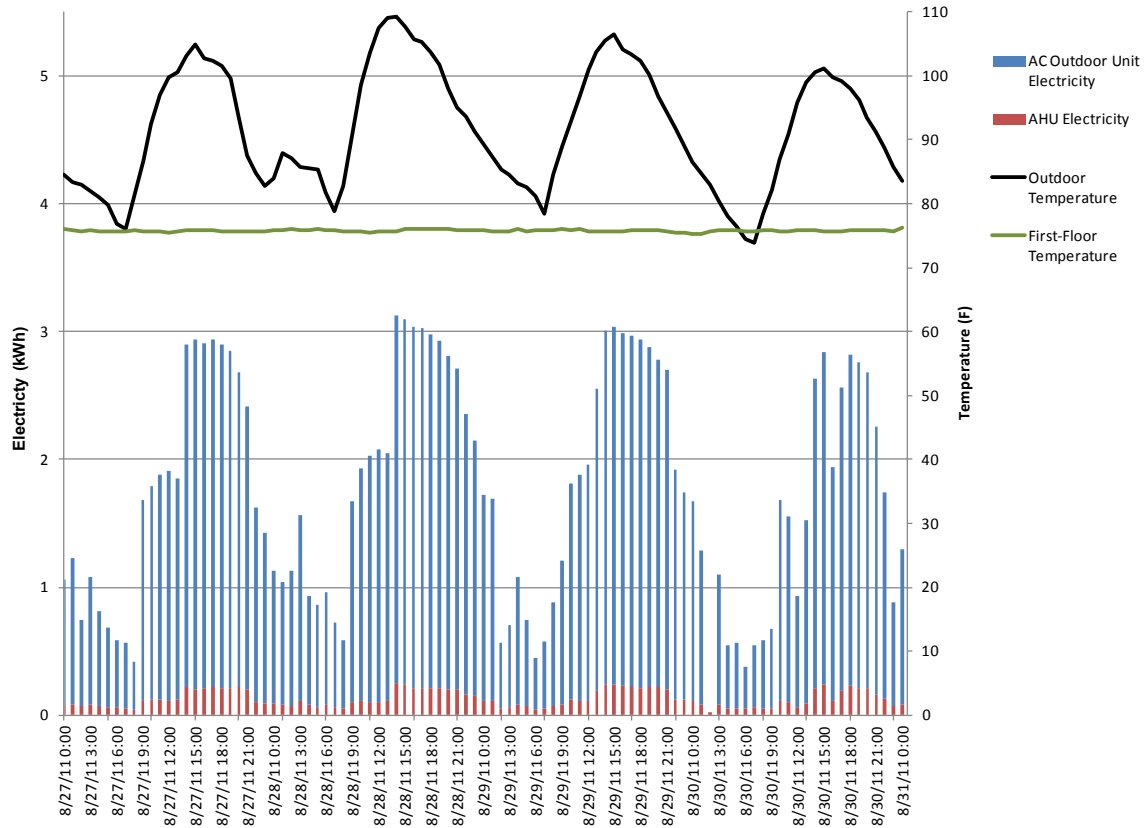
The HVAC system in the home consisted of a gas condensing furnace with variable-speed operation manufactured by Carrier, with the Infinity 96 model with a minimum output capacity of 73 kBtu/h used and a maximum output capacity of 112 kBtu/h used, and an AFUE rating of 93.7. Cooling was provided by a condensing unit manufactured by Carrier, with the Performance model with a maximum output capacity of 36.8 kBtu/h used and a SEER rating of 17.00. Both systems were sized and selected by the HVAC contractor based on the results of Air Conditioning Contractors of America Manual J load calculations (Rutkowski 2006).

Indoor and outdoor temperature and RH data were analyzed at peak and nonpeak (shoulder) temperature periods to determine how the HVAC system performed in those cases. On August 28, 2011, the outdoor temperature reached its peak at 109°F. Figure 7 shows the temperature and RH conditions inside the home and the HVAC system runtimes during the 4-day period surrounding this peak temperature. The runtime of the air conditioner outdoor unit compressor and fan and the AHU are shown as a fraction of an hour, with a value of 1 indicating continuous operation during the hourly data period.

Note that the HVAC system has two-stage cooling and variable-speed operation, and, as shown in Figure 8, its energy consumption varied substantially during a runtime period as it was operating at different airflows and system capacities to match the load on the home. Specifically, from 9:00 to 13:00 on August 27, 2011, the system was operating in low-stage cooling mode, whereas from 13:00 to 21:00 on the same day, the system was operating in high-stage cooling mode. Similar behavior occurred in the following days as the system matched its capacity with the lower loads on the home in the morning and the higher loads in the afternoon and evening.

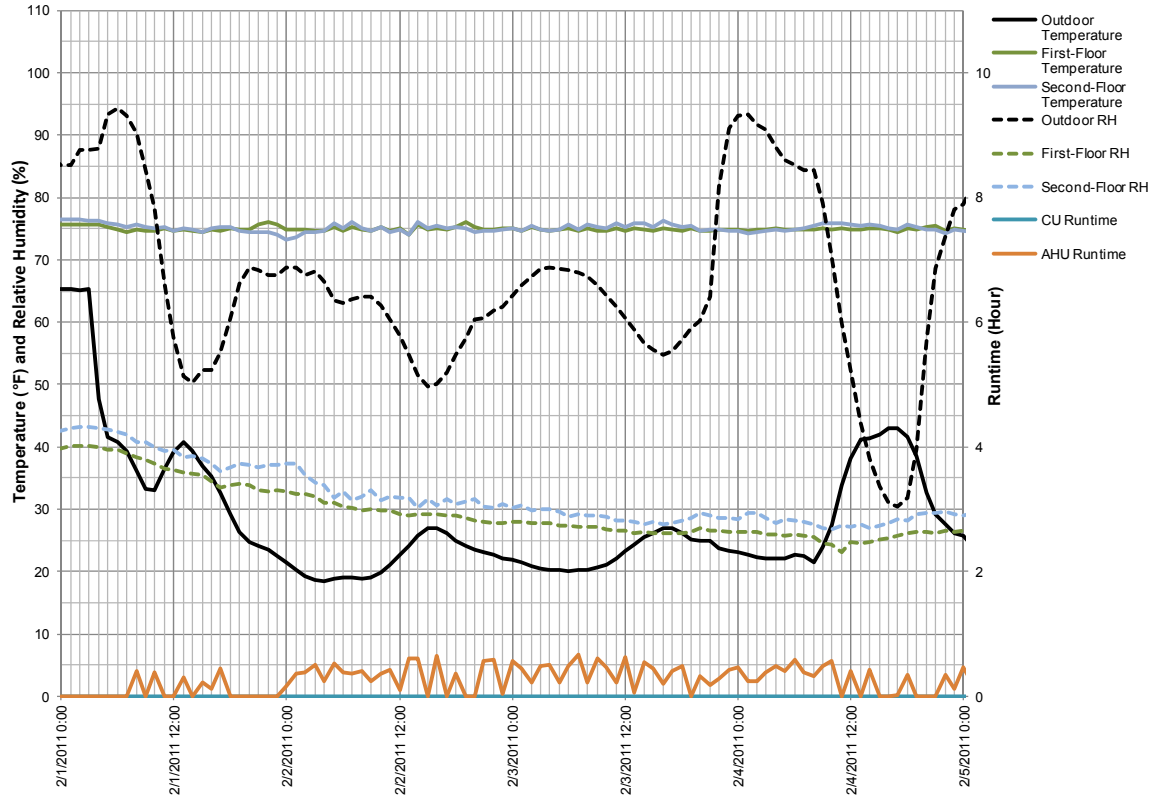


**Figure 7. Temperature, RH, and HVAC system runtime values during the representative hot period of August 27, 2011, through August 31, 2011**



