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Measured Performance of Side-by-Side South Texas Homes

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ABSTRACT

As part of the U.S. DOE Building America program, the Florida Solar Energy Center (FSEC), CPS Energy, and Woodside Homes of South Texas are collaborating to evaluate the performance of three homes in San Antonio, Texas with identical ~2,000 ft^2 floor plans and orientation. Measurements include whole house gas and electric use as well as heating, cooling, hot water, major appliances, and indoor and outdoor conditions. One home built to builder standard practice will serve as the control, while the other homes demonstrate high performance features.

These dual-fuel homes will provide utility peak electric load comparisons to assess the merit of envelope and equipment improvements. The control home uses natural gas for space and water heating only, while the improved homes have gas heating and major appliances with the exception of a high efficiency heat pump in one home.

Data collection began in July of 2009 and will continue for at least one year. Energy ratings for the homes yielded E-Scales (aka HERS indices) of 86 for the control home, 54 for one improved home and 37 for the other home which has a 2.4kW photovoltaic array. Envelope improvements include:

- *Sealed attic with R-28 open cell spray polyurethane foam at the roof deck*
- *Frame walls insulated to R-15 + R-3 rigid insulating sheathing*
- *Energy Star windows, U = 0.34, SHGC = 0.33*
- *Enhanced air sealing*

Equipment improvements include tankless gas water heaters (versus gas tank), right sized (per ACCA Manual J) SEER 18 two-stage air conditioning (versus SEER 14), Energy Star appliances, and 100% fluorescent lighting.

INTRODUCTION

Building America is a private/public partnership sponsored by the U.S. Department of Energy conducting research to improve housing performance including durability, comfort, and energy efficiency. The program goal is to achieve a 70% reduction in building energy use and produce the other 30% with on-site power resulting in homes that cost-effectively produce as much energy as they consume. FSEC has supported many Building America projects with long-term monitoring of building energy use and environmental conditions. Homes are typically monitored using 15 to 50 channels of data to measure indoor and outdoor environmental conditions and energy use of heating, cooling, water heating, whole house, and other points (e.g. Solar PV or Solar DHW) as needed.

CPS Energy is the nation's largest municipally-owned energy company providing both natural gas and electric service. Acquired by the City of San Antonio in 1942, the company serves approximately 700,000 electric customers and more than 320,000 natural gas customers in and around America's seventh-largest city. The partnership with the Building America program and FSEC is critical to helping our community understand how energy is used in homes and guide our community leaders in developing policies and

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Figure 1 *Photos of control, high performance, and PV homes.*

incentives to reduce energy consumption and the associated infrastructure.

Research on these homes focused primarily on comparisons of peak electric load profiles and cooling energy performance. Several electric demand reduction strategies were used to limit demand especially during utility peak periods. These included high efficiency electric equipment and replacement of electric appliances with gas and solar photovoltaic panels.

Heating and cooling is typically the largest portion of a residential utility bill making load reduction strategies a top priority for low-energy home construction. Reductions of over 70% in cooling energy use have been documented in past FSEC projects where an enhanced building envelope was coupled with high efficiency equipment. One example from over a decade ago in Lakeland, Florida compared an improved home with 14 SEER cooling equipment to a code minimum home with 10 SEER equipment (Parker et al. 1998). Results for the San Antonio homes were similar while comparing 18 SEER against 14 SEER equipment although one improved home performed somewhat better than the other.

HOME COMPARISON

Construction of the three homes began in late 2008 and was completed in early 2009 (see Figure 1). Each residence was built on the same street running NNW to SSE within 300 ft of each other. All homes had identical 1,979 ft^2 floor plans and orientation. There were differences in attic construction and wall insulation but otherwise the homes were built in a similar fashion. Gas appliances were used extensively in the improved homes with the exception of a high efficiency, electric heat pump in the high performance home (CP2). The control home (CP1) had mainly electric appliances except for a gas water heater and furnace, all of standard efficiency. Standard appliances and lighting were used in the control home representing higher internal cooling loads than found in the improved homes. See Table 1 for details.

