Towards Zero Energy Demand: Evaluation of Super Efficient Building Technology with Photovoltaic Power for New Residential Housing

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ABSTRACT

This report summarizes the performance of a project designed to test the feasibility of designing and testing very efficient new residential buildings with integrated photovoltaic (PV) generation systems to meet cooling system and other electrical loads in a hot humid climate.

Introduction

The demand for electrical energy in Florida is increasing continually as a quarter of a million people move to the state each year building over 100,000 new homes (Floyd 1997). To meet this demand, utilities must add new generation facilities. Most Florida utilities are interested in controlling load growth during the summer peak demand hours. A typical single family home in Central Florida consumes about 15,000 kWh annually with summer afternoon peak demand of about 4.0 kW between 4 and 6 PM (SRC 1992). Larger new homes use even more electricity.

A 2,425 square foot test home was built in Lakeland which incorporates many measures designed to make it more efficient. This includes a reflective roof system, advanced windows, an interior duct system, wider overhangs, more efficient lighting, a high efficiency air conditioning system and propane used for major appliances which commonly use resistance electricity (range, dryer and heat). For comparison, a control house with an identical floor plan but without the efficiency features was constructed.

Design and Simulation Analysis

Previous work has simulated the possibility of greatly reducing the cooling loads in a conventional new home and then supplying most the cooling and other electrical needs with a grid-connected 3 - 4 kW PV array (Parker and Dunlop 1994). The results showed that the size of a cooling system of such a home might be reduced to as low as a single ton (12,000 Btu) of capacity.

After choosing the specific measures, we simulated the two buildings using a special version of the DOE-2.1E hourly building energy simulation. The version, *EnergyGauge USA,* includes the capability to examine interactions between the duct system location and the space cooling efficiency. This is important since both heat transfer to and leakage of the duct system can substantially influence cooling efficiency (Cummings et al. 1991; Gu et al. 1996). The simulation predicted the annual energy use of the Control building would be 22,740 kWh/year when occupied against 8,489 kWh for the PVRES home. Our initial analysis indicated a 66%

reduction by the PVRES building for space cooling and a 63% overall reduction in electricity consumption in the occupied homes when operated in a similar fashion.

Researchers worked with a builder in the vicinity of Lakeland, Florida to construct the two homes. The builder decided upon a 2,540 square foot one story floor plan for both. Both homes were complete with instrumentation by April 1998. One of the houses was to be of standard construction with typical appliances, insulation and equipment. The experimental home would contain the efficiency improvements and the PV element. Both would be extensively monitored. A description of the energy features are discussed in the following sections.

Wider Overhang

In Florida "Cracker" homes, built at the turn of the century before air conditioning, wide porches and deep overhangs were considered essential to comfort (Haase 1992). However, with the advent of air conditioning, new homes have sacrificed overhangs due to first cost. For solar control on walls and windows, the PV home has a 3 foot overhang around the perimeter of the building while the standard home has one and a half foot overhang.

Exterior Wall Insulation

In conventional residential construction in Florida, walls are insulated with R-3 to R-5 $ft^2 \cdot h \cdot {}^{\circ}F/Btu$ insulation on the interior of the masonry walls. Although low relative to building practices in northern climates, previous field monitoring has shown that wall insulation can only reduce space cooling by 5-10% in Florida's climate (Ternes et al. 1996). The most common wall insulation system in Florida to meet the insulation requirement is a layer of foil suspended between interior furring strips with an equivalent insulation value of R-4.2. We used exterior isocyanurate insulation to encapsulate the building in R-10 insulation so that the masonry portion of the building could be pre-cooled during the daytime hours when solar availability is high and the PV system output is at its maximum.

Solar Control Windows

Windows are a large source of cooling loads in Florida residential buildings (Vieira 1987). Generally, a low Solar Heat Gain Coefficient (SHGC) is needed to keep out the sun's heat, and a low conductance or U-value (Btu/hr-sqft-°F) is important to reduce the design cooling load. The most common windows used in Florida homes do not meet these needs well. Typically, windows are single pane clear glass with aluminum frames (SHGC = 0.875, U = 1.1).

For the project, we chose a spectrally-selective glazing. This refers to a window unit which transmits much of light in the visible portion of the solar spectrum, but limits transmission in the infrared and ultraviolet portions. *Sungate 1000* is a low-E glass product with Argon gas fill. The product has a SHGC of only 0.38, but with a daylight transmittance of 73%. The center-of-glass U-value is 0.24 $Btu/hr \cdot ft^2 - {}^{\circ}F$; we reduced heat transmission through the window frame by specifying white thermally broken vinyl frames (overall U-value = 0.35).

The improved glass had a major impact on air conditioning sizing. With 384 square feet of glass *Manual J* showed a 7,700 Btu/hr difference (0.64 tons) in the required air conditioner size. The difference in the transmitted heat was clearly seen in a thermographic comparison.

Reflective Roofing System

Over the last five years, the Florida Solar Energy Center has conducted numerous residential experiments showing that white roofs can reduce cooling energy needs. Based on testing performed at FSEC's Flexible Roof Facility in the summer of 1997, we learned that, of the evaluated roofing systems, white tile provides the best cooling related performance (Parker et al. 1995, 1998).

Both our test homes have R-30 fiberglass insulation blown in the attic. However, the improved house features a white concrete barrel tile roof. The control home's roof is conventional: popular gray-brown asphalt shingles. The solar reflectance of the white tested at 77% while the gray-brown asphalt shingle was only 7%. Figure 1 shows a plot of the measured attic air and ambient temperatures in the two homes on the utility peak day of June 18. The attic temperature in the control house rises quickly in the afternoon to reach a maximum of 137.9°F at 2:30 PM while the white tile roof attic only reaches 100.2°F – just about the same as the ambient air temperature.

