U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Achieving Very High Efficiency and Net Zero Energy in an Existing Home in a Hot-Humid Climate: Long-Term Utility and Monitoring Data

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BA-PIRC

Revised October 2012

Building America

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Achieving Very High Efficiency and Net Zero Energy in an Existing Home in a Hot-Humid Climate: Long-Term Utility and Monitoring Data

Prepared for:

The National Renewable Energy Laboratory

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Office of Energy Efficiency and Renewable Energy

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Contents

List of Figures

Unless otherwise noted, all figures were created by BA-PIRC.

List of Tables

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Definitions

A/C	Air conditioner, air conditioning
ACH	Air changes per hour
AFUE	Annual fuel utilization efficiency
Btu	British thermal unit
CD	Compact disc
DC	Direct current
DOE	U.S. Department of Energy
DVD	Digital video disc
DVR	Digital video recorder
EER	Energy efficiency ratio
EF	Energy factor
EIFS	Exterior insulation finishing system
FSEC	Florida Solar Energy Center
GE	General Electric
Hp	Horse power
HVAC	Heating, ventilation, and air conditioning
kWh	Kilowatt per hour
LCD	Liquid crystal display
MW	Megawatts
MWh	Megawatt hours
Pa	Pascal
PV	Photovoltaic
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
W	Watt
WH	Whole house

A Note About the Revision

Originally published in February 2012, this revised version of the report contains further research conducted on the Parker residence. Key updates include one full year of additional data, an analysis of cooling performance of the mini-split heat pump, an evaluation of room-to-room temperature distribution, and an evaluation of plug-in automobile charging performance, electricity consumption, and load shape.

Executive Summary

This study summarizes the first full year of detailed data collected about a single-family home that experienced a series of retrofits targeting reductions in energy use. The project was designed to develop data about how envelope modifications in heating, ventilation, and air conditioning (HVAC) and domestic hot water and renewable measures can result in considerable energy reductions and potentially net zero energy for an existing home. Using utility billing records and recent detailed monitoring data, this study was also able to chronicle the progress of energy reduction over a 23-year period.

The home featured in this report was built in 1958. The original structure was 1300 ft^2 and comprised two bedrooms and two baths. At some point, a 15,000-gal pool was installed by the original owners. When the current homeowner initially occupied the house, several changes were immediately implemented that substantially cut energy consumption. This resulted in a first year energy use of about 10,000 kilowatt hours (kWh). These immediate changes had a very large impact on consumption—about half the electricity use of a typical home with similar characteristics.

- Removal of carpet to expose tile floor for earth contact cooling
- Insulation of attic to approximately R-19
- Natural ventilation for cooling during spring and fall
- Limiting air conditioning (A/C) from June to September
- Use of ceiling fans and a cooling thermostat setting of 79°F
- Nighttime setback in winter months
- Lower hot water set temperature, tank wrap, and low-flow showerheads
- Reduction of pool pump operation from 8 h/day to 4 h/days in summer and 3 h/day in other months.

The current homeowner purchased the house in 1989. Initial occupancy was two adults.[1] In 1998, the house was expanded to 2,000 ft^2, and occupancy grew to four as the family expanded. Since the purchase in 1989, many improvements and retrofits were installed (detailed in Table 6 in the report). Recently, these included the installation of a 4.9-kW photovoltaic (PV) system (Figure ES-1), high-efficiency windows, exterior wall insulation, and a supplemental ultra-high efficiency mini-split heat pump.

[1] Unfortunately, utility records for the home were not available from the former occupants.

Figure ES-1. 4.9-kW rooftop PV system is connected in February 2009. The white metal roof was part of house improvements in the 1998 remodel.

When the new owners took possession of the house, the envelope was grossly inefficient, even lacking ceiling insulation. Statistics show that with a family of four in a home built before 1960 with a pool, the average electricity use in Florida is about 20,000 kWh/year (Parker, 2002). The net use of electricity (consumption less PV power production) has been less than zero for the last 12 months.

In 2010, the output of the 4.92-kW PV system totaled 7,415 kWh (20.3 kWh/day), which was 190 kWh more than the house used (7,225 kWh). This made for a home that had zero net electricity use but still some net demand in terms of source energy (20 million British thermal units (MBtu)) as natural gas use was still 221 therms.

In 2011, the output of the PV system totaled 7,197 kWh (19.7 kWh/day), which was 766 kWh more than the house used (6,431 kWh or 17.6 kWh/day). This level of surplus was achieved even after a plug-in hybrid car was added in September 2011. Electrical charging of the car used 568 kWh over the balance of the year—about 5 to 6 kWh per day. Most of the drop in electricity use came from the better windows, insulation, and mini-split A/C, which reduced A/C use significantly. Experiments were also run showing the large differences in the energy use of the mini-split A/C versus the central system as well as the room-to-room temperature achieved.

There was also a sharp drop seen in natural gas consumption in winter 2011 as the improved windows and wall insulation allowed the use of the mini-split for all space heating and discontinuation of the gas heating system. Thus, consumption in the year was cut to only 84 therms versus 221 therms in 2010.

Figure ES-2 shows that the 12-month moving average of source energy consumption in the home had been reduced by 90% to only 1 million Btu/month. Compared to average homes of the same type and vintage, the reduction is more than 95%. *In 2011, the home achieved zero net source energy (in fact, a -0.39 million source Btu surplus) in the calendar year. The additional 766 kWh offset the natural gas use when the comparative generation effectiveness to produce the offset electricity is considered.*

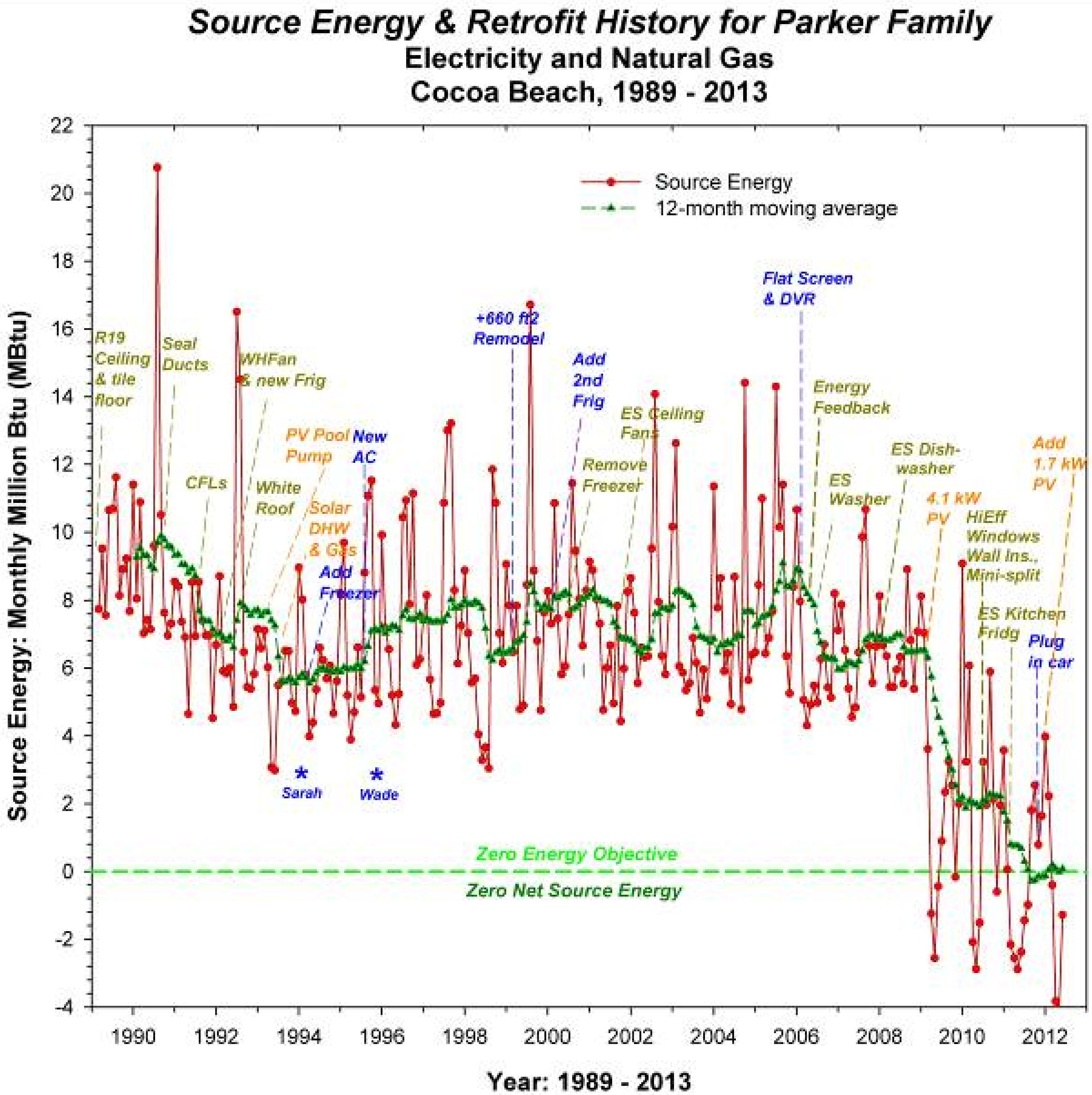

Figure ES-2. Changes in source energy use over the 23-year period of home occupancy. Green triangles are the 12-month moving averages. Source energy use has dropped by about 90% over the period.