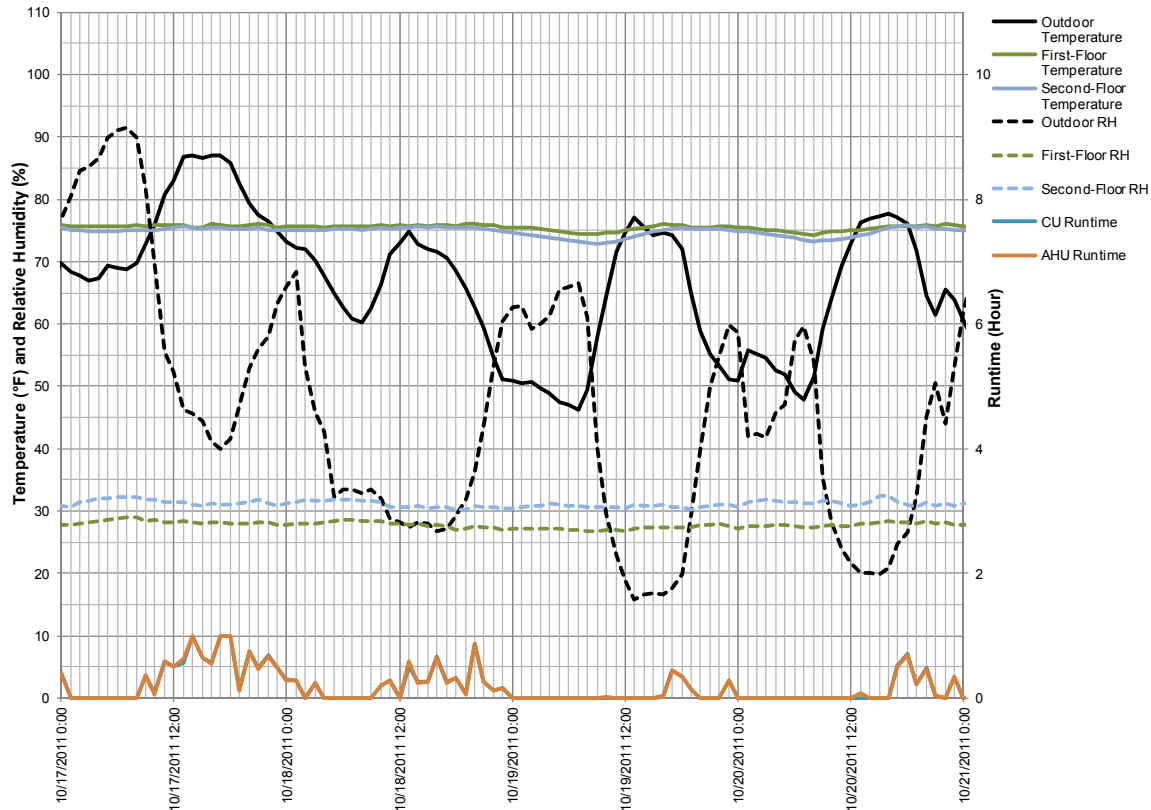
**Figure 8. Temperatures and HVAC system energy use during the representative hot period of August 27, 2011, through August 31, 2011**

On February 2, 2011, the outdoor temperature reached a low of 18.5°F. Figure 9 shows the temperature and RH conditions inside the home and the HVAC system runtimes during the 4-day period surrounding this peak temperature. During this period, the furnace operated in first-stage heating mode (it is a dual-stage unit) with an AHU runtime average of 26.3% each hour.



**Figure 9. Temperature, RH, and HVAC system runtime values during the representative cold period of February 1, 2011, through February 5, 2011**

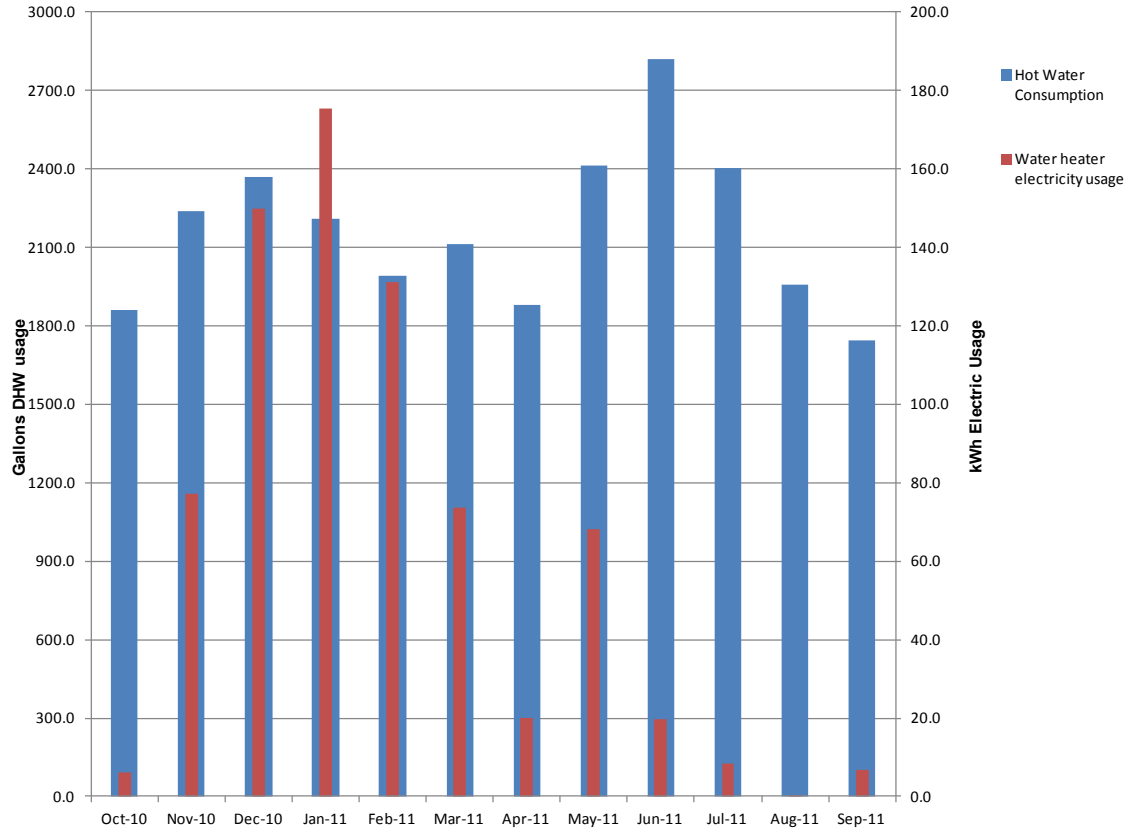
The average outdoor temperature experienced during the annual analysis period was 72.1°F. On October 18, 2011, this temperature was observed. Figure 10 shows the temperature and RH conditions in the home and HVAC system runtimes during the 4-day period surrounding this nonpeak temperature. During this period, the AHU was operating in cooling mode, first-stage, and the runtime average was 18.5% each hour.



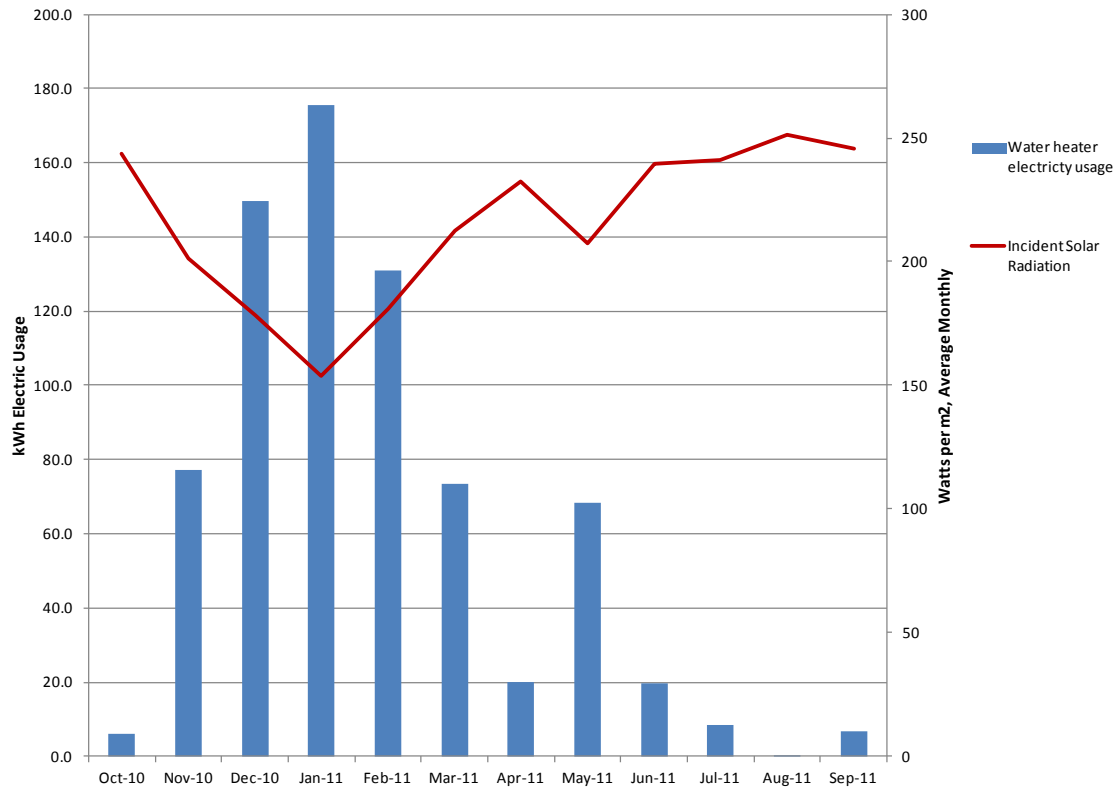
**Figure 10. Temperature, RH, and HVAC system runtime values during the representative nonpeak period of October 17, 2011, through October 21, 2011**