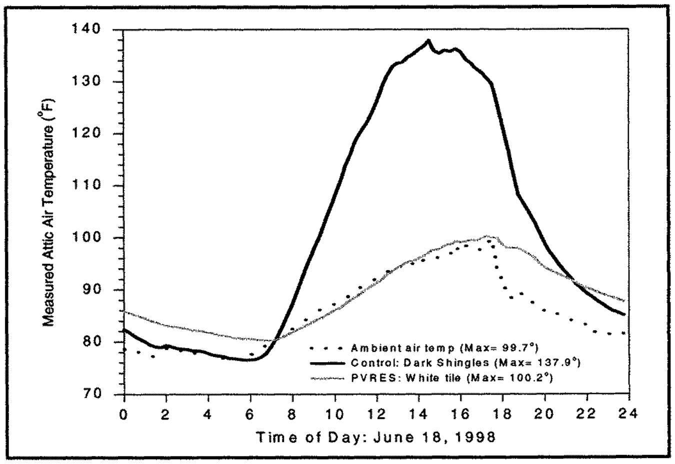

Figure 1. Comparative Mid-Attic Air Temperatures in Control and PVRES Homes on the Utility Peak Day (June 18, 1998)

Low Friction Interior Duct System

An innovative design feature in the PV home is its low-friction interior mounted duct system. In conventional houses the ducts are frequently undersized and are located in the hot attic. Previous research has shown that air handlers located in the attic space can increase space cooling by up to 30% (Cummings et al. 1991). Tests have shown that not only does the attic sometimes reach 135°F in Florida's summers (Gu et al. 1996), but also heat transfer to the duct system can rob the air conditioner of up to a third of its cooling capacity during the hottest hours.[1]

To avoid this problem, we designed the duct system so that it fits inside the conditioned space. Whatever heat is gained by the duct system must be removed from the conditioned space. To hide the ducts, false dropped ceilings, lower cathedral sections and chases were used throughout the interior. To avoid problems with leakage, the duct system was carefully sealed to less than 0.3 cfm/ft^2 at 50 Pa. Finally, we oversized the duct system, so that air flow resistance would be minimized. This not only provides critically important air flow across the evaporator,

[1] The reason is simple: R-6 flex ducts contain the coldest air in the home (~60°F) while being exposed to the hottest temperatures; the area of ducts in a typical home is a third of the floor area. Heat transfer is proportional to surface area, thermal conductance and temperature difference: $Q = UA\,\Delta T$. At 130°F, and a 2,400 square foot home, this equates to over half a ton of air conditioning lost before cooling air reaches the registers.

it also reduces air handler fan power and improves system efficiency while lowering noise. Low friction duct systems can provide up to a 12% improvement in cooling system efficiency at no cost (Parker et al. 1997).

Measured Conductive Heat Gain to Thermal Distribution System

In the Control and PVRES buildings, thermocouples recorded the temperature of the cooling air leaving the air conditioner evaporator as well as the temperature of the air when it reached the exit at the farthest register from the air handler. Half of the temperature difference between could then be used to gauge the average heat gain to the duct system.

Figure 2 shows that heat gain to the duct system of the Control home rose linearly with the measured attic air temperature. A regression line through the trend showed that the temperature rise from the evaporator to the far duct register would increase 0.084 degree (°F) for each degree which the attic air temperature rose. Since maximum attic air temperature of 140°F was measured, this would indicate a corresponding duct temperature rise of 7.3°F. Assuming the typical register exhibits half this heat gain with an air handler flow that was measured at 1,555 cfm, the computed sensible heat gain is 6,130 Btu/hr or about half a ton of lost cooling.

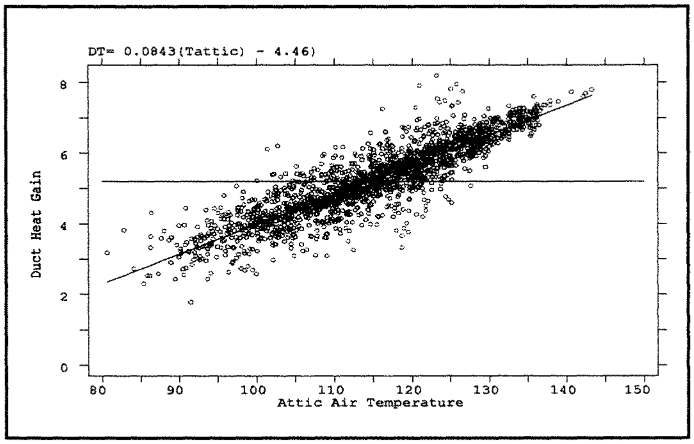

Figure 2. Measured Register Temperature Rise Versus Attic Air Temperature in the Control Home over the Entire Summer

An analysis for the month of June showed conductive heat gains to the duct system to be responsible for about 10% of the 61 kWh per day of space cooling required. Measured heat gain to the duct system in the PVRES home from the evaporator to the far register was about half this level. However, since the gains removed heat from the conditioned space of the home, they did not exert the 10 - 13% penalty in space cooling of the attic duct system.

Solar Water Heating System

The PVRES home substitutes propane for what are normally electric resistance end-uses to better allow the PV system to match the home's load. Propane was used for the oven/range, the clothes dryer, back-up heating for hot water and a direct-vented fireplace. However, propane is a fairly expensive fuel (approximately $1.40/gallon). Our objective was to provide at least 60% of water heat with the solar water heating system.

The solar water heating system consisted of a forty square foot solar collector mounted on the south side of the home's roof. Parasitic pump power is avoided through the use of a 10W PV panel with a magnetic impeller pump. The storage system is made up of two tanks, an 80 gallon primary solar tank and a 40 gallon back-up propane tank. The Control home contains a 52 gallon standard electric resistance storage tank.

Over the occupied monitoring period, daily hot water use in the 2-person household averaged 37.8 gallons per day against a daily propane consumption of 0.09 gallons per day. The installed water heater has a rated energy factor of 0.65 with the measured hot water temperature 130°F. Based on measured hot water use and a 50°F temperature rise shows that propane consumption should be approximately 0.264 gallons/day without the solar contribution. This implies a solar water heating fraction of approximately 66%.

Energy-Efficient Lighting

Like most new Florida homes, the PVRES plan features considerable lighting from recessed cans – thirty in all. In the standard home, each of these contains a 75W R-lamp incandescent bulb. This connected lighting load from recessed cans comprised 2.25 kW. Previous research has demonstrated the large savings potential of using compact fluorescent lamps for residential lighting (Parker and Schrum 1996). In the PVRES home, we used 15 W CFL globes for installation in the recessed cans of the PVRES home. The lamp provides virtually identical light output to the 75BR30 lamp and uses only 15 watts (600 Lumens) rather than 75. It also lasts an average of 10,000 hours of use rather than 2,000 for a standard incandescent lamp. Connected lighting electric load was reduced by almost 80%.