In the first five months of 2012, the plug-in-hybrid used an average 5.35 kWh per day for charging it for the 23-mile daily commute. On February 8, an additional 1.68 kW was added to the final capacity of the PV array. This increased PV energy is reflected in the increased daily average production of 25.50 kWh/day from January–May. During this time, the total average household electricity use averaged 18.75 kWh/day. With gas consumption remaining approximately 0.25/therms per day, the house should again show a zero source energy balance in 2012.

1 Introduction

This report summarizes the first and second years of detailed data collection about a single-family home in Cocoa Beach, Florida (Figure 1). The study is intended to demonstrate the potential of deep retrofits for achieving zero net annual energy with an existing house. We also analyze the 23-year utility bill history over the long period when retrofits were made to the home. This project was designed to develop data to evaluate how efficiency and renewable measures can result in deep energy reductions and potentially zero energy for an existing home. Results demonstrate that useful verification of deep energy reductions can be obtained from the detailed monitoring as well as from utility records.

Figure 1. The home as it appeared when purchased in 1989

2 Importance of Improving Existing Florida Housing

Currently, the residential sector in the Florida uses approximately 1.025 quadrillion Btu of site energy per year; this amounts to fully 5% of all residential energy use in the United States. Florida's residential electricity demand per capita is among the highest in the country, largely because of high A/C use during the hot summer months and the widespread use of electricity for winter heating.

Based on 2008 data, total summer electrical generation capacity exceeds 59,000 megawatts (MW) and annual consumption exceeds 218 million MWh. Both are the third highest of any state in the nation, surpassed only by California and Texas (U.S. Energy Information Administration, 2009a). Florida households consumed fully 52% of all state electricity production and strongly depend on increasing cooling electricity use (U.S. Energy Information Administration, 2009b). Further, supplying energy to the residential sector in Florida is responsible for most of its annual greenhouse gas emissions (115 million metric tons from electric generation alone). Despite technological improvements in refrigerators, A/C efficiency, and energy codes improving insulation, Florida lifestyle changes have placed higher demands on appliance and cooling resources. The reasons are numerous.

Homes built in Florida have increased significantly in size, from an average 1500 ft^2 in 1970 to approximately 1900 ft^2 in 1993 and 2300 ft^2 in 2006 (Shimberg Center for Housing Studies, 2009). The two-person household in a large home has become more common, as has central A/C. In 1960, only 18% of Florida households had A/C, although this increased to 60% by the 1970 census. Moreover, more of the home is being conditioned: just 3% of Florida households had central A/C in 1960 against 38% of Florida households in 1973 at the beginning of the first energy crisis (Schrock et. al., 1975). However, by 1993, that figure rose to more than 98% (Shimberg Center for Housing Studies, 1994). Against that trend, recent analysis of the U.S. Department of Energy's (DOE) Residential Energy Consumption Survey data has shown that central cooling and heat pump systems (as opposed to zoned window or wall systems) are correlated with considerably higher space conditioning energy use in spite of higher machine efficiencies (Steemers & Yun, 2009). Almost 95% of the supply cooling ducts are located in the attic space, leading to large cooling leakage and conduction losses for central systems.

Moreover, the state's housing is very dependent on electricity for nearly all residential energy needs. Fully 87% of the state's homes are electrically heated and about 90% of water heating is electric as well (U.S. Census Bureau, 2011a). The saturation of electric cooking and clothes drying is even greater.

Also, miscellaneous electric end uses in Florida households since 2000 have been rapidly expanding, largely offsetting efficiency gains in the conventional end uses of heating, cooling, and water heating (U.S. Energy Information Administration, 2011). Although not existing before 1978, home computers are now ubiquitous in American households. For instance, the first high-definition digital video recorder (DVR) shipped in 1999; by 2009, 43% of U.S. households had them—an appliance that draws approximately 20–32 Watts (W) even when off and uses half as much electricity as a modern refrigerator (Natural Resources Defense Council, 2011 June).

Similarly, in 1978, the average household had one television. By 2009, the average home had three and often with much larger screen sizes and power levels (Parker & Fairey, 2009). There are approximately 8 million residential dwellings in Florida—6 million of them detached single-family homes—with many of the structures of varying vintages (U.S. Census Bureau, 2011b).[2] For instance, about half of these homes were built before 1990 when building codes began to be significantly improved. Since the construction slowdown in 2007, the emphasis on improving existing homes to realize energy savings has been emphasized. One question that emerges, however, is how energy use in existing Florida homes, particularly older ones, can be realistically reduced through energy efficiency. As newer homes have been thermally improved with better machines and appliances—in most cases due to the energy codes (with the notable exception of windows)—older existing buildings in Florida represent an attractive resource for potential statewide energy reductions.

Over the last 22 years the Florida Solar Energy Center (FSEC) has emphasized finding ways to dramatically improve the energy efficiency of homes in the United States, particularly those in Florida's challenging hot-humid climate. Given FSEC's emphasis on practical empirical research, much has been learned about how to reduce residential energy consumption using a variety of technologies and techniques (e.g., reducing duct losses, high performance fenestration products, reflective roof/wall surfaces, and advanced HVAC equipment). However, a detailed investigation into the cumulative effects of these measures has not been performed.

In 1991, FSEC began simulation work to see if it might be possible to design extremely efficient homes and match them with residential PV to realize an imagined apex of efficiency with renewable resources—houses that produced as much energy as they used (Parker & Dunlop, 1994). In 1998, an attempt to realize that goal resulted in the construction of a "zero energy home" (before the moniker existed) in Lakeland, Florida. The house received much attention, which led to questions about whether this level of performance could be achieved in existing homes. Accordingly, a primary research goal for this project was to develop expertise in the evaluation of such potential in an existing home. Other goals included:

- Gain experience with the processes involved in residential monitoring of an occupied existing home in a cooling-dominated climate to demonstrate the ability to dramatically drop loads.
- Demonstrate the ability to use either utility bills or detailed monitoring data to show progress from improvements.
- Acquire cooling, heating, and appliance load shape data and examine how these are modified by retrofits.
- Investigate other aspects affecting residential energy use in an occupied home and what they might reveal about efficiency improvements for existing Florida housing.
- Document deep energy reductions for the Affordable Comfort Inc. Thousand Home Challenge.[3]

[2] The six million total includes manufactured homes.
[3] This project's energy use for the period April 2010–March 2011 meets its *Thousand Home Challenge* threshold allowance (OPTION B). It will officially meet the *Thousand Home Challenge* when the application is completed.

3 Building Description

The monitored building is a single-family detached structure with a rectangular footprint totaling approximately 1800 ft^2; of that total area, 1300 was conditioned living area, The house has an attached single car garage (200 ft^2) and an enclosed south porch or Florida room (300 ft^2).

In 1998, the house underwent a remodel that added 660 ft^2 living space and converted the Florida room to conditioned area. This brought the total conditioned area to 2000 ft^2. Figure 2 illustrates the residence's general configuration and orientation. The house faces north-south and is located two blocks from the Atlantic Ocean in Cocoa Beach, Florida. The floor consists of slab-on-grade without carpeting (terrazzo). Built in 1958, the building was highly representative of construction techniques and practices of that era (wall and ceilings are devoid of insulation and windows were single glazed, awning style).