Envelope Features

All homes were built on uninsulated, slab-on-grade foundations with 2×4 frame walls and brick veneer. Wall insulation varied with standard R-13 batts used in the control home, R-15 blown fiberglass plus R-3 foam sheathing in the HP home, and R-12 spray foam and R-4 foam sheathing in the PV home. The window to wall ratio of 16% was identical in each home with double-pane low-e used throughout, although those in the improved homes were of higher performance. An additional 12 in. of roof overhang was built into the improved homes over that of the control.

The control home had a vented attic with R-30 blown fiberglass insulation on the ceiling and a radiant barrier roof deck. The improved homes had identical sealed attics with R-28 open cell foam sprayed on the roof deck and at the garage-home attic interface. Reflectance of the roof materials was not known but all were medium to dark in color with the control home having asphalt shingles and the improved homes concrete tile.

Air Sealing

A concerted effort was made in all three homes to airseal the envelope as reflected in the envelope leakage numbers. Slab to wall connections were caulked in all homes, as were wall, window, and ceiling penetrations. Insulated sheathing in the improved homes was taped and all three homes received a taped house wrap. Access to the vented attic in the control home was outside the conditioned space (garage). The control home envelope was reasonably airtight at 5.84 air changes per hour at 50 pascals (ACH50), as might be expected in modern construction in a cooling climate. The improved homes were considerably tighter but with noticeable variation. The PV home was fairly well-sealed at 1.95 ACH50, while the HP home measured in at nearly twice that number. The roof-wall interface was sealed in all homes however infrared images of the improved homes on a cold December day indicated more leakage at this location in the HP home than the PV home (See Figure 2 below of similar wall locations in CP2 and CP3). The roof-wall interface of the HP home was at about 45°F, while the roof-wall interface of the PV home was at about 51°F. This is thought to be the main contributor to higher envelope leakage in the HP home.

Table 1. Home Features Comparison

	Control CP1	High Performance CP2	PV CP3
Foundation	Uninsulated slab on grade	Uninsulated slab on grade	Uninsulated slab on grade
Roof cladding	Brown asphalt shingle	Brown concrete tile	Brown concrete tile
Attic Type	Vented	Sealed	Sealed
Attic Insulation	R-30 blown fiberglass in ceiling plane, Roof deck radiant barrier	R-28 open cell spray foam under roof deck	R-28 open cell spray foam under roof deck
Wall Type	2x4 frame / brick veneer	2x4 frame / brick veneer	2x4 frame / brick veneer
Wall Insulation	R-13 fiberglass batts	R-15 blown-in fiberglass +R-3 insulated sheathing	R-12 open cell spray foam +R-4 insulated sheathing
Windows	SHGC: 0.37 U-factor: 0.53	SHGC: 0.33, U-factor: 0.34 +1 ft. roof line extension	SHGC: 0.33, U-factor: 0.34 +1 ft. roof line extension
Heating	80% AFUE Gas Furnace	9.5 HSPF heat pump + 5kW b/u strip heat	94% AFUE gas furnace
Cooling	14 SEER	17.8 SEER	17.7 SEER
Water Heating	40gal Gas Tank, EF=0.59	Tankless Gas, EF=0.82	Tankless Gas, EF=0.82
Ventilation	None	Passive run-time	Passive run-time
Lighting	Incandescent +5% Fluorescent	100% Fluorescent, timers and occupancy sensors	100% Fluorescent, timers and occupancy sensors
Cooktop	Electric	Natural Gas	Natural Gas
Refrigerator	775 kWh/yr	Energy Star, 505 kWh/yr	Energy Star, 505 kWh/yr
Washer	Standard Top-loader	Energy Star Tier 3	Energy Star Tier 3
Dishwasher	EF=0.46	Energy Star, EF=0.66	Energy Star, EF=0.66
Dryer	Electric	Natural Gas	Natural Gas
Thermostat	non-programmable	programmable	programmable
PV	None	None	2.4 kW roof tiles
HERS Index	86	54	37
Envelope Leakage	5.84 ACH50	3.64 ACH50	1.95 ACH50
Duct Leakage	70 CFM25, Qn= 0.035	47 CFM25, Qn= 0.024	65 CFM25, Qn= 0.033