Air Conditioning Equipment

An important objective in selecting the cooling equipment for the PVRES home, was to take advantage of the features designed to reduce cooling loads. We used *Manual J* to calculate the cooling system size for both the standard home and the control home. *Manual J* indicated a cooling system of 3.88 tons for the Control and 1.73 ton for the PVRES house.

We selected a *TWY024A* two-ton heat pump for the PVRES house. We used the *TWE040E13* variable speed indoor air handler to provide optimum efficiency and humidity removal. The Seasonal Energy Efficiency Ratio (SEER) of the combination is 14.4 Btu/W; the analogous Heating Season Performance Factor (HSPF) is 8.5 Btu/W. For the standard home we utilized a standard efficiency 4-ton *Trane* heat pump which the project builder typically installs in his homes – a *TWR048C* (SEER = 10.0 Btu/W; HSPF = 7.0 Btu/W). After each air conditioner was installed, we performed tests to establish the installed performance.

The measured air flow for the four ton heat pump at the Control house was 1,555 cfm or about 390 cfm/ton. A 16.5 degree temperature drop was measured across the coil. The measured sensible cooling capacity of the unit at an 87.4 degree outdoor temperature was 26,680 Btu/hr; the latent cooling capacity was 8,560 Btu/hr for a total capacity of about 35,240 Btu/hr. With a 4,181 Watt power draw; this works out to an EER of 8.4 Btu/W.

The variable speed air handler (VSAH) operates much of the time at less than half speed.[2] At full speed we measured an air flow of 1,380 cfm (690 cfm/ton). A 12.9 degree temperature drop was measured across the coil with a sensible cooling rate of 18,530 Btu/hr. Latent performance was good with 8,770 Btu/hr of moisture removed. Total capacity was 27,300 Btu/hr with measured power at 2,074 Watts – an overall EER of 13.2 Btu/W. The nominal SEER of the

[2] For each cooling cycle, the unit operates at 50% flow for the first minute, then 80% flow for the next 7.5 minutes and finally 100% flow after that if the thermostat has not been satisfied.

specific unit is 14.5 Btu/W. The rated capacity of the unit at the closest rated condition (85°F outdoor dry bulb, 72°F entering dry bulb, 63°F wet bulb) was 25,200 Btu at 900 cfm with an EER of 14.1 Btu/W.

House and Duct Airtightness

We used a blower door to measure house tightness in both homes on April 22, 1998. For the Control home the total overall building tightness of the control house was 2,025 CFM_{50} or 6.3 ACH_{50} with a house equivalent leak area (ELA) of 95.2 square inches. The overall tightness of the PVRES home was 1587 CFM_{50} or 4.9 ACH_{50} with a house ELA of 69.0 square inches. In both homes, much of the leakage is from the 30 recessed lighting cans in the ceiling.

We used a *Duct Blaster*™ testing device to determine the relative leakage in the return and supply sides of the duct systems. In the Control home, the duct system leakage to outside the conditioned space was 122 CFM_{25}. Given its 2,425 square feet of conditioned area, the duct leakage to outside is 0.05 cfm/ft^2. This compares to the 0.03 cfm/ft^2 proposed as a standard for utility new homes programs. In the PVRES home, the total CFM_{25} leakage of the duct system from outside the conditioned space was 50 CFM_{25} or about 0.021 cfm/ft^2 – a low value.

One limitation of the tests, however, is that, with the air handler operating, all leaks are not the same. Ceiling penetrations close by the air handler can bring air from the attic – air that is super heated in the Control home. Moreover, any of the 50 cfm outside air that is unintentionally drawn from the attic in the PVRES home is being taken from a space that typically gets no hotter than the outside ambient air temperature. Evidence of unintended air leakage in the Control home from the attic to the air handler casework in its interior closet was clearly seen in infrared thermography on the air handler (see source report). This is contrasted by the lack of such leakage with the interior duct system in the PVRES house. Although the duct work is well sealed in the Control home, the leakage to the air handler case itself suggests that ceiling penetrations by the air handler closest will lead to air being drawn from the space. It also suggests significant impact of allowing air handlers to be located within attic spaces – a very common practice in Texas and other states.

Measured Building Infiltration Rates

To supplement the blower door test, we evaluated the *in situ* air infiltration rate in both homes using sulfur hexafluoride (SF_6) tracer gas decay. The blower door indicated that the PVRES home was tighter with less leakage area, but how the tightness will impact actual air leakage rates is strongly influenced by the operating pressures within the building, particularly when the mechanical air distribution system is operating.

Both homes were evaluated on May 20, 1998 with the air handler on and off. The tracer gas concentration decay was measured by two multi-gas monitors over a one hour period subsequent to SF_6 injection as shown in Table 1. The *air handler off* test provides information on the "natural air infiltration rate" from air leakage driven by temperature differences and wind on the external building envelope. The *air handler on* test shows how operation of the mechanical air handler equipment can impact the overall building leakage rate in air changes per hour. Past studies have shown that operation of the air handler will typically increase building air leakage rates by two to three times the "natural" rate which is typically low in Florida homes due to the small driving forces – buoyancy and wind (Cummings et al. 1991).

Table 1. Measured House Air Infiltration Rates

Case Description	AH Status	Air Changes Per Hour	Interior Temp (°F)	Exterior Temp. (°F)	Wind Speed (m/s)
Control	Off	0.131	76	90.6	5.2
Control	On	0.349	76	89.9	8.0
PVRES	Off	0.085	74	86.5	9.5
PVRES	On	0.131	74	85.6	10.2

The PVRES home evidenced tighter construction and in all cases the air change rates were low. The natural infiltration rates (air handler off) were 0.085 and 0.131 ACH in the PVRES and Control homes respectively. The air change rates with the air handler operating was 0.131 in the PVRES and 0.349 in the Control revealing that the air handler operation increased building air leakage by 54% and 266%, respectively.

Appliance Monitoring

Table 2 shows the average recorded appliance electrical loads at the PVRES home since the home was occupied on June 4. Loads are not shown for the Control home since it was unoccupied.