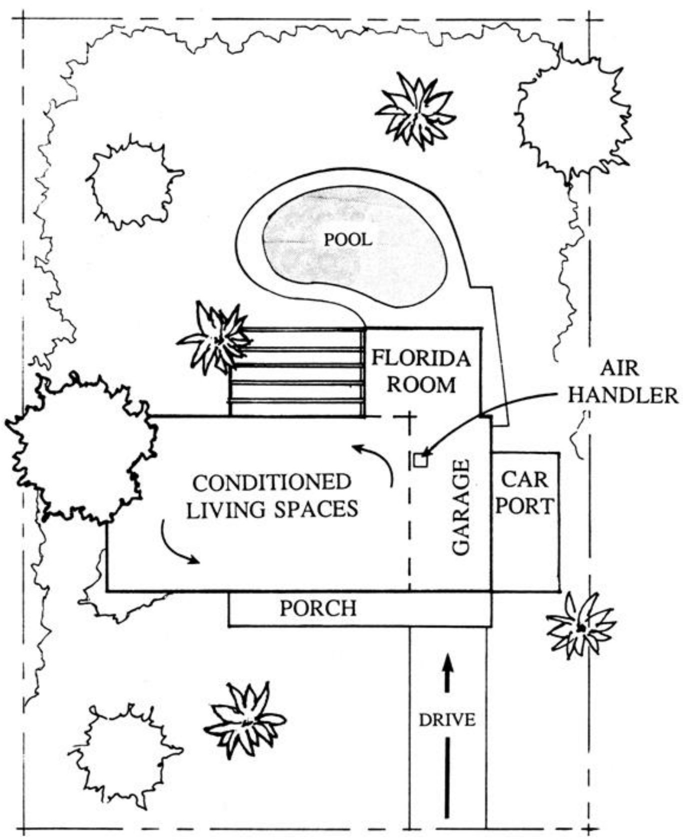

Figure 2. Lot and floor plan schematic for house in 1989

Approximately 7 in. of fiberglass insulation was blown into the attic immediately after occupancy. The attic space was ventilated by soffit vents and two rooftop rotary ventilators. The garage does not have a ceiling and is directly exposed to the roof decking. It is also directly connected to the attic space over the living area. The house was fairly well shaded by a tree on the east face; a 15,000-gal outdoor swimming pool is situated on the south side of the building.

4 Initial Measures: Exposure of Tile Floor, Ceiling Insulation, and Reduction of Pool Pumping

When the house was purchased, all carpet was removed to expose terrazzo flooring underneath in an attempt to take advantage of the slab's thermal mass cooling effect (Figure 3). Benefits to terrazzo or tile flooring include:

- Tile flooring typically is 4°–5°F cooler than the space in the spring months, providing free cooling (Figure 3). Given standard heat transfer rates, this results in a free cooling rate of approximately 0.5 tons (5000–8000 Btu/h) under spring conditions.[4]
- Reduced exposure to indoor allergens, dust mites, and fleas (Chandra & Beal, 2002).
- Given the subtropical location, bulk moisture is more readily removed. This greatly reduces the incidence of mold and mildew issues.

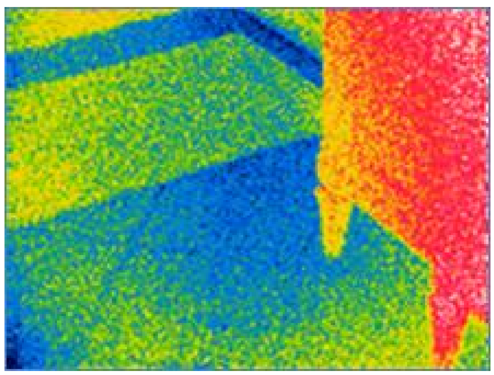

Figure 3. Thermographic image of the thermal influence of the floor on space cooling needs. Color is proportional to temperature with the furniture at approximately 79°F. The tile floor is about 5° cooler with the throw rug surface between.

Within two weeks of taking occupancy of the home, insulation was added to the attic of the home. The existing attic floor was completely uninsulated. Seven inches of blown fiberglass was blown into the attic in February 1989 at a cost of $254. This achieved an R-value of approximately R-19/h/ft^2/Btu.

Pool pumping hours (Figure 4) were reduced by more than 50% (3–4 h/day seasonally versus 8 h/day), based on research showing this is an adequate time for pool circulation (Messenger & Hays, 1982).

[4] However, later summer warmer soil temperature conditions argue for more detailed full year data.

Figure 4. Pool pump timer. Immediately after taking over the house, this was set from 8 h/day to only 3–4 h/day, saving an estimated 2000 kWh annually

One apparent question from examining the early utility data for the home was the low level of electric energy consumption—only about 10,000 kWh in the first year of occupancy. How can a consumption level, half of that typical, be understood? A partial explanation comes from evaluating how the home was operated differently from a standard home and the collection of measures that were instituted immediately upon taking occupancy.

To illustrate, a building energy simulation model was created for the home using EnergyGauge USA. The predicted consumption of the home with its initial characteristics prior to occupancy was 20,598 kWh. The model was then altered to reflect the actual energy reduction strategies incorporated by the new homeowners. Those strategies and their cumulative effects are as follows:

- Reduce pool pump hours by two thirds: 18,598 kWh.
- Reduce hot water consumption to 45 gal to reflect a two-person household with low-flow shower heads, external tank wrap: 17,826 kWh.
- Use natural ventilation and limit cooling season to June–August, inclusive: 14,506 kWh.
- Set back thermostat at night in winter: 14,111 kWh.
- Remove all carpet to expose tile floor: 13,824 kWh.
- Add R-19 ceiling insulation: 13,110 kWh.
- Alter cooling setting to average 79°F from 78°F: 12,843 kWh.

Although still somewhat higher than the first year utility billed consumption, the evaluation clearly shows that the change in pool pump operation and the comfort-related compromise to limit the cooling season had very large impacts on the consumption in the first year. Some of the overprediction is likely associated with less dryer, dishwasher, range, and miscellaneous electric use with a two-person household as well a conservative behavior relative to lighting and other such loads.

This evaluation also suggests that homeowner adoption of an energy-conserving lifestyle (or conversely unwillingness to adapt) can have major impacts on real home electricity use. Such adaptation can often compromise the reputation of efficiency, because comfort can be adversely affected. Also, some effort and vigilance is required to achieve the best results.

5 Audit Evaluation and Infiltration Characteristics

Because a single building is monitored, a before-and-after experimental design was used to evaluate the impact of retrofits. The prime advantage of the before-and-after design is that there is little introduced variation due to occupancy behavior, assuming that lifestyle remains constant during the monitoring period. However, it must be admitted that the addition of two additional occupants (children) provided strong upward pressure on consumption levels. Thus, stable energy use during this period can be looked on as a favorable result. Detailed monitoring began in November 2010. Monthly utility bill data collection has been ongoing since the house was occupied in 1989.

The house was audited according to an established protocol for existing residential buildings (Ternes, 1987). The audit examines all the characteristics of the building that may be related to energy use along with the contained equipment that uses electricity or other fuels.

In 1990 and 1991, detailed submetered data were obtained about interior temperatures and weather conditions to evaluate replacement of the old, pre-existing refrigerator, to examine the potential of duct sealing and to examine how a whole-house (WH) fan might help reduce household cooling needs.

A series of tests was also completed to establish the airtightness of the structure, before and after duct leakage repair. This consisted of blower door fan-pressurization tests and sulfur hexafluoride (SF_6) tracer gas tests to determine the house air infiltration characteristics. The latter test was completed, both with the house exposed to local weather only as well as with the air handler powered. The infiltration test results are described in Table 1.

Table 1. Infiltration Tests of the Monitored House

Test	Test Results
Blower Door Air Change Rate @ 50 Pa*	9.3 ACH**
% of Leakage in Duct	18.2%
Tracer Gas Tests	
Natural Air Infiltration	0.58 ACH
Air Handler Operating	0.86 ACH
Return Leak Fraction	9.7%

* Pascal
**Air changes per hour

In 2010, the blower door tests were repeated for the home, which had become much leakier in the meantime—growing to 24 ACH @ 50 Pa pressure. The large increase in house envelope leakages were subjectively observed to be associated with:

- Awning windows that no longer closed properly
- Added recessed can lights in the kitchen area that leak
- Bathroom fans that are undampered.