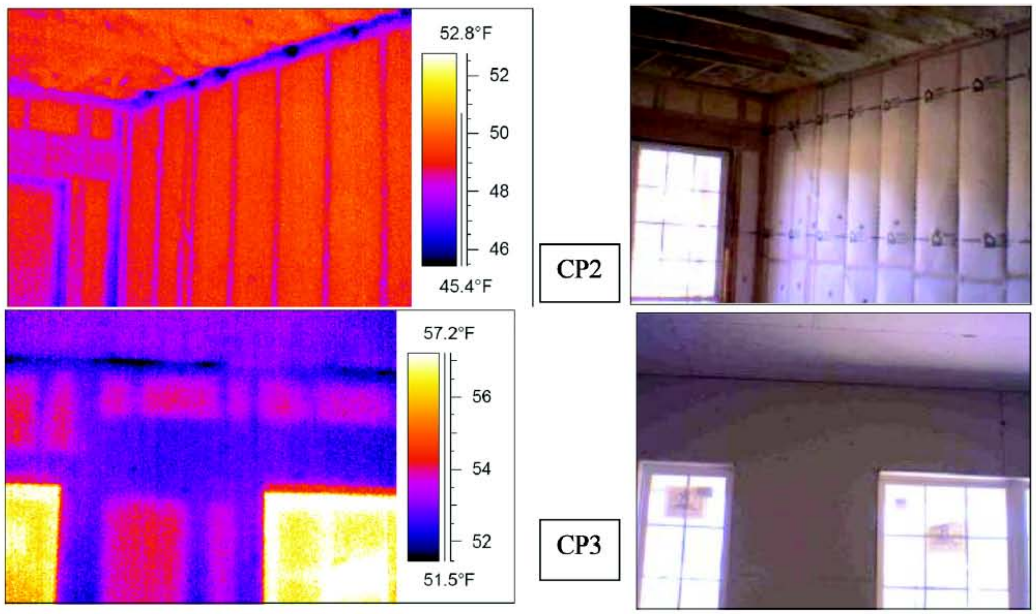

Figure 2 *Infrared and visible images of HP home (top) and PV home (bottom).*

Figure 3 *Images of hub and branch ducts (left) and tapered ducts (right).*

Ducts

Air distribution systems consisted of R-6 flex duct located in the attic in each home. All ducts were sealed with mastic resulting in test numbers of no more than 3.5 % leakage in terms of CFM25 per conditioned floor area. One difference between the homes is reflected in the summer measured attic conditions which show an average temperature of 95°F for the control home and 79°F for the improved homes. This illustrates the affect of the sealed and insulated attics in the improved homes during the hottest months of June through August 2009. Maximum attic temperatures reached 129°F and 85°F in the respective homes during these months. Another difference was that the improved homes had the ducts engineered for optimum distribution efficiency with tapered duct transition pieces whereas the control home had a standard hub and branch design (Figure 3).

ELECTRIC DEMAND

Many construction options are available to homebuilders for meeting a home's energy needs—either to meet customer preferences, construction cost targets, or simplify construction practices. From a utility's perspective these builder choices alter the home's real-time electric load profile and influence the community's overall electric infrastructure costs because it needs to be sized for the peak electric load rather than the average load. Electric utilities refer to the peak load as "demand".

In San Antonio, the highest system-wide loads are encountered in the summer months. CPS Energy's current demand management program runs between the months of May through September between the hours of 3 p.m. and 7 p.m. CDT. Demand is managed through voluntary subscription programs that remotely cycle residential air conditioners off and curtail load from commercial customers upon CPS Energy request. While these programs are successful, the community-wide system peak is growing much faster than the overall energy consumption and the need to add additional power plant capacity has not significantly slowed.