Table 2. Measured PVRES Appliance Energy Consumption

Appliance	Mean Power	Total Estimated Annual Consumption	
Refrigerator[3]	106.7 W	935 kWh	
Washer	6.9 W	60 kWh	
Dryer #	5.7 W	50 kWh	
Range #	5.8 W	51 kWh	
DHW blower #	1.7 W	15 kWh	
Lighting, plug loads	368.8 W	3232 kWh	
Propane End-Uses	**Mean Rate**	**Total Annual**	**Estimated Annual Propane Gallons**
DHW burner	0.134 ft^3/hr	1174 ft^3**	32.3
Range	0.030 ft^3/hr	263 ft^3	7.2
Dryer	0.053 ft^3/hr	464 ft^3	12.8

** 2,522 Btu/ft^3 of propane with 91,500 Btu/gallon; 36.3 ft^3/gallon
# Electricity consumption for propane appliances (blowers, ignitors, motors)

[3] For the project we obtained the most efficient refrigerator available from Sears in a large side-by-side type. This was the 25 cubic foot *Kenmore* 57572 model with an estimated annual energy consumption of 777 kWh/year. Over the warmer summer period from June - August, consumption has averaged 2.56 kWh/day – about 20% greater than the nameplate rating.

Utility Interactive Photovoltaic System

The photovoltaic (PV) solar electric generation system is grid-interactive, producing DC power which is inverted into AC current and then directly fed into the local utility feeder of *Lakeland Electric and Water Company*. The PV generation system was sized to provide power that would offset as much of the household loads as possible. The *PV Form* simulation model (Menicucci and Fernandez 1988) provided an estimate of the usage and the PV array output. Based on the predicted loads for a peak day, a 4kW solar array was specified. Based on an analysis it was determined that the array would be split into 2 sub-arrays, one facing south and the other facing west to better match cooling loads. Simulation models indicated that the west-facing array would be slightly less efficient at utilizing the solar radiation because of the orientation; but the west sub-array would generate appreciable power later in the day, after the output of the south sub-array had diminished and when power generation is most important to the utility.

Siemens SP75 solar modules were selected for the installation. These single crystalline modules have a maximum power rating of 75W. Thirty-six modules make up the south-facing sub-array (array rating of 2,700 W) and twenty-four modules face west (rated output = 1350 Wp). The combined total rating of all 55 modules (18 sub-arrays with six source circuits) is 4050 Watts at standard operating conditions. A *SW4048UPV* sine wave AC power inverter from *Trace Engineering* was selected to convert the DC from the array to AC power. This inverter has a 240VAC - 60Hz output and provides high quality power, for utility line-tie applications.

Figure 3 plots the AC power (watts) sent to the grid by the PV system over several days with varying sky conditions in April 1998. Over this short period, the average daily total power to the grid was 15.2 kWh with a peak 15-minute power production of 2.9 kW. When profiled over a daily schedule, the average peak power produced was 2.3 kW at 1:30 EST.

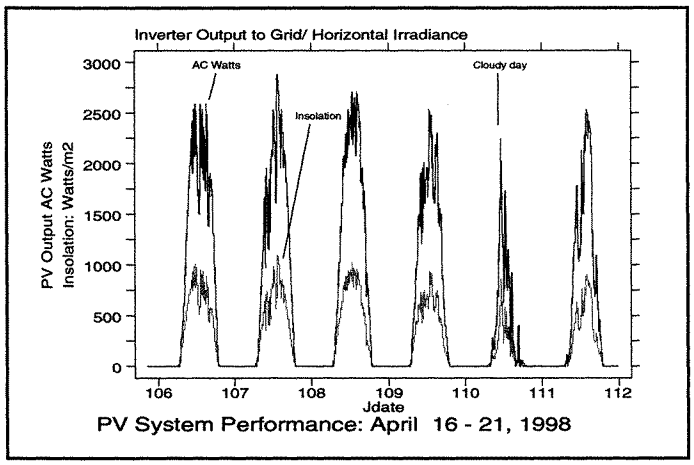

Figure 3. PV System Performance in April 1998

Array and Inverter Performance

The maximum peak AC power (2.9 kW) measured is considerably less than the nominal 4.05 kW nameplate rating of the installed system. There are several reasons – all expected. The power production performance of the PV modules is fairly dependent on the array temperature. The modules experience a 0.4% drop in their nominal energy conversion efficiency for each degree celsius which the arrays are warmer than 25°C. Since array temperature is monitored, a rough correlation with the first week of recorded data shows that module temperatures averaged 55°C at full irradiance (1,000 W/m^2). Thus, power production performance would be about 88% of the nominal value at full insolation based on temperature influences.

Some 1.3 kW of the nominal 4 kW installed faces the west azimuth. We intentionally installed this segment to explore how this array would assist in meeting late afternoon peak electrical needs for the home. Peak power production is somewhat out of phase with that of the larger south facing array (the reason why the observed system peak output is at 1:30 PM rather than noon). The ratio of the two orientations will change seasonally, but the insolation from the west array averaged 880 W/m^2 when the south array was receiving 1000 W/m^2. The west array is of advantage in the later afternoon. At 6 PM EST when many homeowners are returning home and turning on appliances, the insolation on the 23° array tilt averaged 133 W/m^2 on the south, but was over 250% greater (354 W/m^2) on the west array.

On average at 1000 W/m^2 of horizontal irradiance, the PV system produced approximately 2925 W of direct current power. However, some losses are experienced from the conversion of DC to AC power. The average inverter or Power Conditioning Unit (PCU) average efficiency from April to August of 1998 was 89%.

Seasonal PV System Performance

Daily PV power production of the array over the analysis period from April - August averaged 17.64 kWh DC with 15.66 kWh delivered to the utility grid. Over the course of the summer total PVRES building loads averaged 22.0 kWh/day so that the PV system produced 71% of the daily electricity required for the building operation. During daytime hours the net impact on the grid is near zero; during evening hours all power required for the PVRES building must come from the utility.

We used the PVFORM hourly simulation program to predict the annual performance of the PV system and its sensitivity to the off-azimuth orientation of the west-facing sub-array. The simulation predicted that the split array configuration would produce an annual DC energy of 6,269 kWh (~5,580 kWh in AC power to the grid). The model predicted the array would have produced 6,604 kWh DC if all 54 modules had be oriented facing south. This indicates that the annual power production penalty from the west facing array was only 4.2%.