As will be seen, the retrofit of the windows done in the summer of 2010, made very large changes to the building overall leakage.

6 Space Conditioning Equipment

The original space conditioning system in 1989 consisted of an aging seasonal energy efficiency ratio (SEER) 10.0 2.0 ton Sears Climate Master water-to-air heat pump using aquifer well water. The A/C and air handler were located in the west-facing single-car garage. The air distribution system consisted of approximately 60 ft of R-5 rigid-fiberglass ducts passing through the unconditioned attic. A total of seven supply registers provided conditioned air to the house interior.

The relative performance of this cooling system was poor compared to newer, more efficient units. Maximum compressor current power draws approximately 4,370 W. The measured cooling capacity under minimum capacity conditions (67.4°F dry bulb) was 20,884 Btu/h, corresponding to an energy efficiency ratio (EER) of 5.2 Btu/W. The measured before and after coil enthalpy showed a 18°F temperature drop across the evaporator when in cooling mode under normal summer conditions. Capacity at 88°F outside temperature was measured at 28,478 Btu/h or an EER of 6.5 Btu/W.

A four-day test of the A/C thermostat performance was performed in 1991 beginning on July 16 with a separate data logger to characterize its operation. The tests revealed an average summer A/C runtime of 27% and an average interior relative humidity of 60%.

In June 1995, a new SEER 10, two-ton A/C was installed (Figure 5). Air handler and outdoor unit power were approximately 2,800 W at 92°F and constant run. For two years prior, the household had used a whole-house (WH) fan for summer cooling and suffered through the cooling season in a failed effort to see if comfort could be achieved without A/C. An annual fuel utilization efficiency (AFUE) 78% natural gas furnace was installed in January 1993.

Figure 5. Outdoor unit for SEER 10, 2-ton A/C installed in 1995 and still in use

In October and November 2010 a 0.75-ton SEER 26.0 mini-split heat pump was centrally installed for experimental evaluation.

7 Instrumentation

There have been two periods when the house was instrumented: in 1991–1993 and then in much greater detail in November 2010. Below, we describe the more recent instrumentation effort.

The installed instrumentation in September–October 2010 consisted of a total of 29 measurements considered important to document research results (Table 2). Site weather data are gathered on temperatures, relative humidity, and insolation. Temperature, humidity, and power consumption measurements are taken on the interior of the building.

Table 2. Monitoring Dataset

Monitoring Data Parameter	Units
Outside Air Temperature	°F
Garage Air Temperature	°F
Return Air Temperature	°F
Supply Register Temperature	°F
Slab Floor Temperature	°F
Attic Air Temperature	°F
PV Array Temperature	°F
Indoor Temperature by Thermostat	°F
Indoor Temperature In Kitchen	°F
Ground Temperature (1 Ft Depth)	°F
Tile Surface Temperature	°F
Water Inlet Temperature	°F
Solar Hot Water Outlet Temperature	°F
Outlet Water Temperature From Instantaneous Gas Water Heater	°F
Single-Ended Voltage Measurements	
Pyranometer (Horizontal Rooftop)	W/m^2
Pyranometer (Plane of PV Array)	W/m^2
Ambient Relative Humidity	%
Interior Relative Humidity (Thermostat)	%
Interior Relative Humidity (by Kitchen)	%
Electric Power Measurements	
Household Total Power	Wh
Central A/C Watt-Hours	Wh
Mini-Split Watt Hours	Wh
Refrigerator Watt-Hours (Kitchen Refrigerator)	Wh
Refrigerator Watt Hours (2nd Refrigerator in Garage)	Wh
WH Fan Power	Wh
Gas Measurements	
Furnace (ft^3)	ft^3
Clothes Dryer (ft^3)	ft^3
Oven/Range (ft^3)	ft^3
Instantaneous Tankless Water Heater (ft^3); Auxiliary for Solar	ft^3

Type-T copper-constantan thermocouples were used to record air and surface temperatures. Vaisala resistance temperature detector probes were used to measure interior temperatures and relative humidities. Measurements of tile and earth temperatures were made using double-ended thermocouples. Single-ended thermocouples were used for most other measurements. Insolation was measured using a silicon-cell pyranometer with a current output. Electrical consumption was recorded using pulse-initiating power meters. Gas consumption was measured using four positive displacement pulse-initiating gas meters (Figure 6).

Figure 6. Multiple pulse initiation gas meters to measure gas end use

8 Analysis of Savings From Duct Repair

An objective of the early monitoring in 1990–1992 was to ascertain the effect of duct repair on the house A/C demand. The experiment began in July 1992. Two weeks of 15-minute data were collected with the A/C and duct system in an as-is configuration.

After another three weeks, the duct system was sealed with mastic on August 27, 1992 (Figure 7). The initial 18.2% duct leakage was reduced to 5.3% measured leakage. Blower door testing before and after the duct repair showed that 71% of the measured duct leakage area was sealed. The A/C consumption was then monitored for another two weeks. Data showed that the garage temperature where the duct plenum was located had the most pronounced influence on hourly A/C demand.

Figure 7. A/C evaporator and plenum showing segments sealed with mastic

The duct repair did show major savings in A/C energy use. The strongest correlation of cooling compared the interior temperature to that in the garage where the air handler was located. As shown in Figure 8, the duct repairs reduced A/C use by about 19% for a group of days with similar interior-exterior temperature differences (interior temperature was measured by the thermostat).

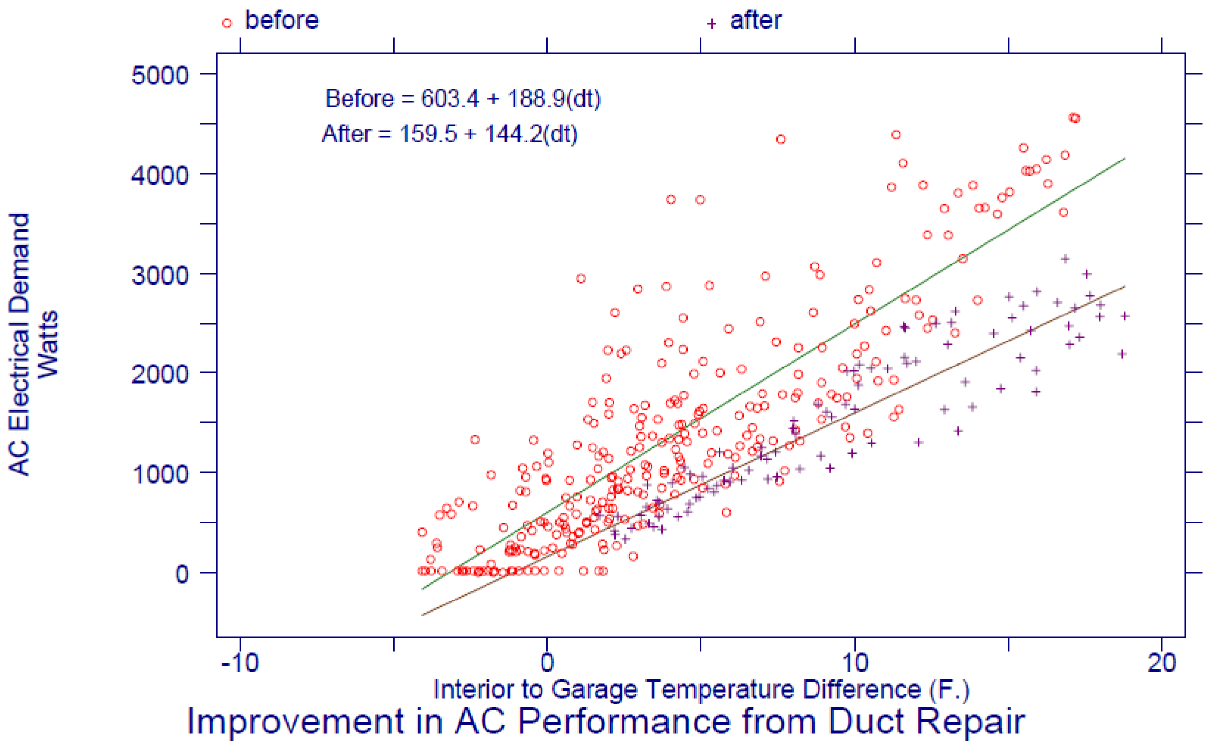

Figure 8. Hourly A/C demand before and after duct leakage repair, plotted against interior to garage temperature difference in 1992

This result compares favorably with the 17% savings realized in 46 homes with duct systems that were repaired in a similar climate (Cummings, Tooley, & Moyer, 1991). The data collected for the single house are summarized in Table 3.