One of the goals of CPS research is to learn how the energy systems in the three South Texas homes affect their peak load profiles during the hottest weather conditions. That information can be used to help design incentive programs for builders and homeowners to help manage demand in addition to energy consumption.

While many demand reduction strategies are possible, the strategies our team chose for study were:

- High efficiency air conditioning paired with envelope upgrades,
- Solar photovoltaic panels,
- Electric versus gas cooking, and
- Electric versus gas clothes drying.

As of this date, full cost data for the upgrades is not yet available from the homebuilder. For this reason, this discussion will be limited to the observations about the peak loads in the test homes.

Figure 4 is a side-by side comparison of the electric load profiles on the hottest summer day in 2009 (July 8) for the control home, the home with the upgraded envelope and SEER 18 heat pump, and the solar home with the upgraded envelope, SEER 18 AC unit, and 2.4 kW solar array. The graphs show that the envelope and HVAC equipment upgrades effectively reduce the peak air conditioning loads by 1.17 kW or 28% during the utility peak hours in the heat pump home and 2.88 kW (68%) in the solar home. Because the solar home was unoccupied at the time these data were taken, it is not possible to determine whether occupant behavior or differences in the energy efficiency features was responsible for the difference. The graph for the solar home also shows that the southwest-facing panels do an effective job of removing the entire household electric load off the grid during the utility peak hours and even export excess power to the grid to help reduce grid loads from other homes. While these results will vary from day to day, depending upon solar insolation conditions, the greatest system-wide utility peaks will be associated with hot and sunny days.

While air conditioning loads contribute greatly to the system utility peak in San Antonio, other intermittent loads have contributions as well. Data on these intermittent loads is limited for a variety of reasons, including: lack of widespread in-home monitoring systems, variability in household behavior patterns, and differences among household miscellaneous load selections. The electric utility community is responding to these challenges with data gathering efforts to estimate the system-wide demand contributions from these miscellaneous loads and consumer willingness to time-shift use of these loads. Additional efforts include the development of a smart grid infrastructure that can either directly control the miscellaneous loads or send price signals to consumers to alter their behavior.

Our team selected a detailed look at demand contributions from electric cooking and clothes drying because the associated appliances use large amounts of electricity when they are on, they have the potential to significantly increase the utility peak load, fuel switching (e.g., electric to natural gas) could potentially be used as a strategy to control demand, and fuel switching to gas cooking and clothes drying is much less common in San Antonio than for gas water heating.

Figure 5 shows the electric monitoring data from the control home on a day when cooking, baking, and laundry is all going on during the utility peak hours on a hot day. Above the 4 kW air conditioning load, cooking, baking or laundry each added another 1 to 2.5 kW of load to the total. While this day may not be typical of every day, it conveys the significance of the miscellaneous loads toward the utility peak. For example, a look at the demand reductions on the hottest day (Figure 4) shows that peak electric use is reduced by over 6 kW for the high performance home and over 8 kW for the PV home during the utility peak period. Fortunately, the system-wide utility peak benefits from the averaging of the differing behaviors among many homes. By incorporating gas cooking and gas clothes drying in the high performance homes these spikes in electric grid use are eliminated with minimal impact on the natural gas infrastructure.

COOLING ENERGY

The summer of 2009 was one of the hottest on record in San Antonio, Texas. The months of July and August were especially hot with on-site instruments recording 34 days at or above 100°F. The average daily temperature during these months was 86.3°F compared to 76.6°F for the month of September. Accurate data collection for all homes was established in late June, so cooling season analysis was limited to July, August, and September. The control home was occupied in early May, versus July 1 and September 1 for the high performance and PV homes respectively.