Thermal Performance Monitoring

Comparative monitoring of the thermal performance of the two homes (Control and PVRES) began on April 15, 1998. Appliances were turned off in both closed-up homes with data recorded for a six day period (April 16 - 20) in an unoccupied and (mostly) unconditioned state. The data loggers sampled the weather conditions and temperatures around the homes. The two plots below (Figures 4 and 5) show the following measurements taken:

- Ambient air temperature
- Interior air temperature

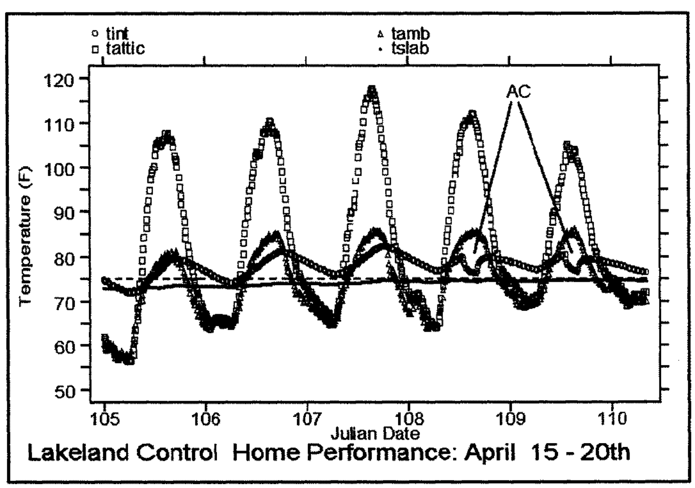

Figure 4. Control House Thermal Performance when Unconditioned

- Temperature of the floor slab
- Attic air temperature

Large differences in the attic air temperatures were observed in the two homes – even in mid April. The attic air reaches nearly 120°F in the Control home under its dark brown shingles while the attic under the white tile roof ranges only slightly around ambient air temperature. The interior air temperature in the PVRES home averaged 4 degrees cooler and showed much less daily variation than the Control home.

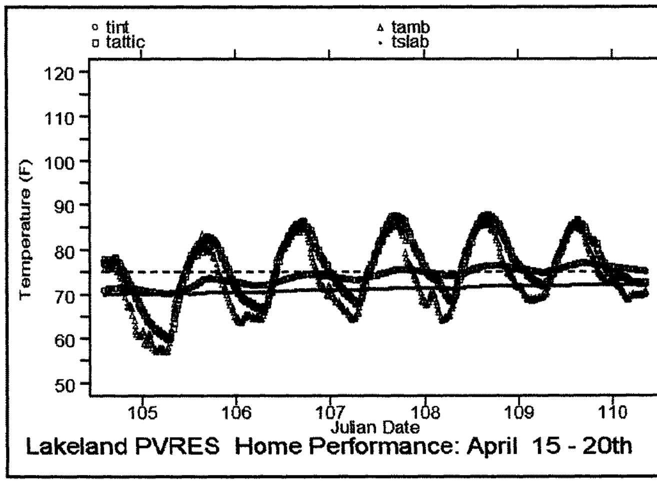

Figure 5. PVRES House Thermal Performance when Unconditioned

Infrared thermography in both homes showed beneficial heat loss to the tile/slab floor as opposed to carpeted sections. Measured surface temperature differences were on the order of 4°F for tiled versus carpeted sections. Under these spring-time conditions this would indicate a passive slab heat sink cooling rate on the order of 9,700 Btu/hr had the entire floor been tiled based on standard surface conductances.

In summary, thermal performance monitoring of the two buildings showed large differences – a reflection of the influence of the cooler attic, the exterior insulation on the PVRES home and its high performance windows. So successful did these features work in concert, that the PVRES building showed little need for air conditioning in late spring. Conversely, the Control required mechanical cooling to keep its interior temperatures below 80°F when shown to prospective customers on weekends.

Unoccupied Monitoring Under Summer Conditions

Monitoring in May 1998 concentrated on direct comparison of the performance of the unoccupied two homes when air-conditioned. The Control home was set to 76°F in cooling mode, while the PVRES house was set one degree cooler to insure no favorable bias. Both homes were left vacant and unattended without appliance loads.

Figure 6 shows the measured cooling load profile on a hot day (May 17, 1998) the Control home has a measured air conditioning load averaging 3.62 kW during the peak hour between 5 and 6 PM EDT, while the PV home has a measured average AC load during the hour of 0.50 kW – a reduction to the utility

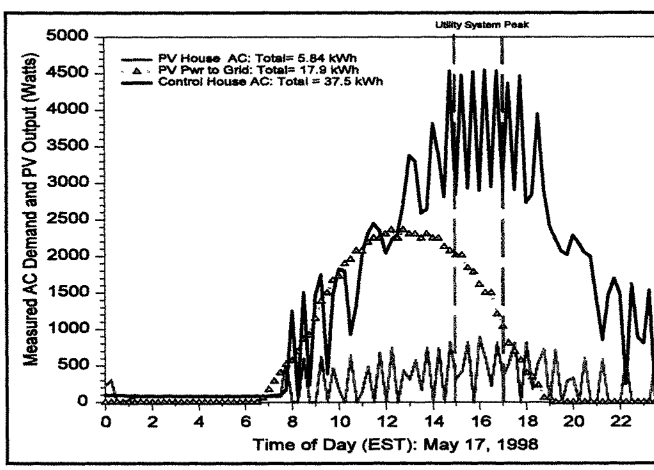

Figure 6. Measured Control and PVRES Cooling Electric Demand and PV Power to Grid on May 17, 1998

coincident peak load of 86%. At the same time, the average PV power production during the hour averaged 619 Watts. Total daily electricity consumption for cooling was 37.5 kWh in the Control home against 5.84 kWh in the PV home – a reduction in cooling load of 84%. Moreover, the PV system produced 17.9 kWh more than was used during the peak hour. The PV system produced three times as much electricity over this day as the cooling system used.

Evaluation of Load Shift Potential

On June 4, 1998, the new PVRES owners moved into their new home. After the new owners took occupancy, monitoring continued for the rest of the summer with a load shift strategy utilized. The PVRES home was pre-cooled during the late morning and early afternoon using a programmable thermostat while allowing the temperature inside to rise during the afternoon hours. On June 11, we reset the programmable thermostat so that it would pre-cool the building to 74°F between 11 AM and 5 PM and then 76 during the rest of the day in an attempt to shift the load away from the utility peak coincident hours 5 - 7 PM. During the entire period, the thermostat in the Control home remained set at a constant 76°F, although without occupants. The PVRES home had the heat generated by the occupants, appliances and lighting.