Table 3. Daily A/C Electricity Consumption Before and After Duct System Repair in 1992

Case	Number of Days	kWh/Day	dT (°F)
Before Repair	6	45.5	5.15
After Repair	4	36.7	5.83
Difference		8.8 (19% reduction)	

9 Refrigerator Retrofits

A total of four refrigerators have been utilized in the home over the 23-year period of monitoring. Part of the high turnover rate comes from the beach environment, which promotes rust. However, a larger explanation was the growing household size in the 1990s.

The original kitchen refrigerator (Figure 9) was in service for approximately 15 years before the house was purchased. The unit was a 19.2-ft^3 frost-free Sears Coldspot refrigerator-freezer with an automatic ice maker and a water dispenser. Monitoring showed its summertime utility peak hour (5:00 p.m. to 6:00 p.m.) electricity demand to average approximately 303 W with annual consumption of about 2,510 kWh—a very substantial end-use of electricity in the home. Based on monthly utility bills from the monitored house when occupied, the initial refrigerator represented more than 25% of the total annual electrical use in the home.

Figure 9. Original kitchen refrigerator in 1990

This estimate is in line with another monitoring study in Florida in the 1980s, which found the average annual use for each monitored refrigerator-freezer was 2,361 kWh (Messenger et al., 1982). Refrigeration in that study accounted for 15% of overall residential electrical consumption.

Refrigeration electricity consumption was measured in detail prior to replacement. Consumption was metered for an entire year from June 1990 to June 1991 at a 15-minute resolution. Both kitchen refrigerator and freezer temperatures were collected as well as recorded door openings. The existing refrigerator was replaced in July 1991 with the most energy-efficient model of its size possessing the consumer desirable amenities (automatic ice maker, automatic defrost), a 1991 Frigidaire FPES19TIP (Figure 10). This model had a DOE estimated annual energy use of 760 kWh.

Figure 10. Replacement refrigerator in August 1991

The upper plot in Figure 11 depicts the electricity demand of the original refrigerator over the month of June 1990. Even with the scatter, a time-of-day use pattern for the refrigerator is apparent; electricity demand is highest at 6:00 p.m. after dinner preparation. The lower plot in Figure 11 plots the load shape for the first month of data collected on the more efficient refrigerator. The average electricity demand is reduced by more than half (287 versus 122 W), although the newer refrigerator appears to use more electricity (300 kWh/year) than the DOE test predicts. Parker and Stedman (1992) provide a full description of the original replacement study.

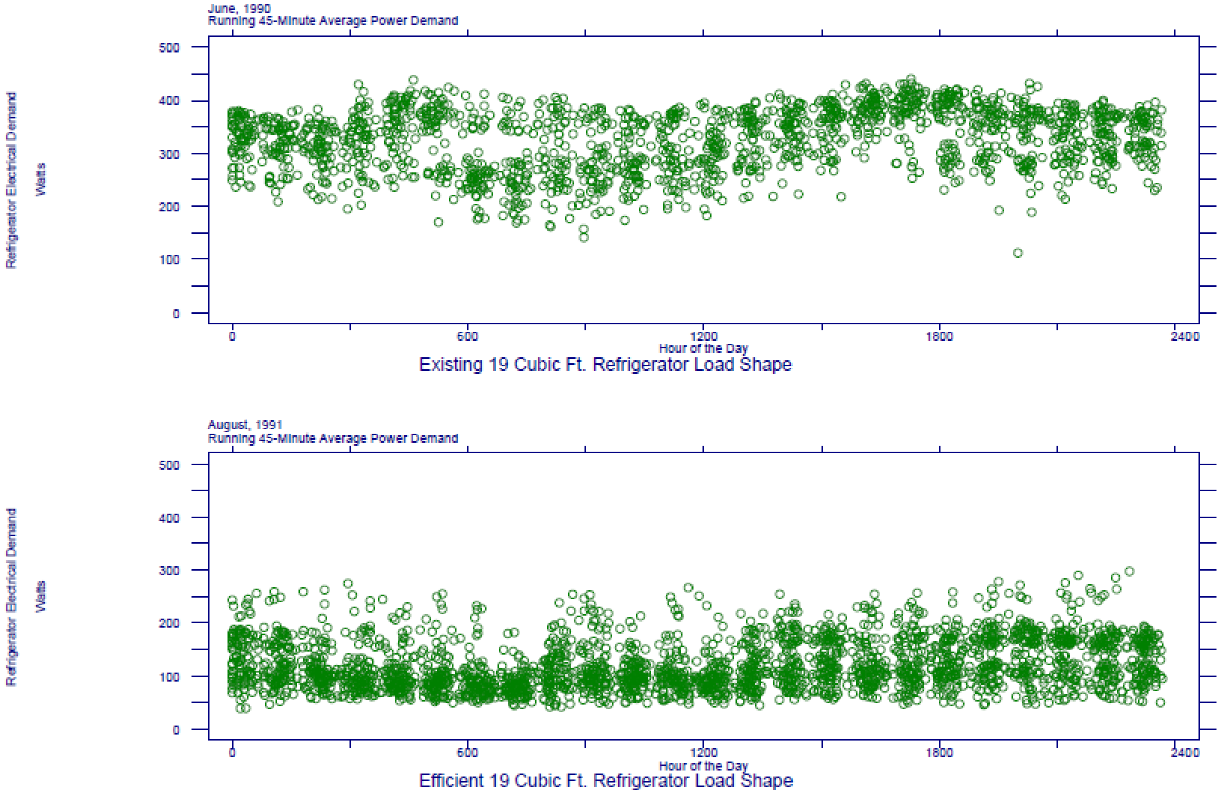

Figure 11. Month of June 1990, showing the measured 15 minute W of the original refrigerator. The lower plot month of August 1991 shows the power of the replacement more efficient refrigerator.

10 Impact of Cleaning Refrigerator Coils

In 1998 during the house remodel, a side-by-side 25-ft^3 unit, with an Energy Guide label of 777 kWh (2.12 kWh/day) was installed. Coils are in the bottom of the refrigerator and discharge out the front. Figure 12 shows an infrared image of the front discharge. In the initial data stream, we had about five days pre and post the coils being vacuumed on September 22 at 5:00 p.m. It took about half an hour to clean the coils, which were completely faced over with dust and dirt.

Figure 12. Infrared image of 25-ft^3 refrigerator showing heat rejection at the base of the unit, but also warm temperatures near through the wall ice and water access. The unit was using 4.4 kWh/day prior to replacement in January 2011.

Prior to cleaning, consumption was 4.37 kWh/day, which was quite high. After cleaning, consumption was better, but still high: 3.90 kWh/day—a reduction of 0.44/ kWh/day or 11%, but far from the rated performance for this unit (2.12 kWh/day). This is virtually identical to the 12% saving (0.36 kWh/day) we measured from coil cleaning in eight Habitat homes in 1997 (Parker et al., 1997). Still the kitchen refrigerator needed replacing as there are several units available today with similar features that use less than 1.5 kWh/day.

In the plot below (Figure 13), we can see that the unit has shorter compressor run times after cleaning, as one would expect. The vertical red line at Julian Date 265.75 is the point where the coils were cleaned. The values around 200 W show the compressor power; the occasional 500 W values are the activation of the resistance heaters for the periodic freezer section defrost cycle.