Cooling equipment consisted of split systems with ducted central air handlers. Sub-metered energy from the condenser and air handler was stored at 15 minute intervals

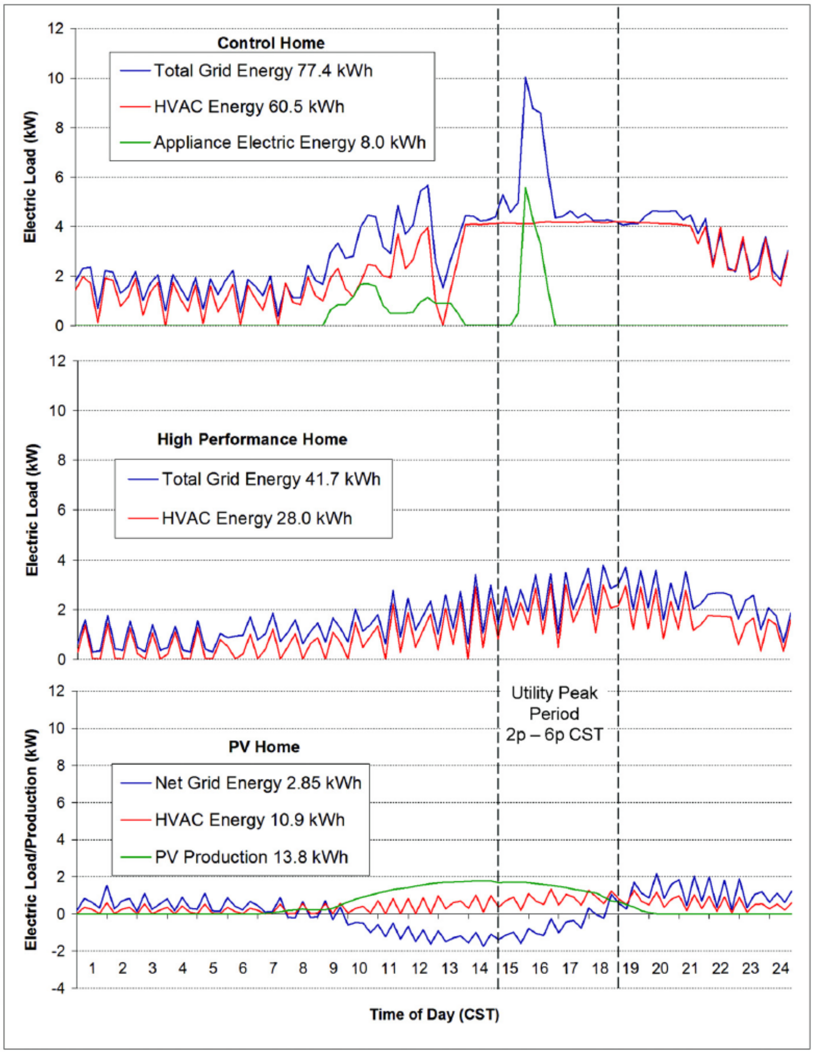

Figure 4 *Measured electric load on the hottest summer day—July 8, 2009.*

and subsequently combined and totaled on a daily basis. Energy generated by the PV home was not factored into its cooling energy total; it consisted solely of equipment energy use. Daily cooling energy totals (Figure 6) were plotted against average daily temperature difference between outdoors and indoors for the 24 hour period starting at midnight. Weather measurements were collected at one of the homes and consisted of dry bulb temperature, relative humidity, and solar radiation. Indoor temperatures were taken very near the thermostat. The use of temperature difference is intended to account for indoor temperature variations due to occupant determined thermostat settings.