In June of 1998, the Central Florida area experienced a record heat wave and drought which touched off numerous wildfires. The Tampa National Weather Service – only about 30 miles from Lakeland – reported that the average June '98 temperature was an all-time record high. Figure 7 shows how the average cooling electric demand in the two homes over the entire month of June. The "load shift" related electric demand increase in the PVRES home (thermostat goes down from 76° to 74°) at 11 AM is very noticeable, as is the drop in load at 5 PM. The total average cooling energy use in the unoccupied Control home is 61 kWh a day ($147 for the month at current utility rates). Even with the internal heat from appliances and occupants the measured cooling was only 18 kWh ($42 for the month) a day in the occupied PVRES house – a reduction of 70%. When *total* power from the occupied PVRES home is considered (30.3 kWh/day), it still uses only 50% of the *air conditioning* of the Control.

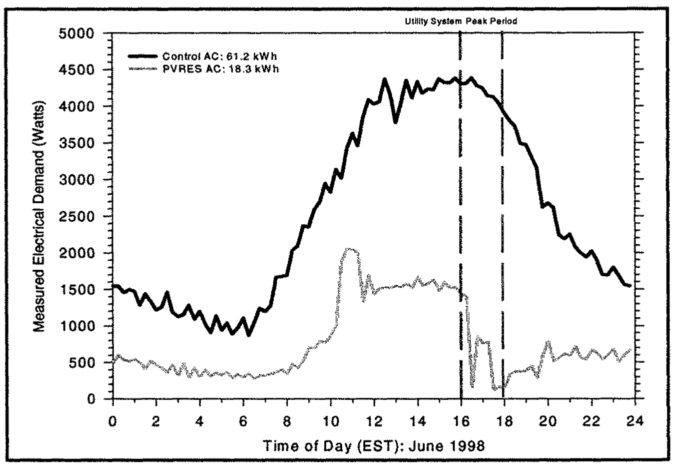

Figure 7. June Cooling Energy Use Profiles in Control and PVRES Houses

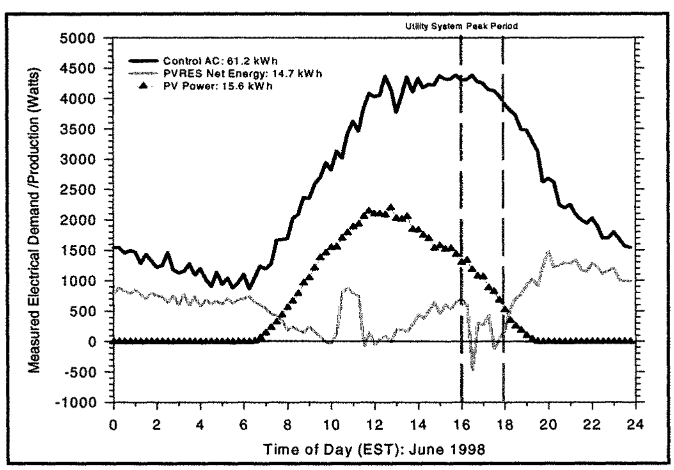

Figure 8. June Net Loads and PV Power Production at Control and PVRES Homes

Figure 8 shows how the average daily AC electric consumption (61 kWh/day) at the Control house compares with the PV electric power production (15.6 kWh/day) at the PVRES home. The gray line shows the PVRES Net power demand (Total electric load - PV power to the grid). Note that the late afternoon PV electric production was sufficient to zero out the total PVRES electric demand during the peak hours between 4 and 6 PM EST (5 and 7 PM EDT). The net power use of the PVRES home is only 24% of air conditioning alone at the Control.

Comparison to Neighboring Conventional Homes

Within the PV portion of the project, two additional homes were monitored in the same immediate neighborhood as the PVRES and Control houses. Both were constructed by the same builder and are very similar in size, features and construction to the Control home. PV House #1 has a 2 kW utility-integrated south-facing PV array and PV House #2 has a similar 1.8 kW PV array. Both were monitored to provide data on PV power and total household electric demand. Neither home has any special energy savings measures, but are within one block of the Control and PVRES house. The fact that both homes were occupied provides an interesting comparison with the PVRES home and unoccupied Control home. Table 3 shows a comparison of total electricity consumption, monthly cost and PV Array output for June 1998.

Table 3. Comparison of All Homes for June 1998

Site Description	Power Use (kWh)	Monthly Cost ($)	PV Array Output AC kWh	Percent PV Output of Total Loads
PVRES	837	$ 67	502	60.0%
Control	1,839*	$147	None	0.0%
PV#1	2,970	$260	255	8.6%
PV#2	2,435	$195	224	9.2%

* air conditioning only

Note that both of the occupied homes use considerably more than the Control home does for air conditioning alone. This would suggest that had the Control home been occupied, its total energy use would have been 30-60% greater than recorded.

Figures 9 and 10 show a comparison of the total loads and PV output for the PVRES and PV house #1 over the month of June showing the importance of efficiency in making the PV output. Whereas the solar electric system in the PVRES home provides 60% of total electrical needs, the smaller system in the other two homes provide only about 9% of total electricity consumption.[4]

[4] A recent report issued by the Electric Power Research Institute (EPRI) further under-scores the importance of building efficiency, load shift and array orientation in the making PV contributions meaningful to controlling utility peak loads. Within this research, 2.3 - 3.2 kW PV arrays were used to power 3 - 5 ton variable speed heat pumps at four monitored test sites in Arizona, Texas and North Carolina. The initial findings showed that the PV arrays were only able to reduce space cooling demand by only 15% under peak conditions (EPRI 1998). This is largely due to the poor match between PV and inefficient buildings.