## 4.2 Hot Water System Evaluation

The DHW system consisted of a 115-gal electric backup tank, 0.85 EF, with 55 ft<sup>2</sup> of solar thermal collector (two panels). Figure 11 displays the monthly DHW and electricity usage of the system for the 1-yr period. Figure 12 shows the average monthly solar radiation incident on the solar collectors along with the monthly electricity usage of the system for the 1-yr period. The solar collectors are tilted approximately 34° (8/12 pitch) from the horizontal. The system used a total of 737 kWh of electricity and 25,987 gal of water during this period (an average of 71 gal/day). For half of the year, the DHW system used 20.7 kWh or less in electricity per month. In August 2011, the solar thermal system handled all hot water demands, with several events calling for more than 40 gal of hot water in 1 h. The amount of electricity usage of the system directly tracked the available solar radiation incident to the collectors.



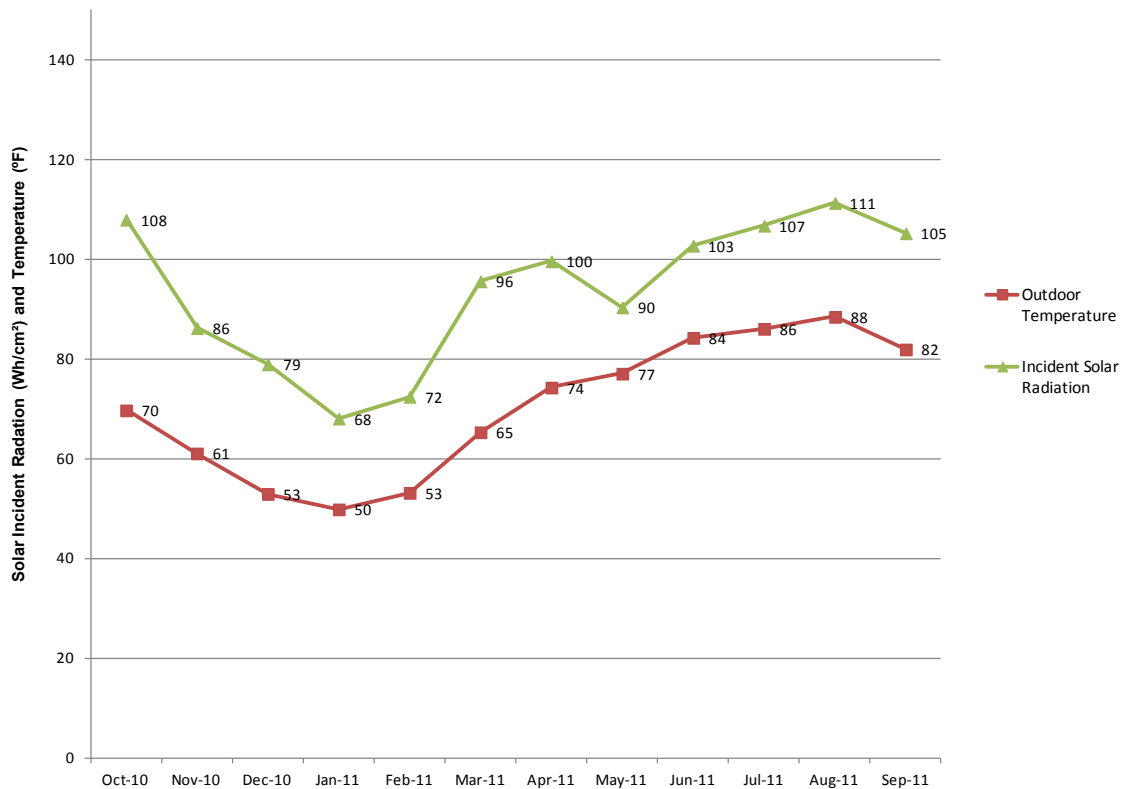
**Figure 11. Monthly DHW and electricity usage from October 1, 2010, to September 30, 2011**



**Figure 12. Monthly incident solar radiation and DHW electricity usage from October 1, 2010, to September 30, 2011**



Figure 13 displays, on a monthly average basis, the outdoor temperature and incident solar radiation experienced by the solar water heating system. The solar radiation measured is not global horizontal, but rather is the solar radiation incident on the PV and solar thermal systems that are on the southwestern roof orientation, which has a slope of 8/12 that corresponds to a 33.75° angle with respect to the horizontal. Incident solar radiation varies seasonally, with an anomaly seen in May 2011 that is most likely due to the increased rainfall and cloud cover that occurred in that month.



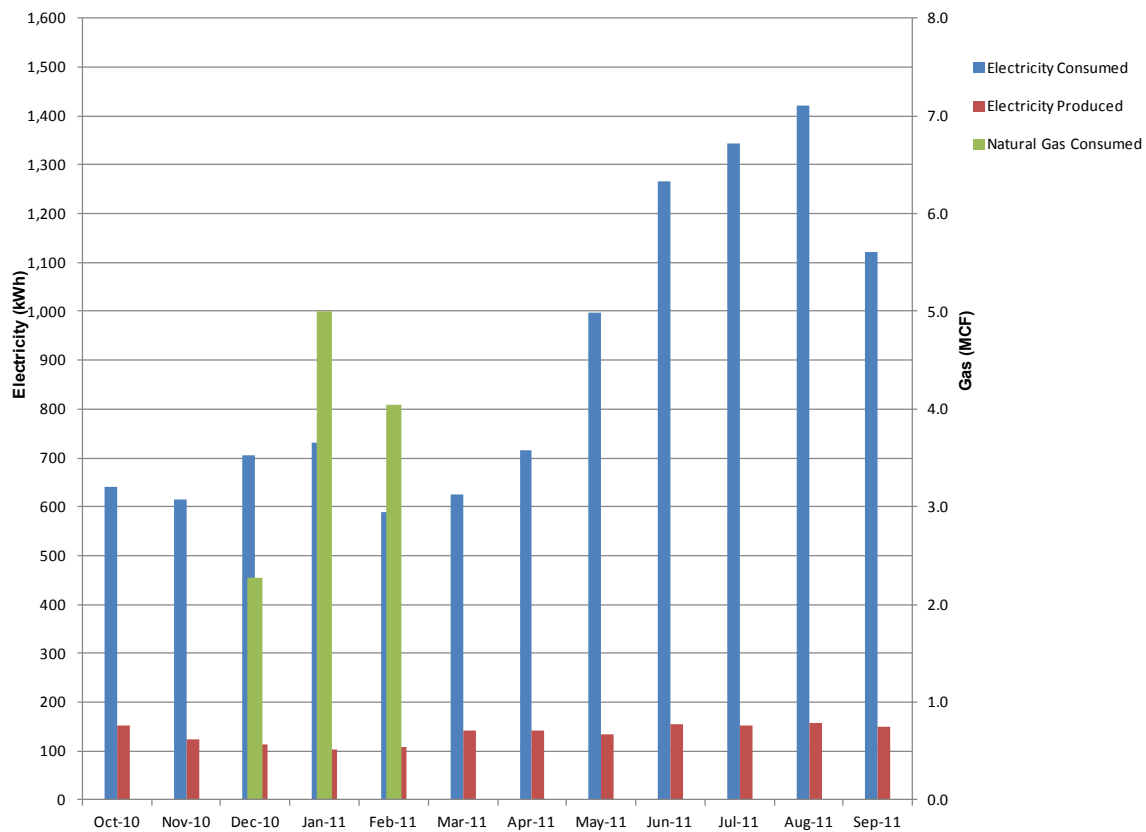
**Figure 13. Monthly outdoor temperature and incident solar radiation experienced by the solar water heater from October 1, 2010, to September 30, 2011**

The greatest amount of hot water was used during the late evening of May 23, 2011, when 79.8 gal were used in 1 h and 94.2 gal were used over a 2-h period. The DHW system was able to supply water at a temperature between 111°F and 113°F for this event. The reason for this peak event is unclear, although presumably the family occupying the house may have hosted guests during this time period when additional showers and laundry use may have occurred. In addition to this peak event, there are approximately 85 hot water draws of 35 gal or more in 1-h time periods that occurred during the monitoring period, with an average supply water temperature of 117°F. Most of the remaining water draw events were less than 35 gal (3 gal average). Because the system was able to provide sufficient water temperatures during the peak event periods, this indicates the ability of the system to provide sufficient hot water.