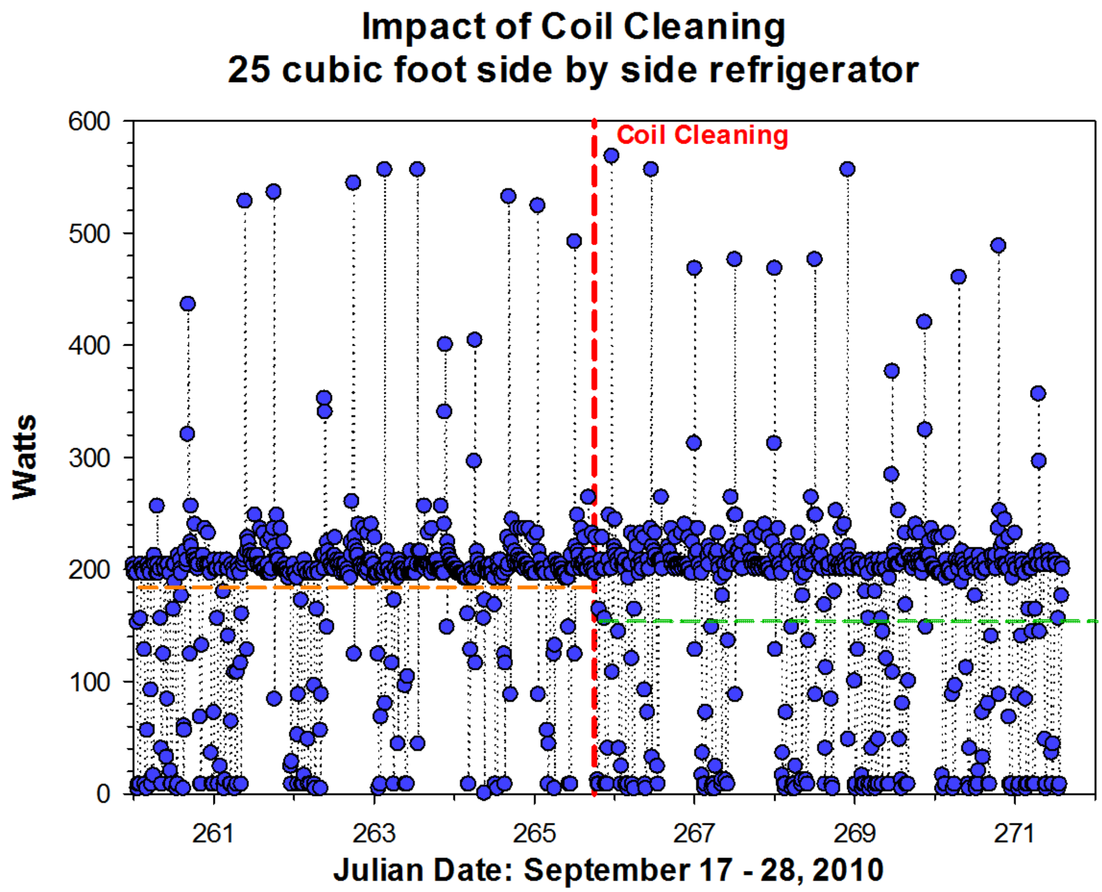

Figure 13. Kitchen refrigerator power before and after coil cleaning on September 22, 2010. Orange line is average power in days before cleaning (182 W); green line is average power after (165 W). Energy reduction is about 10%, but daily power use (3.96 kWh) is far above rated performance for the refrigerator (2.12 kWh/day) later replaced in January 2011.

10.1 New Kitchen Refrigerator

The side-by-side kitchen refrigerator was replaced with a General Electric (GE) Profile 22.2 ft^3 French Door Bottom Freezer Refrigerator (PFSS2MJY) on January 8, 2011 (Figure 14). The unit has an estimated annual energy use of 463 kWh/year (1.3 kWh/day). Figures 14 and 15 show the unit and Energy Guide label, respectively.

Figure 14. Kitchen refrigerator installed in January 2011

Figure 15. Energy Guide Label for new bottom freezer ENERGY STAR GE refrigerator

10.2 Detailed Monitoring of Refrigerators in 2011

In early shakedown monitoring from September 17–23, 2010, we saw that the new kitchen and garage refrigerators were using substantial electricity. For example, it looked like spending $3000 on two new refrigerators could save more than the anticipated insulation and window retrofits. Estimated savings from this would be about 1500 kWh/year or ~$180.

The garage and kitchen refrigerators in autumn 2010 were measured to use almost exactly the same electric power at 4.3 kWh/day each (>1,500 kWh/year). These were judged ready for replacement as there are now models of 26-ft^3 models now using less than 500 kWh/year.

The kitchen refrigerator that was replaced in 1991 used considerable electricity: 2510 kWh/year. There are certain to be many of those in Florida in need of replacement. Many of them have compressors that run constantly at 200 W (which is about 2600 kWh), and a simple test with a Kill A Watt meter over a two-day period may be the single most important retrofit test to be conducted in homes by auditors. The potential for savings by replacing such units is illustrated by what we found at a comprehensive retrofit site in 1995—an existing indoor refrigerator that was measured to use 3,040 kWh/year (Parker et al., 1997). We replaced it with an efficient unit using 849 kWh—the single largest saving measure in the project.

In our climate the consumption is certain to be 20%–30% more than the DOE label value (higher kitchen temperatures in Florida directly increase consumption). Note too that these refrigerators are not the worst possible models. The unit in the garage of this report's study home was the interior refrigerator (1991) vintage. Located inside in that year, it was measured to use about 2.1 kWh/day or 760 kWh in 1991–1992. Now almost 20 years later and located in the garage, the same refrigerator is using 4.4 kWh/day in summer or 1600 kWh over the year if that continued (Parker & Stedman, 1992).

The newer indoor refrigerator—installed in 1998 (Kenmore 5756079)—has a DOE label estimated energy use of 777 kWh/year. However, over the week of September16–23, it used 4.3 kWh/day—the equivalent of 1,570 kWh per year. Although consumption is certain to be less in winter, before replacement, both of the refrigerators would likely use about 1300–1400 kWh/year each, which is largely disadvantageous for an effort to reach a zero energy home design.

As a first step, the kitchen refrigerator was replaced in January 2011.

Measured electricity in Figure 16 shows detailed monitoring of the new refrigerator compared with the older unit in the garage in April of 2011. Figure 17 shows the average power demand profile of the two refrigerators over the 24-hour cycle from January 2011 through January 2012. Note that the new kitchen replacement unit uses only half the electric power of the garage refrigerator despite being 10% larger in interior volume. The Energy Guide label shown on Figure 15 indicates a rated energy consumption of 463 kWh/year. However, we measured 595 kWh—28% higher than suggested by the label and in keeping with previous observations that energy use of refrigerators in warm climates are often 20% higher than the DOE labels.

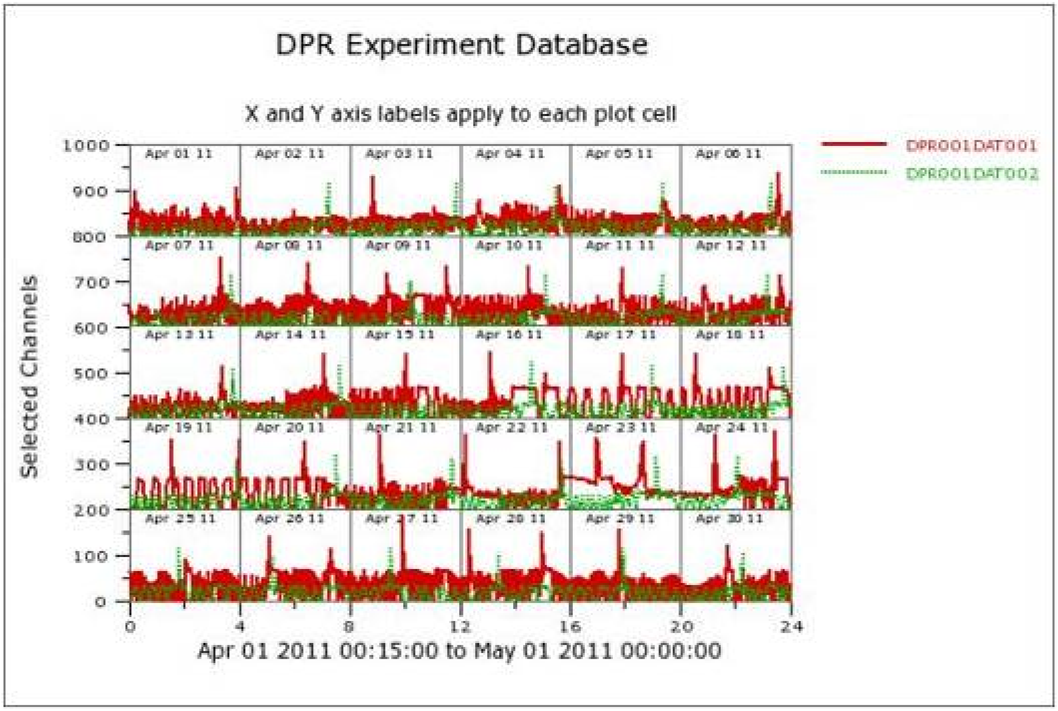

Figure 16. Calendar plot of measured garage refrigerator power (red) and new kitchen refrigerator (green) in April 2011 showing power and periodic defrost cycles. Y-axis is Watts (0–1000).