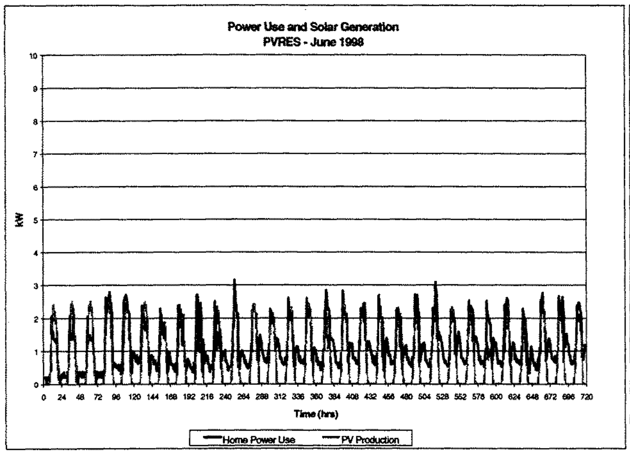

Figure 9. PVRES Total Loads (black) and PV Output (gray) for June 1998

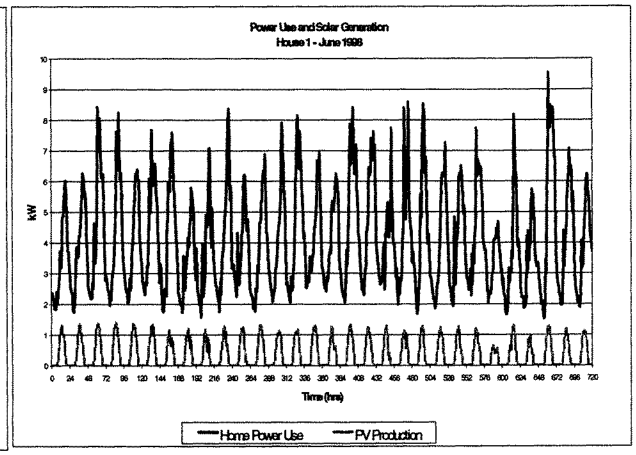

Figure 10. PV House #1 Total Loads (black) and PV Output (gray) for June 1998

Utility Peak Day Performance

On June 18, 1998, Lakeland Electric and Water experienced their maximum annual utility peak for the summer, recording a record one-minute demand of 578 MW at 5:03 PM. Maximum recorded ambient air temperature was 100°F (a record) with bright sunny conditions. Figure 11 shows that the Control home used 71 kWh on this day – with the 4-ton air conditioner running constantly between 11 AM and 6 PM. Meanwhile, the 2-ton AC in the PVRES home only runs constantly for the one hour from 11 AM to noon while it pre-cools the building from 76° to 74° and uses only 20 kWh – a 70% reduction in cooling. During the utility peak period it ran less than half the time (908 W) with a demand difference between the homes of 3.82 kW.

Interior comfort conditions (Figure 12) show that the PVRES home was also better able to maintain space conditions. Running constantly from 11 AM onward, the Control home AC was unable to maintain interior temperature conditions at its 76°F set point. The recorded interior temperature slowly rose to a maximum of

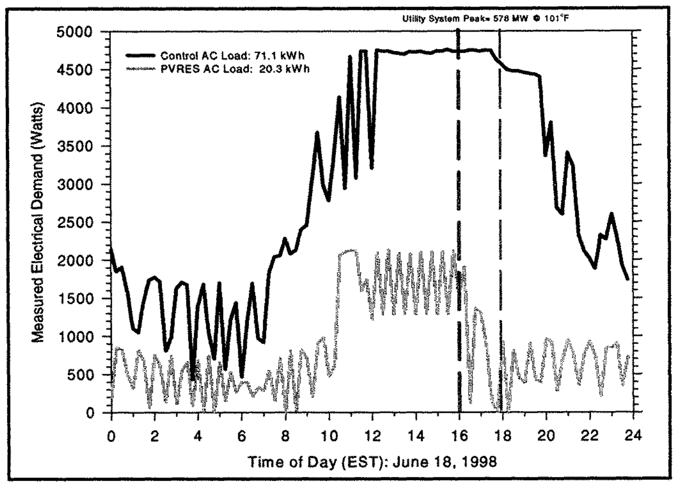

Figure 11. Measured Cooling Energy Use in Control and PVRES House on Utility Peak Day

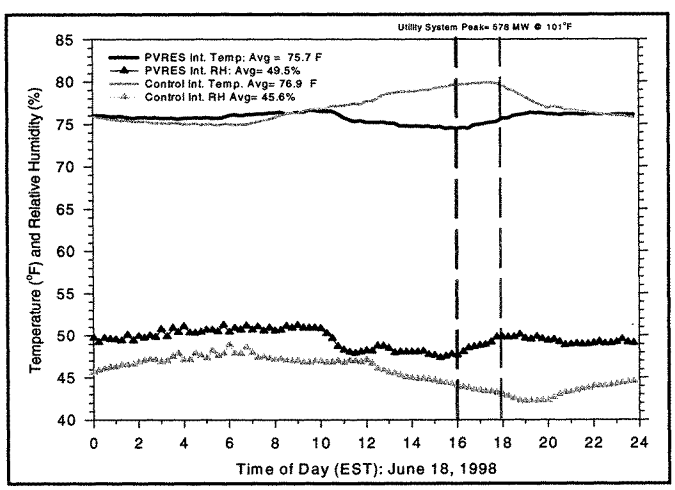

Figure 12. Measured Interior Comfort Conditions in Control and PVRES Homes on Peak Day

79.9°F. Meanwhile, the PVRES home easily maintained 74°F during this with an air conditioner half the size. Both the Control and PVRES homes were able to maintain interior relative humidity below 50%.

The PVRES home is occupied on the peak day while the Control home is not. Even though not comparable, Figure 13 shows that the daily total electricity consumption (33 kWh) in the PVRES home was less than half the air conditioning load alone at the Control. Non-cooling loads at the PVRES home totaled 13 kWh about 40% of total consumption.

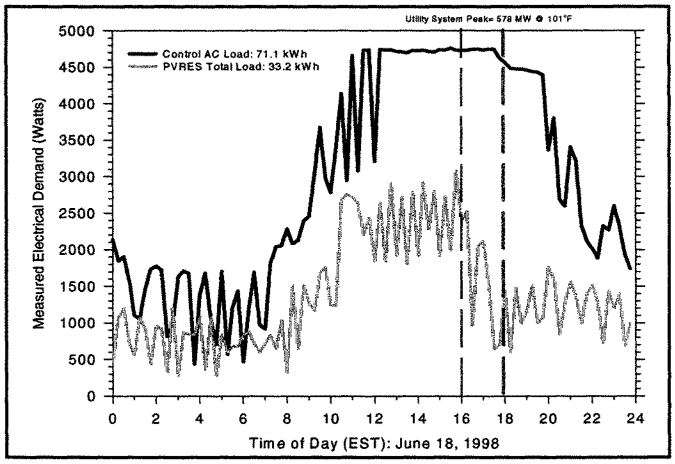

Figure 13. Measured Total Loads on Control and PVRES Homes on Utility Peak Day

Figure 14 shows how solar photovoltaic (PV) power production affects peak day performance. PV electrical generation sent to the grid totaled 15.6 kWh. Most utility electricity use (15.2 kWh) occurred during the evening hours. PVRES net demand during the two hour utility peak coincident period varied around zero. Average peak period PVRES net demand was 225 Watts with a measured average difference against AC use in the Control of 4.5 kW – a peak demand reduction of 95%.