During a 3-h span on the morning of December 26, 2010, the system used the most electrical energy, 10.1 kWh, with 71.1 gal of hot water used and the hot water temperature reaching 120°F.

### 4.3 Whole-House Energy Use and Generation

Figure 14 shows, on a monthly basis, the electricity consumption and production and the natural gas consumption of the home. During the study period, 10,615 kWh of electricity were used, 1,633 kWh were produced (15% of total consumption) by the PV system, and 11.3 thousand cubic feet or 113 therms of natural gas were used. Monthly electricity consumption and production peaked in August 2011. The lowest electricity consumption occurred in November 2010, and the lowest electricity production occurred in January 2011; January 2011 is also the month with the lowest recorded incident solar radiation, which supports the measurements of lowest electricity production by the PV system.

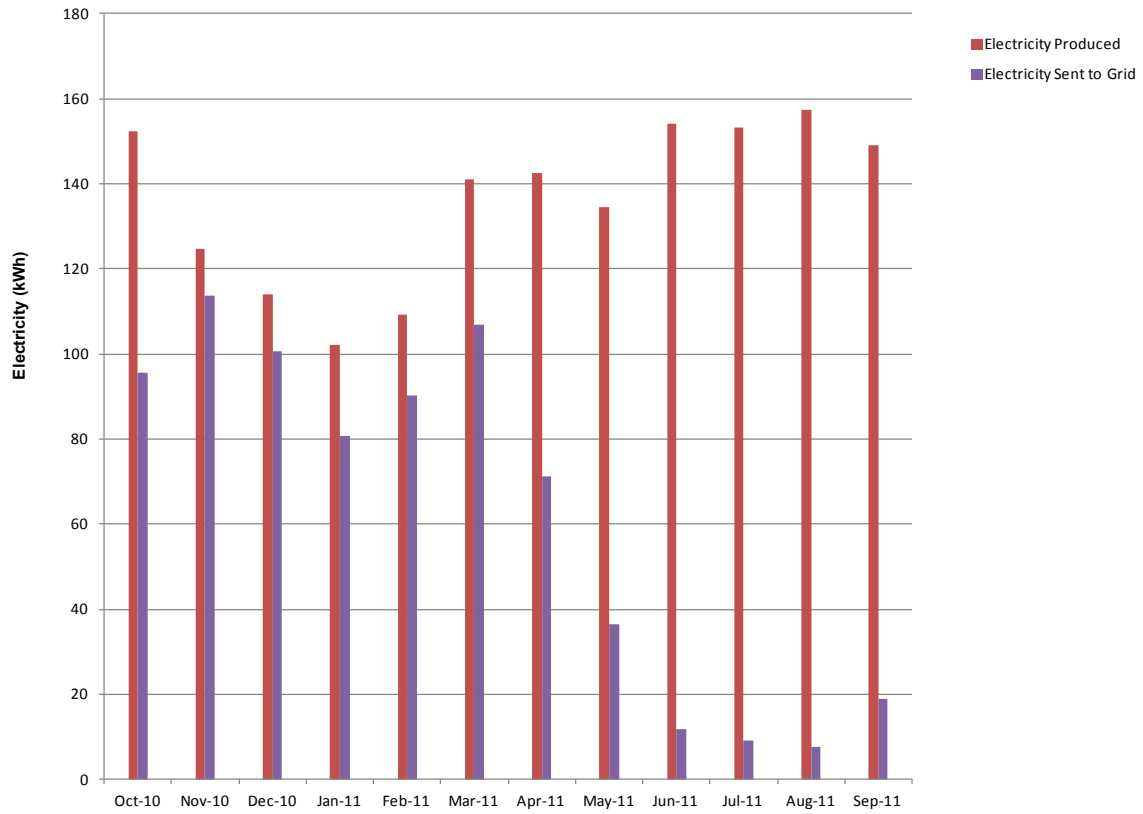


**Figure 14. Monthly electricity consumption and production and natural gas consumed from October 1, 2010, to September 30, 2011**

Figure 15 shows the electricity produced and sent to the electricity grid on a monthly basis. From October 2010 through March 2011, more than half of the electricity produced in those months was sent to the grid. Of the 1,633 kWh of electricity produced annually by the PV system, 749 kWh (46.8%) were sent to the electricity grid.

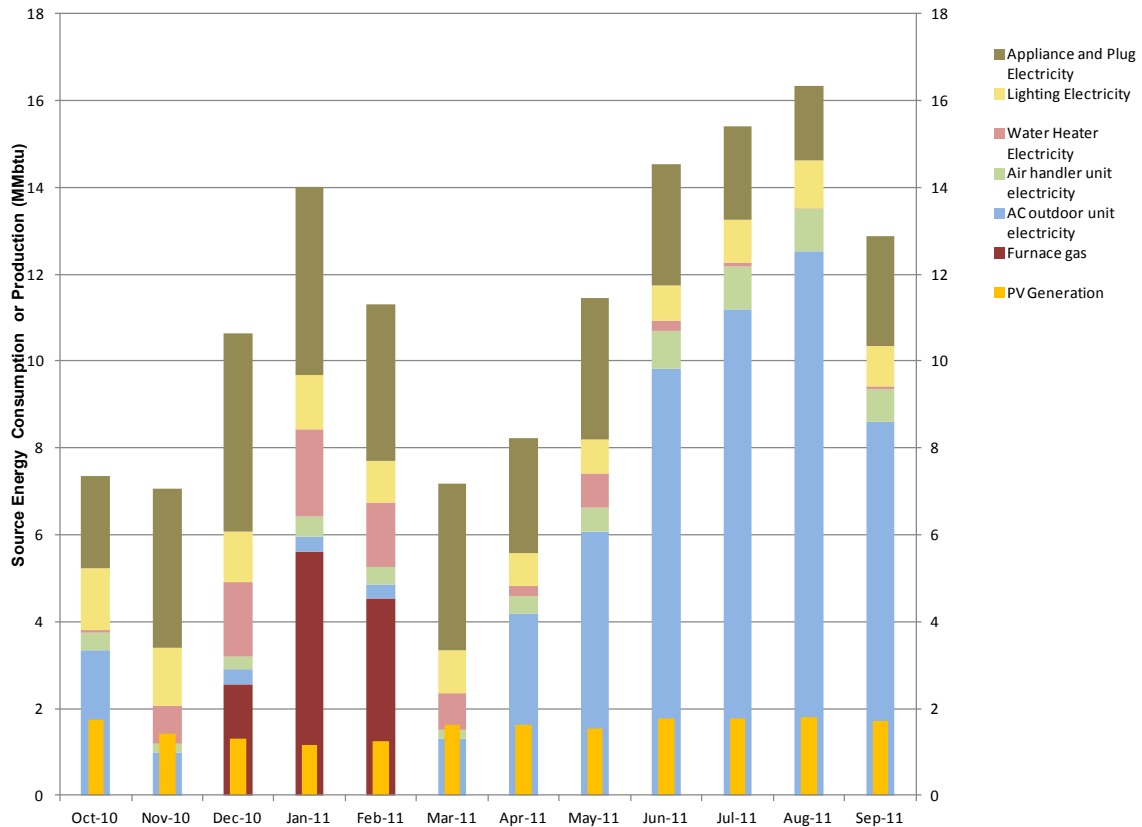
In November 2010, 91.2% of all electricity produced was sent to the grid, which contrasts with August 2011, when this value was only 4.9%. An examination of hourly data determined that, on

a typical day in November 2010, electricity was produced during daylight hours but was seldom used because the heating system is gas fired, peak heating loads occurred at night, and there were few other electrical loads.