The cooling performance levels shown in Figure 6 were determined by comparison of the areas under the least-squares line. This assumes the areas are directly proportional to energy use and are affected by the length chosen to makeup the bottom edge of the area along the x-axis (–5 to 14 for this analysis). Also shown in Figure 6 is the coefficient of determination (R^2) for each regression line. This measure of "goodness of fit" of the line to its associated data points ranged from 0.62 to 0.92. For the 92 day period a total of 4 days were removed from each home's data set, three of which were due to a temporary cold front and the other because of datalogger collection errors. Two additional days were

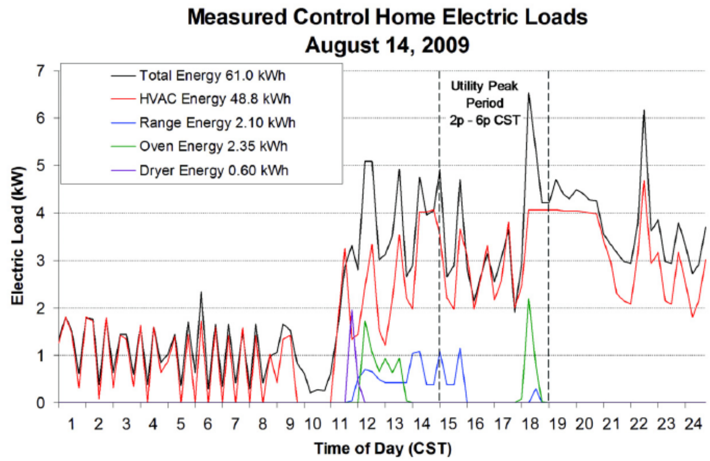

Figure 5 *Measured control home electric loads.*

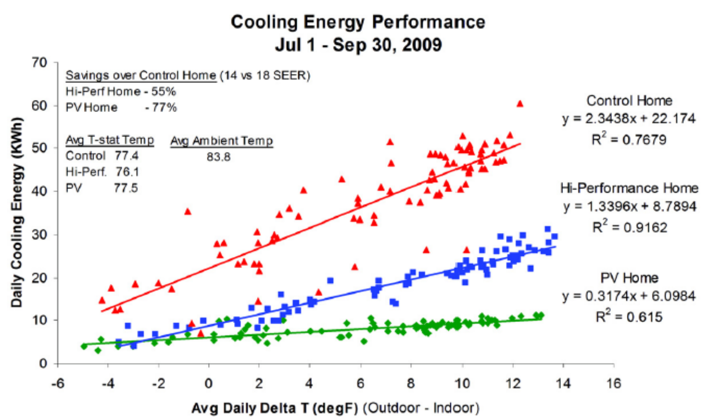

Figure 6 *Cooling energy versus outdoor-indoor temperature difference.*

removed from only the Hi-performance home data set due to collection errors. It should also be noted that only two of three homes were occupied during the entire three-month period. The PV home was unoccupied until September 1.

Cooling savings over the control home were significant with the high performance home saving 55% and the photovoltaic home 77% for the three months from July 1 to September 30. These savings numbers are strictly attributed to cooling equipment energy use with no impact from the PV system in the PV home. The difference in equipment efficiency alone (14 vs. 18 SEER) is expected to account for 28% savings with the remainder attributed to improved construction, reduced internal loads (appliances, lighting, etc.), and occupant impacts.

There was an unexpected difference in cooling energy savings (55% vs 77%) between the two improved homes compared to the control. Each improved home had cooling systems with nearly identical 18 SEER ratings, although the PV home had a straight-cool system with gas heat while the high performance home had a heat pump. Diagnostics performed by the contractor in November showed the heat pump to be operating within specifications, which alleviated concerns that the heat pump system was underperforming. Some of the savings discrepancy can be attributed