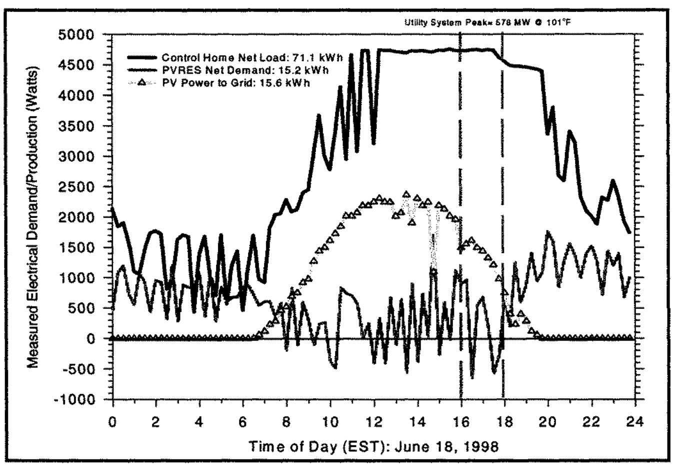

Figure 14. Net utility Loads and PV Power Production in Control and PVRES Homes on Utility Peak Day

Project Economics

The project objective was to explore the maximum feasible energy savings in a new Florida residence combined with PV electric power. As such, the project was not intended to be economic. Nevertheless, the builder did track the cost of the various measures shown in Table 6.

Since measures were combined in a single package, the *DOE-2.1E* building energy simulation (*Energy Gauge USA*) was used to estimate the relative contribution of the various measures. The results are shown in Tables 5 and 6. The simulation worked reasonably well at predicting the relative performance of the two buildings. For the extreme weather conditions seen in June of 1998, *DOE-2* predicted the Control home to use 60.5 kWh per day for cooling against the 61 kWh/day which was measured. In the PVRES home, the model predicted cooling energy consumption of 19.4 kWh/day versus the 15.6 kWh which was measured in June. The model predicted 68% less cooling for the PVRES house in June compared with 74% savings measured.

Table 5. Parametric Analysis of Heating and Cooling Energy Savings

Case	Fan	Heat	Cool	Total Heat	Total Cool	Total	% Cool Reduction
Base	1338	1,068	8,915	1,211	10,093	11,321	0.0
Hi Perf Windows	1,005	619	7,072	700	7,986	8,696	20.9
White Roof	1,115	1,119	7,376	1,266	8,328	9,610	17.5
R-10 Walls	1,297	945	8,539	1,074	9,691	10,781	4.0
3 Ft Overhangs	1,255	1,043	8,271	1,184	9,369	10,569	7.2
House Tightness	1,317	988	8,626	1,123	9,791	10,931	3.0
Duct Tightness	1,207	993	8,101	1,125	9,161	10,301	9.2
Hi-Effic. AC	1,367	319	5,709	391	6,988	7,395	30.8
Interior ducts	1,202	928	7,508	1,060	8,561	9,638	15.2
PVRES (All)	655	347	2,868	418	3,440	3,870	65.9
PVRES w/blinds	606	376	2,673	451	3,192	3,655	68.4

Table 6. Preliminary Economics of Efficiency Measures

Component Description	Cost ($)	Savings kWh ($)	Simple Payback (Years)
Advanced Windows	$ 4,266	1,610 ($129)	33
White tile Roof	$10,829	1,342 ($107)	101
R-10 Walls	$11,500†	307 ($25)	460
Wider Overhang	$ 1,882	537 ($43)	44
Interior Duct System	$ 950	1,150 ($80)	12
High Efficiency AC	$ 1,263	2,376 ($190)	7
Efficient Lighting	$ 525	1,479 ($118)	4
High Effic. Refrigerator	$ 298	388 ($31)	10
Solar Water Heater	$ 2,989	2,097 ($123)	24
Utility Integrated PV System	$40,000	5,600 ($448)	89

† Cost of the wall system was very large due to cost increases associated with a first time installation.

As a technical research demonstration project, a number of the items did not appear cost effective. However, several measures were economically attractive: the interior duct system and a high efficiency air conditioner, high efficiency lighting and refrigeration. Also, it must be pointed out that there are side benefits for some components. For instance a tile roof will have greater longevity than a shingle roof with energy savings a cost-effective by-product. Also, advanced insulated windows will produce a quiet home with rooms less prone to uneven temperatures.

Further, the cost of the measures might be considerably reduced. A fundamental scheme is to use surround porches to keep solar radiation off walls and windows to allow for less rigorous treatment of these building components. Other strategies are to use less expensive white metal roofing and an integrated storage water heater. By such, it would be possible to reduce the incremental cost of the improvements by over $22,000 while preserving performance.

Conclusions

Based on a side-by-side evaluation, energy efficient housing incorporating utility-integrated PV power can reduce total electrical consumption by 70% or more over traditional housing. *Lakeland Electric & Water* experienced their annual summer peak power demand at 5 PM on June 18, 1998. On this day, the occupied PVRES home showed dramatically lower cooling and total electricity requirements than the unoccupied control house. Over the 24 hour period, the PVRES home only used 28% of the air conditioning power that the Control required. During the utility coincident peak period the Control home air conditioner required 2,980 Watts as opposed to 833 W for the PV home – a 72% reduction. Moreover, when the PV electric generation is included during the peak period, the PVRES home net demand was only 199 W – a 93% reduction in electricity requirements over 3 kW required for the control home. The project successfully demonstrated its fundamental objective – the ability to greatly reduce space cooling loads and when matched with PV electric power production, to bring the house utility coincident peak demand close to zero.

Acknowledgments

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