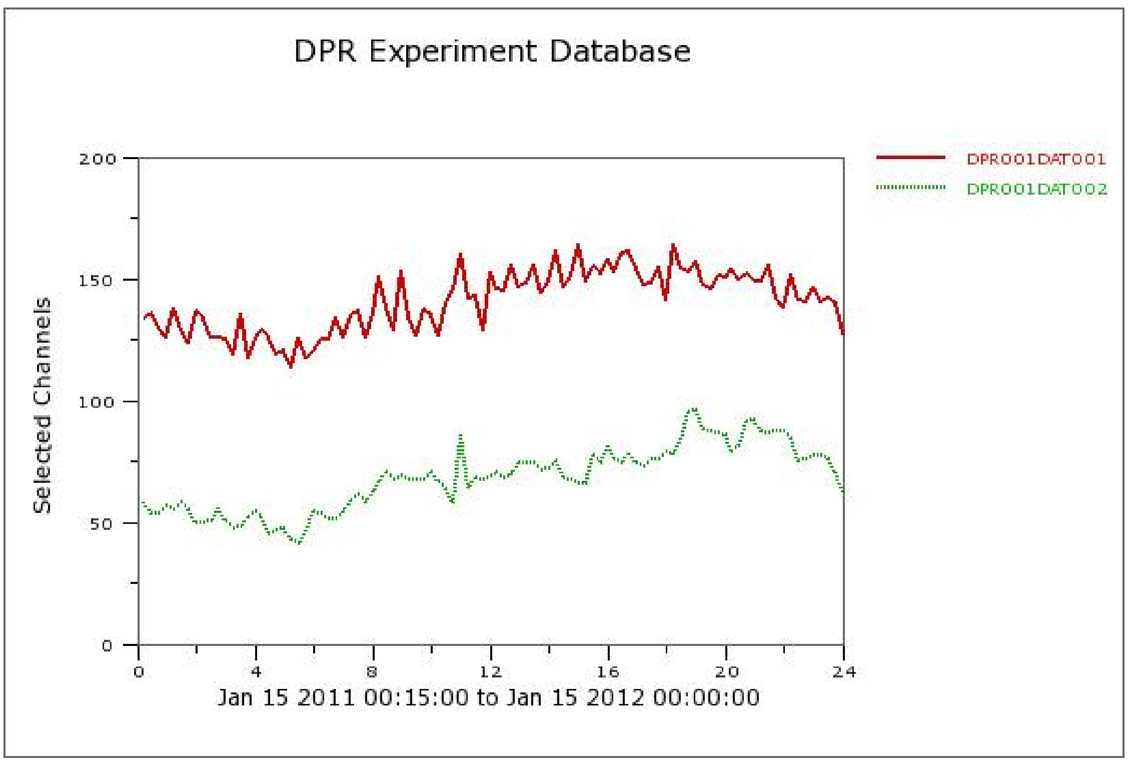

Figure 17. Average measured garage refrigerator power (red) and new kitchen refrigerator (green) draw profile by time of day. The average power demand for the 24 h is shown on the X-axis (January 15, 2012). Y-axis is Watts (0–200). Average daily power seen was 3.38 kWh/day for the garage refrigerator and 1.63 kWh/day for the new ENERGY STAR kitchen model.

Because refrigeration is so important in Florida homes (and important for energy-reducing retrofits), how they interact with thermostat set point, refrigerator location, and their internal gains is important to understand and account for. Also, their electricity use will vary with the season whether cooling or heating (something that might be useful to eventually model).

A common idea would be to get rid of the outdoor refrigerator. However, this is not really feasible in our household. Lots of Florida houses have second refrigerators (the saturation is 1.2 per household): We have two, and with two teenagers, these get a lot of use. In colder climates, a pantry can hold wine, crackers, cookies, bread, and flour, but in Florida, such items would spoil without cooling.

10.3 Garage Refrigerator Performance

Although the kitchen refrigerator in the home was replaced with a new ENERGY STAR model, the old refrigerator (1991 vintage), which was efficient 20 years ago, now uses much more electricity than it did previously.

As seen in Figure 18, the indoor 24-ft^3 refrigerator (green) used 2.4 kWh on April 23, 2011, whereas the garage model (red) used 6.4 kWh, and the compressor never turned off (~250 W). Red spikes are defrost cycles. A single defrost spike for the indoor unit can be seen at 19:00 hours.

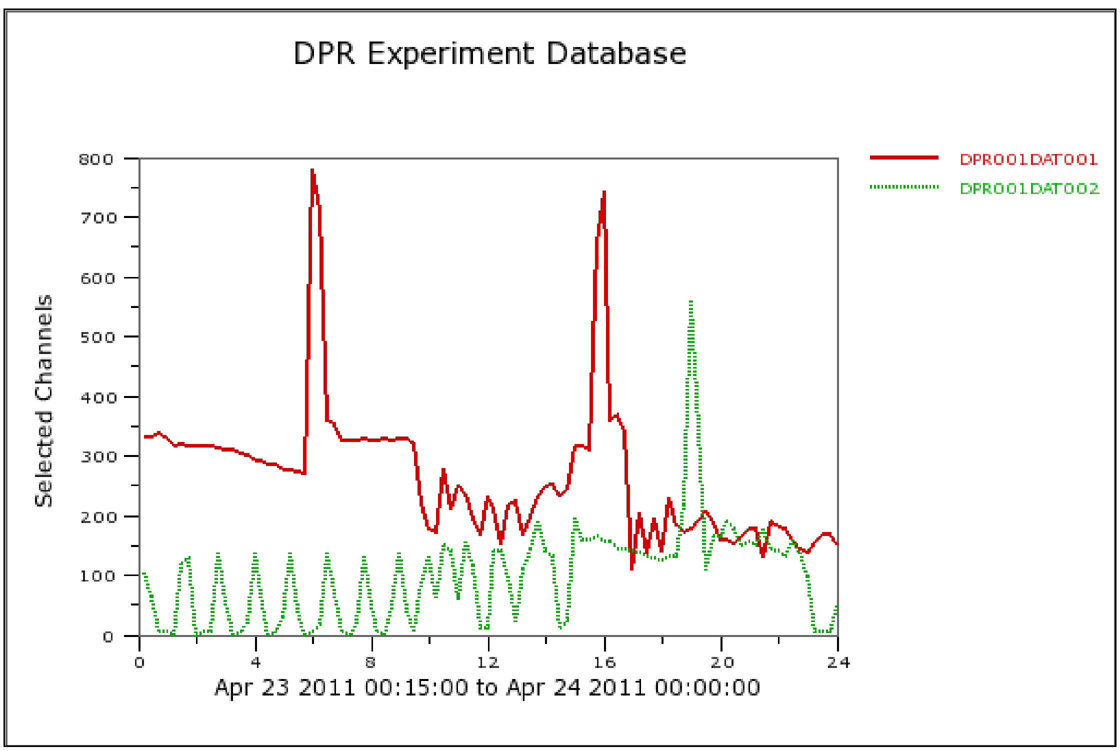

Figure 18. Measured power of new kitchen refrigerator (green) and garage refrigerator (red). Y-axis is Watts; X axis is the recorded 24-hour period.