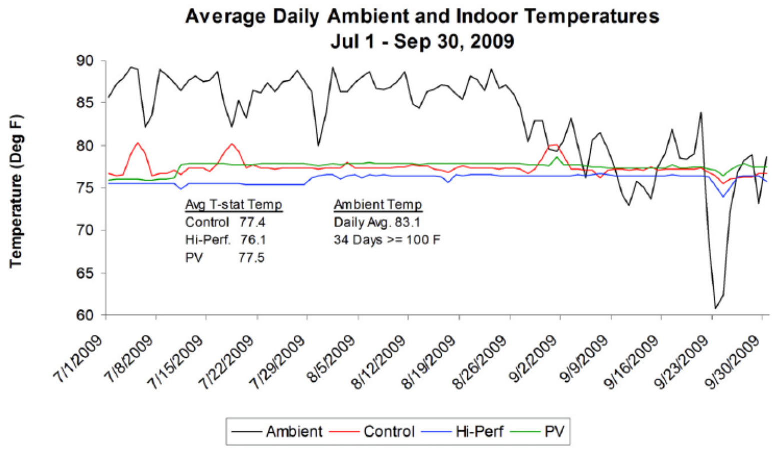

Figure 7 *Average daily ambient and indoor temperatures.*

to occupancy and occupant behavior as the PV home was unoccupied during July and August. All homes were occupied in September when temperatures were much cooler. Additional summer data is scheduled for collection in 2010 to provide a more consistent cooling energy comparison with all three homes occupied.

Figure 7 shows the average daily indoor and outdoor temperatures for each home. The very hot weather in June and July gave way to much cooler temperatures in September where the difference between outdoors and indoors was negative for several days. The coolest weather near the end of the data period was removed from analysis but the rest of the September data was used and contributed the points making up the far left portion of the trend lines in Figure 6.

The thermostats in all three homes were kept at relatively stable set point temperatures throughout the summer. It appears none of the occupants used programmable functions but there are a few notable days where the control home set point was raised considerably possibly due to a period of vacancy. These periods of high indoor temperature settings are consistent with reduced energy use as illustrated in Figure 6 by a spread of seven days in the control home data set (red triangles) with low energy use relative to the other days. The days on which these data points fell were sometimes followed by days with relatively high energy use. While these outliers, both above and below the trend line, caused a reduced coefficient of determination (R^2) for the control home, they effectively offset one another in terms of their impact on final savings calculations. Removing these outliers changed the improved homes savings values by only one percentage point.

PV PERFORMANCE

The 2.4kW grid-tied photovoltaic array was activated in mid-June providing energy for the PV home and feeding unused energy back to the utility. Nine months of data were analyzed from July 2009 through March of 2010. The home was unoccupied during the first two months of this period during which the air conditioner was set to maintain an interior temperature of about 77°F, similar to that of the occupied control home.

Figure 8 illustrates total electric energy used by the PV home and the percentage offset by the grid-tied system. The components of each bar are comprised of: (1) PV-generated energy used directly by the home, (2) the portion fed to the utility grid, and (3) the net grid energy used by the home. Total electricity use was notably lower during the unoccupied months of July and August. Even unoccupied, air conditioning energy was the highest during these very hot months averaging 266 kWh and accounting for 44% of total electric consumption. Monthly PV energy production was also greatest in July and August averaging 370 kWh and providing 60% of total electricity needs. A little more than half of this solar energy was fed back to the utility by the grid-tied system with the remainder used directly at the home.

Total electricity use in the PV home increased once occupancy began on September 1. Outdoor temperatures steadily declined from this time onward with an associated reduction in air conditioner energy use. Electrical energy use other than air conditioner energy remained relatively stable during the months of September, October, and November, averaging 640 kWh with no more than a 5.5% variation. The noticeable spike in energy use for December was attributed to extensive holiday lighting and the addition of a 1 kW kiln and electric resistance space heating for a garage-based glass making operation.