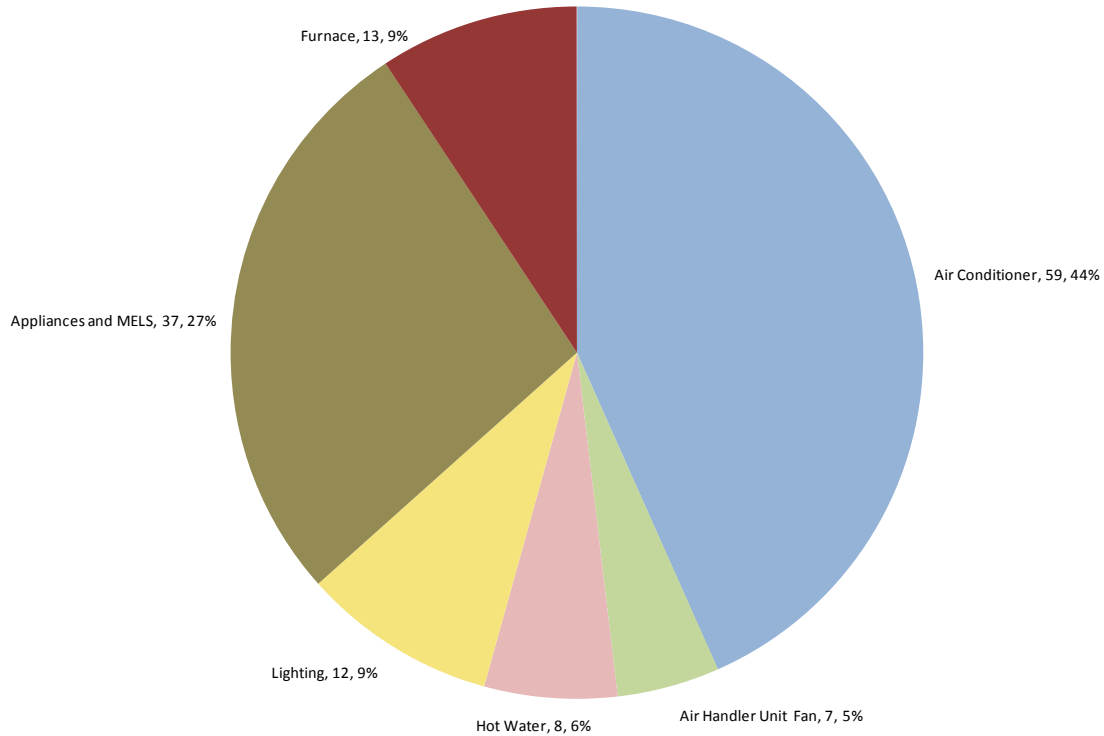
**Figure 15. Monthly electricity production by PV and surplus electricity sent to the electricity grid from October 1, 2010, to September 30, 2011**

Figure 16 shows the source energy consumed or produced monthly for the 1-yr period. The energy used by the furnace (red bar) clearly outlines the heating season, and the energy used by the air conditioner outdoor unit/compressor (light blue) outlines the cooling season, which is predominant. Energy use from LAMELs is significant; lighting energy is slightly higher in the winter months (probably due to a greater number of hours of darkness), and appliance/plug loads show great variability (3:1) between cold and warm months.



**Figure 16. Monthly source energy consumption or production according to measured area from October 1, 2010, to September 30, 2011**

Figure 17 shows the distribution of source energy according to end use for the 1-yr study period. The air conditioning system consumes the most source energy, followed by LAMELs.



**Figure 17. End-use source energy consumption (MBtu/yr) and percentage of total during the 1-yr analysis period from October 1, 2010, to September 30, 2011**

#### 4.4 Comparison of Modeled to Monitored Source Energy Use

The actual measured energy consumption of five major subcategories (heating, cooling, hot water, LAMELs, and PV panel generation) was compared to projected energy consumption using BEopt version 1.3. Table 2 shows the results. As stated in Section 3 (Experimental Methods), the gas consumption of the range and fireplace were not directly measured, but their estimated influence is included.

As indicated in Table 2, there were significant differences in predicted versus actual energy consumption for several end use categories, particularly for space heating and for appliances/miscellaneous electrical loads (MELs). Temperature readings at the first- and second-floor thermostats are consistent with the 75°F cooling set point used in BEopt, and settings for miscellaneous loads (electric, gas, hot water) in the model are based on the HSP for the size and presumed occupancy of the house. Actual occupancy of the house is unknown; however, it would make sense if actual occupancy were less than the BA HSP predictions because fewer occupants would likely result in reduced appliance/MELs energy consumption than predicted by the model. At this time, there is no catalog of actual plug-in loads for this test house.

**Table 2. Monitored Source Energy Use Compared to Modeled Source Energy Use**

Description	Modeled Annual Source Energy						Monitored Annual Source Energy
	BA HSP*	Regional Standard Practice	Builder's Standard Practice	Prototype Home (TMY)	Prototype Home (AMY)	Prototype Home (AMY and Set Points)	Prototype Home Monitored Source Energy (Sept. 2010–Aug. 2011)
End Use	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)	(MBtu/yr)
Space Heating	43	28	29	22	18	29	14
Space Cooling	61	76	52	37	49	55	63
DHW	41	19	12	8	5	5	9
Lighting	35	35	28	26	26	26	13
Appliances and MELs	84	82	76	76	76	76	37
Outdoor Air Ventilation	3	0	2	2	2	2	6
<b>Subtotal</b>	<b>267</b>	<b>240</b>	<b>196</b>	<b>170</b>	<b>176</b>	<b>194</b>	<b>141</b>
PV Panel Generation	0	0	0	-31	-34	-34	-18
<b>Total</b>	267 <b>(250 Adj)</b>	240	196	139	142	160	123

\*Hendron and Engbrecht (2010). TMY is Typical Meteorological Year.

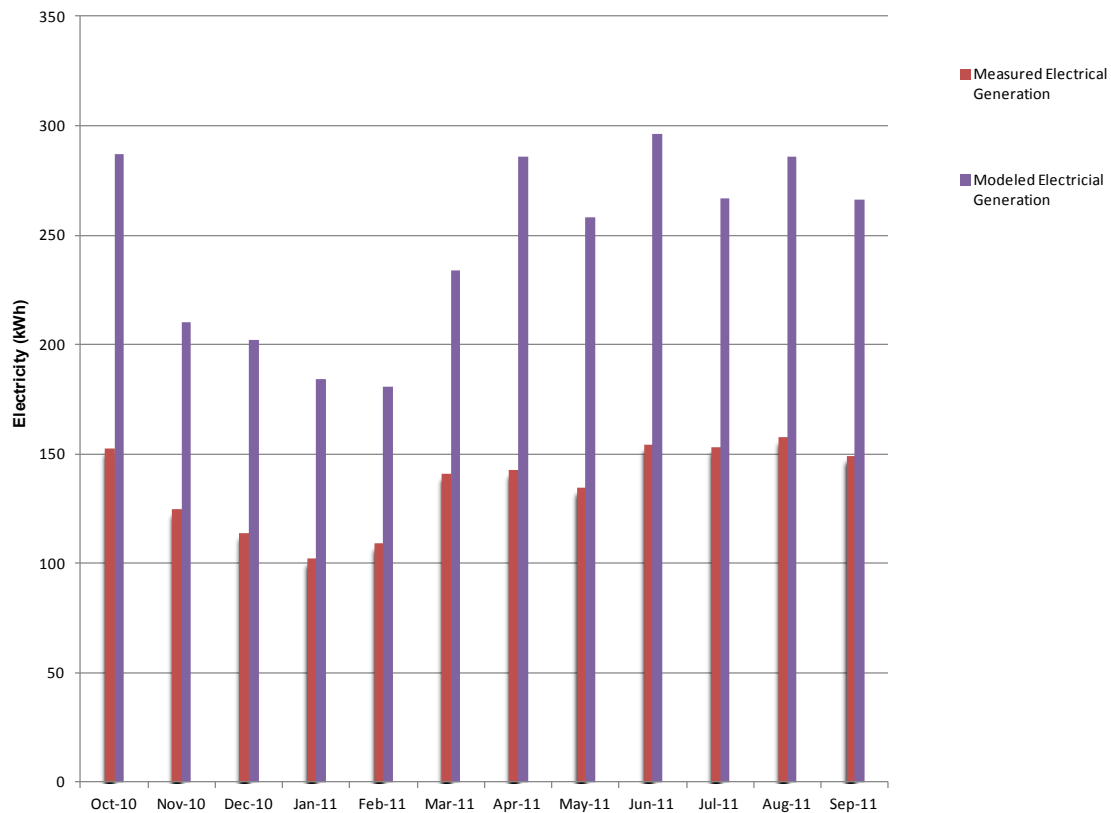
An AMY weather file for the local weather station at the San Antonio International Airport was purchased from Weather Analytics<sup>2</sup> and was used in place of the local TMY3 weather file in the BEopt energy model. Also, the indoor set point temperatures in the model were adjusted to match the measured indoor set point temperatures of 75°F for cooling and 75°F for heating. Table 2 includes the results of these predictions. As indicated, there is a large gap in predicted versus measured heating energy consumption. Because gas consumption of the fireplace was not measured, IBACOS assumed that much of this gap in heating energy use is due to fireplace use. This assumption has not been confirmed with the occupants.

As indicated in Table 2, the predicted cooling energy consumption using the AMY file and measured set point temperatures is closely aligned with actual usage, indicating fairly accurate prediction by the model.

Measurements indicated that the PV system produced 1,633 kWh of electricity annually. Modeling predicted that the PV system would generate 2,955 kWh of electricity annually. There is no clear explanation for this large discrepancy between the modeled prediction and actual performance of the PV system, except perhaps for inherent errors in the modeling software calculations or operational issues due to installation errors or equipment malfunction. However, follow-up conversations with the builder, homeowners, and solar installer did not indicate any system malfunction during the monitoring period, and additional modeling using the National Renewable Energy Laboratory's PVWatts (version 1) online performance calculator for grid-connected PV systems (NREL 2012) verifies the predicted PV system production. Figure 18 shows a comparison of the monthly values for modeled and measured electricity generation during the study period. Each month the predicted electricity generation was greater than the actual amount. Figure 19 shows the electricity produced versus the electricity sent to the grid during the study period, and the percent of electricity produced that was used by the house. The highest percentage of electricity produced was used by the house in August 2011 at 95%, and the lowest percentage of electricity was used by the house in November 2010 at 9%.

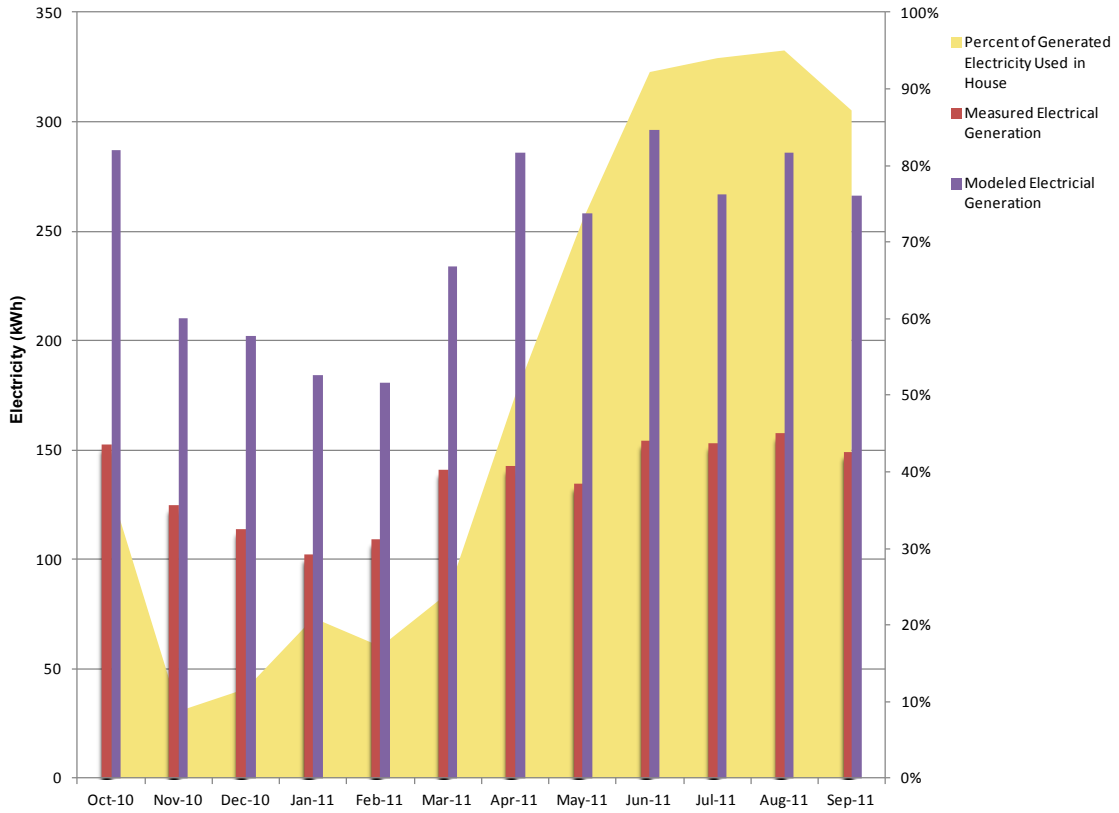
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<sup>2</sup>Weather Analytics, Inc., Winchester, MA, <http://www.weatheranalytics.com>.



**Figure 18. Monitored electricity generation compared to modeled electricity generation on a monthly basis from October 1, 2010, to September 30, 2011**





**Figure 19. Electricity produced versus electricity sent to the grid, and percent of produced electricity used in the house from October 1, 2010, to September 30, 2011**

## 5 Discussion

Prior to moving forward with this test house project, the builder had expressed concern about the HVAC system maintaining comfortable temperatures and humidity levels because of the changes that were made to the thermal enclosure. With a standard practice of insulating the floors, walls, and roof deck with low-density spray foam, the builder had high confidence in achieving a tight, well-insulated enclosure and in meeting the comfort needs of the occupants. The only additional air sealing performed by the builder as a standard practice was the use of expanding foam or caulk to seal around penetrations. Because this test house eliminated the use of spray foam in the walls and floors in favor of the lower cost cellulose insulation, the builder was unsure if the completed home would be as comfortable for the occupants as the builder's standard home and whether the HVAC system would sufficiently maintain acceptable temperature and humidity levels. To allay some of these concerns, the builder performed additional air sealing practices such as sealing the bottom plates of the exterior walls to the subfloor, gluing the perimeter of the drywall to the wall framing, taping the seams of the ½ in. of XPS sheathing, and using spray foam insulation in several key locations (e.g., at all band joists and at several dormer wall locations with difficult access for hand-applied air sealing). To the satisfaction of the builder, tested air leakage measured 1.3 ACH50, which is about half of the average leakage of 2.58 ACH50 for the builder's standard product. Also, the HVAC system of the test house performed efficiently during the hottest and coldest periods of the analysis, with first- and second-floor temperatures consistently maintained between 75°F and 76°F and RH maintained at levels no greater than 45% during peak heating and 30% during peak cooling. Similar indoor temperature and RH values were observed during the nonpeak period. Occupants should have been comfortable during all of these periods because the indoor temperatures varied very little and the RH levels were within healthful levels (ASHRAE 2008).

During the peak cooling period, the HVAC system operated at least once during most hours of the day; in some cases, it ran for several hours without interruption. There were periods overnight when the system ran less frequently as the outdoor temperatures dropped. Considering the peak temperature reached 109°F, which is substantially higher than the 0.4% cooling dry bulb temperature of 98.5°F (ASHRAE 2009) often used for mechanical system design, the system did very well to maintain temperatures at both locations within close range of the set point. If the system did not have adequate cooling capacity, set point temperatures would not have been reached, and there would not have been any system downtimes. During the coldest period, the system never ran for a full hour during any hourly measurement period. Temperature levels were consistently maintained at both set point levels, indicating the HVAC system had ample load capacity.

A total of 61% of electricity use by the DHW system occurred during the months when heating occurred. During the other nine months, the solar water heating system was more active, with that system predominantly being used six months of the year. During August 2011, the solar thermal system handled all hot water demands. Examination of data indicated that the DHW system had enough capacity to meet all hot water demands.