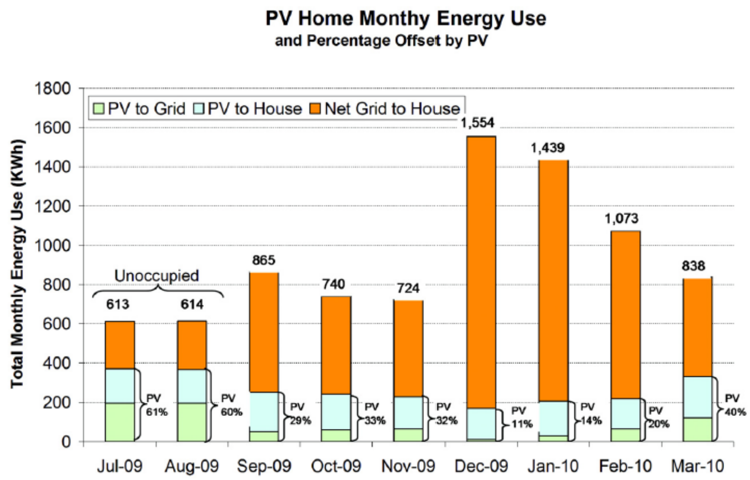

Figure 8 *Monthly electricity use in the PV home: July 2009 through March 2010.*

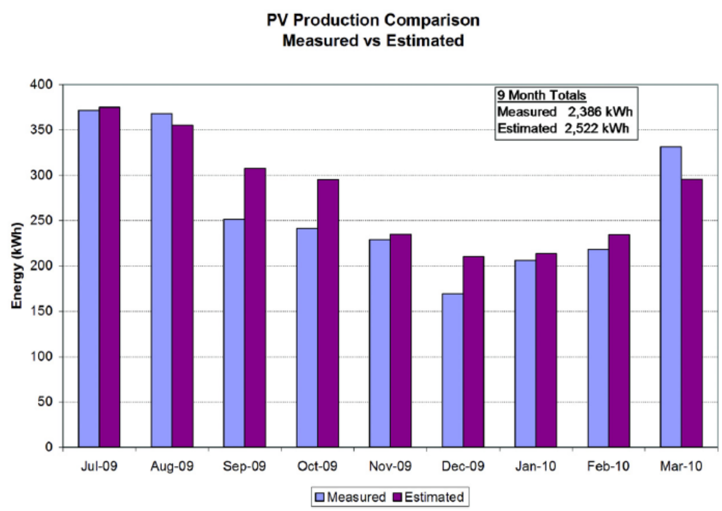

Figure 9 *Comparison of measured and estimated monthly PV production.*

While the extreme electric energy use continued in January and February, the homeowner has since agreed to stop using this equipment though the end of summer 2010 to prevent further confounding of collected data and allow for a more reasonable cooling energy comparison. Excellent PV energy production in the month of March allowed the array to provide 40% of total electric energy needs with two-thirds of this used directly by the home and the remaining one-third fed back to the utility.

Figure 9 provides a comparison of measured PV energy production to estimated performance calculated by the manufacturer on an equivalent 2.4 kW System with an azimuth of 230 degrees and a 6:12 roof pitch in San Antonio, TX. Five of nine months of measured data were similar to predicted energy production varying by no more than 7% of the monthly prediction. Each of the months of September, October, and December produced 18 to 19% less PV energy than predicted while the month of March produced 12% more energy than predicted. The months of September and October 2009, were unusually overcast and rainy which accounted for the lower PV productivity. Overall for the nine month period, the system has produced 5.4% less energy than the manufacturer's predictions. Generally, variations associated with weather data can cause measured and modeled PV performance to vary by as much as ±40% for individual months and ±20% for individual years (NREL 2006).

CONCLUSIONS

Three homes with identical floor plans and orientation in San Antonio, Texas demonstrate reduced energy use and electric demand by comparing high performance construction with builder standard practice. Cooling energy savings ranged from 55 to 77% in two improved homes over the control home. Total demand reductions observed between the control and improved homes ranged from 6 to 8 kW (62 to 83%) on the hottest day during the utility peak period. Peak air conditioning loads in the improved homes on the same day were reduced by 1.2 to 2.9 kW (28 to 68%) over the control. A 2.4kW grid-tied photovoltaic array on one home provided 60% of total electric energy needs during the hottest months, although the home was unoccupied during this period. During subsequent months with the home occupied, the array provided about 30 to 40% of total home electric energy except during a three-month period with excessive electric loads from a glass making operation.

ACKNOWLEDGEMENTS

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