Electricity consumption in the home was greatest during the cooling season, from May to September, when the air conditioning system was operating frequently. Overall, the occupants

did not use much electricity, considering the size and climatic location of their home, with 2.75 kWh used per square foot of gross finished floor area (30 kWh/m<sup>2</sup>).

The PV system consistently produced energy, with production varying from a high in August 2011 (a level of 157.4 kWh) to a low in January 2011 (a level of 102.1 kWh). On a monthly basis, the PV system did not have the capacity to cover all of the electricity needs of the home. In November 2010, on a monthly basis, the PV system supplied 20% of the electricity that was used. However, an examination of the amount of electricity sent to the grid reveals that, for November 2010, only 9% of the electricity produced that month actually was used in the home. Utilization of less than half of the PV-generated electricity occurred in the six coldest months of the year (when air conditioning was not operating). Every month some generated electricity was sent to the grid. Annual electricity generation predicted by modeling was 67% greater than the amount of electricity actually produced. Some of this discrepancy could be due to the modeling assumptions built into the default input for a 2.0-kW PV system in BEopt, which may be different from the actual performance characteristics of the PV system (e.g., panels, inverter). Although PV azimuth and tilt were selected in the model to most closely match the actual installation of the system on the test house, there might have been some discrepancy in the actual insolation achieved on site (e.g., a neighboring house that was constructed midway through the monitoring period may have cast a shadow on the installed PV). Follow-up conversations with the builder, homeowners, and solar installer did not indicate any system malfunction during the monitoring period, and additional modeling using the National Renewable Energy Laboratory's PVWatts (version 1) online performance calculator for grid-connected PV systems (NREL 2012) verified the production of the PV system as predicted by BEopt. Future investigation into this issue could involve measuring PV production directly from the installed inverter instead of using the wattnodes and comparing these measurements with the predictions; this method would need to be performed on site and with the permission of the current homeowners.

Total space conditioning source energy usage measurements were 9 MBtu/yr (11%) lower than the space conditioning source energy use predicted by modeling (adjusted for AMY weather conditions and actual set point temperatures), with space cooling measurements 8 MBtu/yr (15%) higher than modeled and space heating measurements 15 MBtu/yr (52%) lower than modeled. As indicated earlier, the fireplace could account for much of the large gap in heating energy consumption, although the results of other occupied test house research would suggest that variations in occupancy and errors in modeling could account for some of this gap (Stecher and Allison 2011, Stecher and Brozyna 2013).

Measured DHW source energy use was 4 MBtu/yr (80%) higher than the modeled value. The model predicted that 5 MBtu/yr of electricity would be used for hot water production, which is based on 55 ft<sup>2</sup> of solar collectors and an average hot water demand of 80 gal/day (in accordance with BA HSP simulation procedures) (Hendron and Engebrecht 2010). This was compared to the measured value of 9 MBtu of energy use, which does not include pump energy for the system and is based on 55 ft<sup>2</sup> of solar collectors and an average hot water demand of 71 gal/day. Again, this discrepancy may be due, in part, to differences in the modeled and actual efficiency of the solar thermal system (e.g., panels, tank) or to differences in actual insolation versus the modeled insolation to the panels. No damage or installation errors were identified by the builder or contractor during the installation and operation of this system.

The month with the highest level of source energy usage was August 2011, which was the month with the most space cooling energy usage. Appliances and MELs measured source energy use was highest during the months when heating occurred.

Measured source energy for LAMELs was 52% of the modeled value and was the primary reason that the actual source energy usage (without electricity generation contribution) of the home was close to 40 MBtu/yr less than modeled. The model predicted that the home would use 194 MBtu/yr of energy (160 MBtu/yr with PV), which compares to the measured value of 141 MBtu/yr (123 MBtu/yr with PV). Actual source energy contribution from the PV system was 55% of the modeled value.

Overall, the builder viewed this project as a success. The builder's initial concern for meeting the comfort needs of the occupants was subsequently alleviated. In general, the annual energy consumption of this house was lower than predicted, and the builder was able to achieve a low enough incremental cost for these upgrades to his standard specifications to justify the investment in the higher performance package of measures. Moving forward, the builder has continued to use ½ in. of XPS insulation as an exterior sheathing for a standard product on his homes in place of the noninsulating sheathing. The use of higher performing windows on this project also has become standard for all of this builder's homes. The builder continues to install solar thermal water heating systems and PV as an option and has utilized advanced framing techniques on other projects as well.

This builder strives to lead the local market with energy-efficient green construction practices and is now looking closely at the space conditioning and ventilation systems currently being installed to identify additional opportunities for efficiency and cost-effective energy savings.

## 6 Conclusions

The HVAC system effectively maintained acceptable temperatures and humidity levels during peak cooling and heating and nonpeak operating periods. Occupants would likely be comfortable in the home year round (ASHRAE 2008). The equipment did not run continuously for the entire peak operating 4-day period, indicating that it can contribute more capacity if needed. In the San Antonio climate, ensuring that the HVAC system is properly sized for cooling is the main objective of equipment-sizing calculations. The ability of the system to maintain consistent temperatures and humidity levels and to have extra capacity to offer during outdoor conditions that greatly exceed the summer design situation indicates that the system is not undersized and may even be oversized. However, the system has a high enough level of energy efficiency and performance to discourage any lowering of equipment load capacity. Future opportunities exist to improve the efficiency and performance of the space conditioning system, and the builder is actively pursuing research into the next generation of HVAC for his company.

Airtightness levels for this test house well exceeded the standard levels achieved by the builder, helping to reduce additional loads on the HVAC system and to maintain sufficient comfort levels in the house. Strategic air sealing of the band joists and dormer walls using spray foam, gluing drywall to the interior framing, and taping the seams in the exterior sheathing were all helpful in achieving the lower levels of airtightness.

The solar thermal DHW system was the main source of hot water for most of the year, and it performed well in that function. During the summer months, electricity use by the backup system was rare. The whole system provided adequate delivery temperature and capacity year round as it met all loads. Going forward, the builder will offer a solar thermal system as a standard option and is considering opportunities to improve performance and to reduce costs for these systems.

Of the 1,633 kWh of electricity produced annually by the PV system, 46.8% was sent to the electricity grid. Utilization of less than half of the PV-generated electricity occurred in the six coldest months of the year. This time of production versus time of demand issue was not incorporated into the models used in the design of this house (e.g., BEopt) but would indicate that a greater capacity PV system is not warranted unless electrical utilities offer generous feed-in-tariff rates. The builder currently offers PV as a standard option.

There were discrepancies between modeled and actual energy use values. After adjusting the predicted consumption using actual weather and indoor set point temperatures, actual space cooling energy use was the closest of all end uses to the corresponding modeled value. Heating energy use did not include the installed gas fireplace, which was likely a significant contributor to heating energy usage. The energy consumption predicted for LAMELs was significantly higher than the measured amounts. The energy consumed in these end uses depends greatly on occupant preferences, which are difficult to predict.

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## Appendix A: Imagine Homes Floor Plans

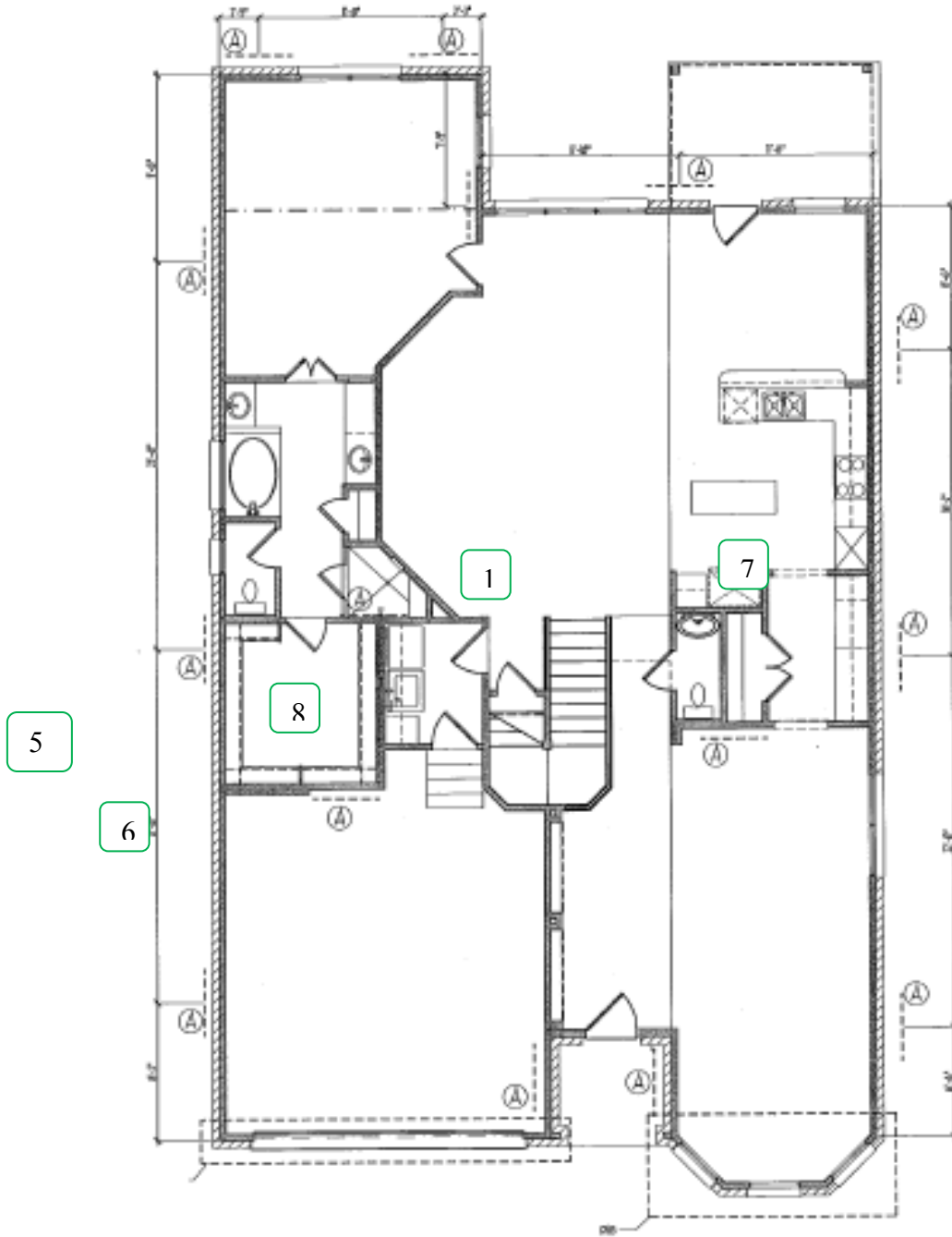
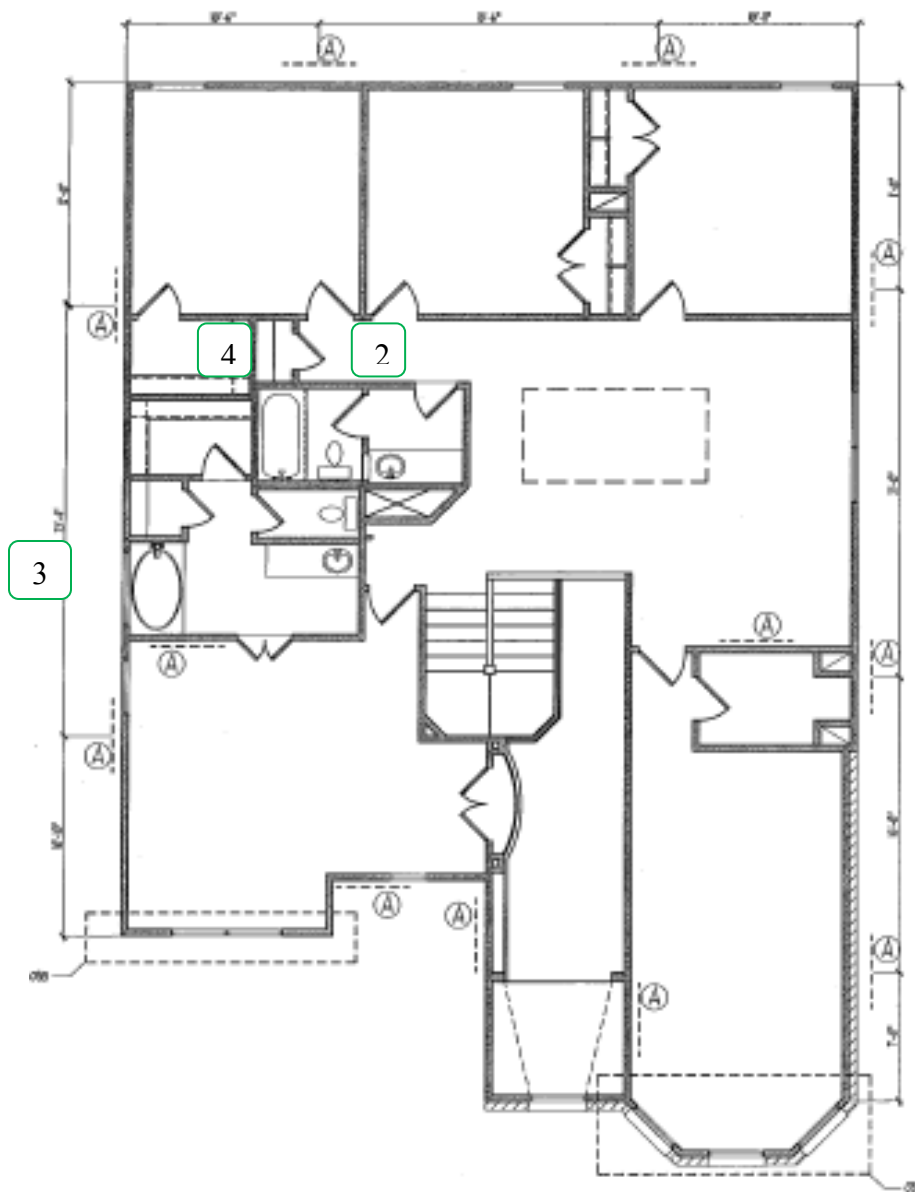


Figure 20. First-floor plan (numbers on drawing refer to photos in Appendix B)



**Figure 21. Second-floor plan (numbers on drawing refer to photos in Appendix B); #3 and #4 are on the roof and in the attic, respectively**



## Appendix B: Photographs of Sensor Locations from the Imagine Homes House from December 2010



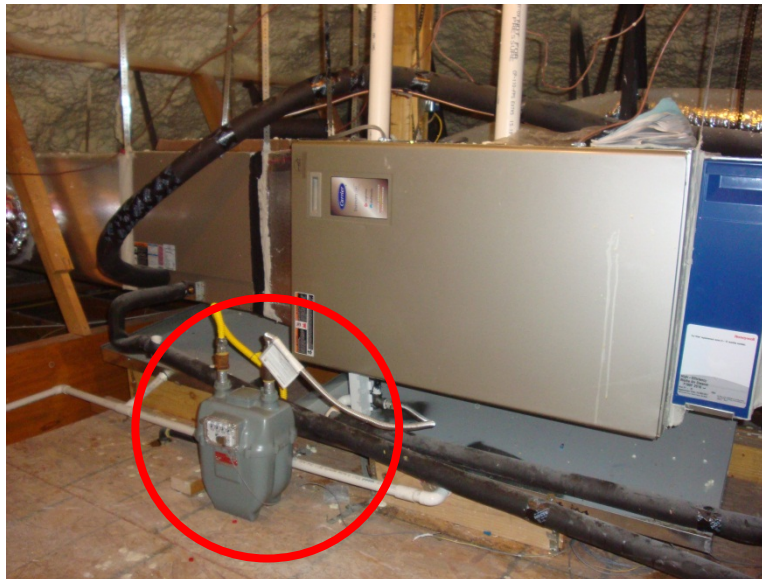
**Figure 22. Location #1; first-floor temperature and RH measurement at the thermostat location**



**Figure 23. Location #2; second-floor temperature and RH measurement at the thermostat location**



**Figure 24. Location #3; incident solar radiation sensor on the roof in plane with solar DHW and PV panels**



**Figure 25. Location #4; furnace measurements**



**Figure 26. Location #5; outdoor temperature and humidity measurement**



**Figure 27. Location #6; flow and temperature measurements at the water heater location**





**Figure 28. Location #7; electrical measurements at the outdoor electrical panel**



**Figure 29. Location #8; wires at the data logger location near the indoor electrical panel**



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