A key question to understand is how refrigerator performance can be degraded over time. In 1992, the refrigerator used only about 2 kWh/day in the kitchen, whereas now it uses 70% more electricity (3.4 kWh/day) in the garage. If it is not coil fouling, then what could lead to degraded performance over time? Certainly it is not the higher garage temperature, as lower garage temperatures were seen during the autumn monitoring period.

10.3.1 Possible Explanations for Degraded Refrigerator Performance

There are several possible reasons for refrigerator energy performance to be reduced, including:

- Out-gassing, shrinkage, or diminishment of refrigerator shell insulation
- Failing performance of door gaskets
- Refrigerant leakage (unless this is very slow, then this would seem less likely; most units will present complete failure with a refrigerant leak)
- Compressor efficiency degradation (this seems less likely).

Although this seems poor, there are certain to be millions of refrigerators like these in Florida as seen in earlier monitoring efforts that found refrigerators using even more electricity (Parker et al., 1997). This suggests that the garage refrigerator (in lieu of data) should be assumed to be worse than the indoor unit in simulation analysis and audit. In any case the garage refrigerator is now the major load for the home. The garage refrigerator used a total of 1,234 kWh in 2011, so that the garage refrigerator represented 20% of total daily electricity use.

With more than 6 million refrigerators in Florida, substitution with more efficient units represents a major opportunity for statewide utility demand reduction particularly. The average demand of these units is at least 1000 MW. The least efficient refrigerators are older existing models, of which approximately 5% of the stock is replaced each year. The average life expectancy of a residential refrigerator is 20 years, such that at least 25% of Florida's existing stock is old inefficient units. Moreover, the ownership of second refrigerators in the state is generally higher than elsewhere in the United States. Fully 20% of Florida households have second refrigerators, which often are much older and less efficient units, often located in a garage.

11 Attic and Garage Temperatures

Data analysis of the A/C load in 1990 revealed that with the A/C evaporator located in the garage, its electricity demand was more closely linked to garage temperatures than to ambient conditions. We also found with a gray shingle roof that the attic reached very high temperatures with large potential heat gain to the attic duct system. The data illustrate the importance of the thermal conditions in buffer spaces in determining A/C electricity demand when there is substantial return side leakage that may be linked to these spaces. We also used developed data to target retrofits to reduce cooling use.

Figures 19 and 20 show that the summertime temperatures in the garage and attic spaces in the monitored home are quite high. The summer garage temperatures were almost always higher than the ambient daily temperature—commonly exceeding 90°F. The difference between the garage and ambient temperatures were most pronounced during the afternoon peak load hours. The rapid drop in garage temperature on the final day shown was due to a sudden afternoon rainstorm.

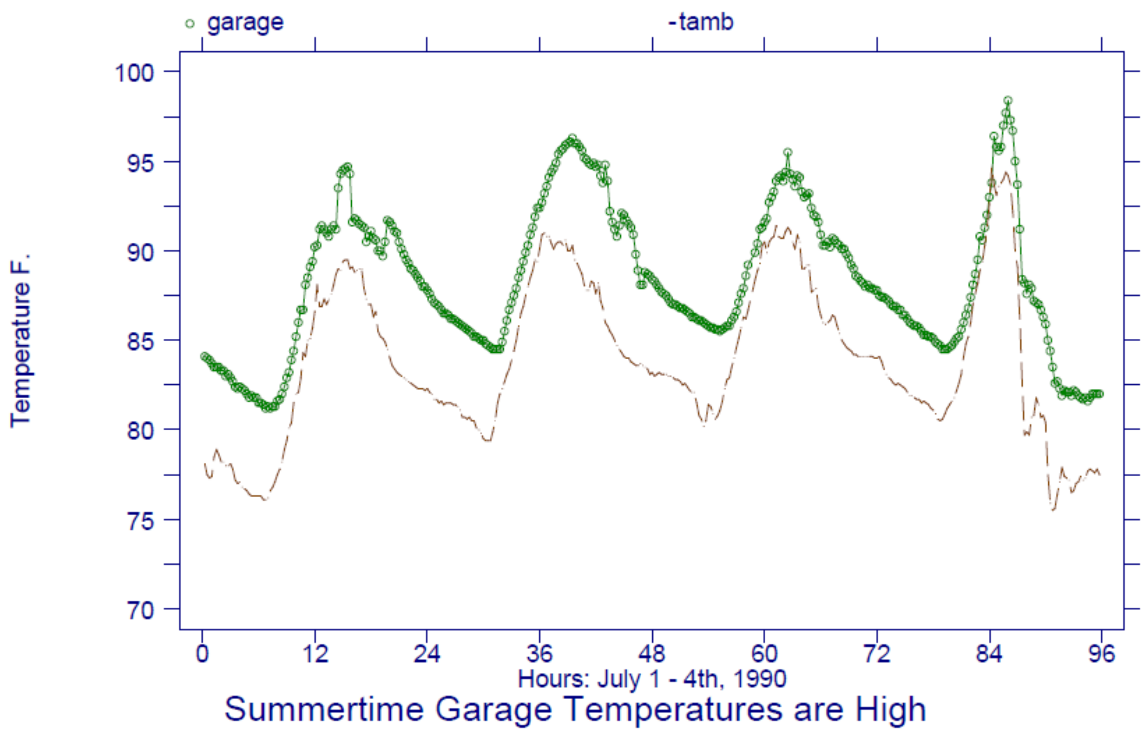

Figure 19. Garage (green) against ambient air temperature (brown) over a four-day period in the summer 1990

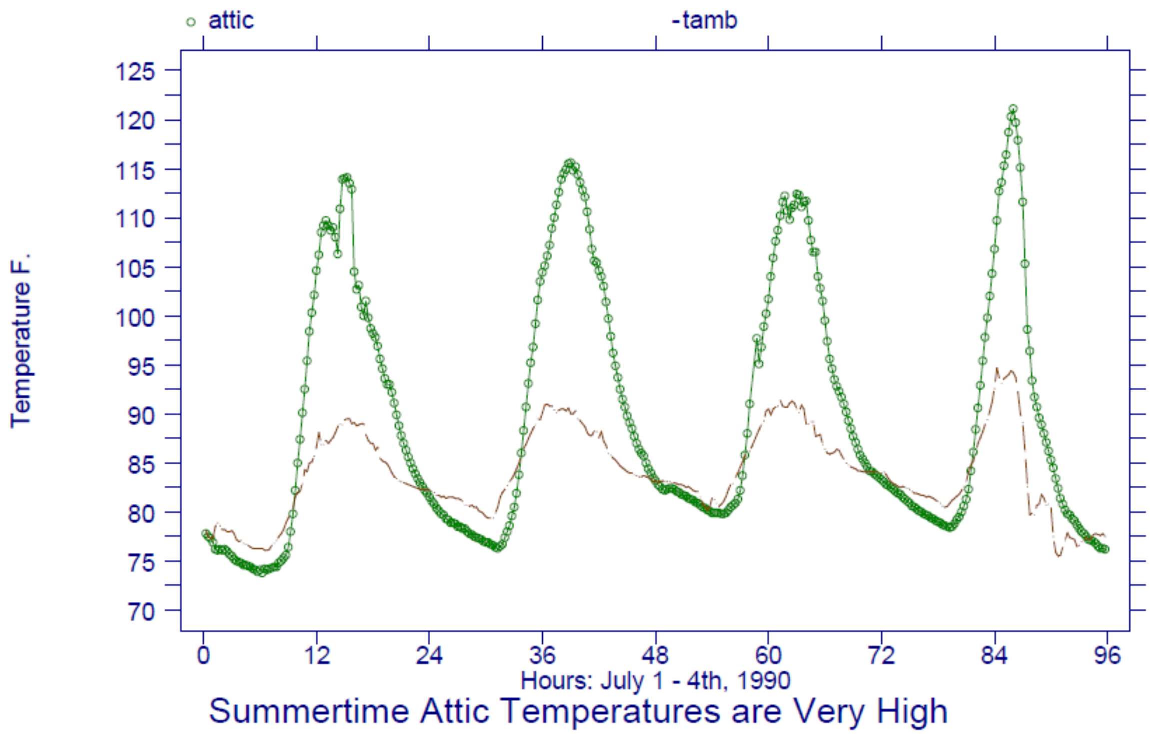

Figure 20. Attic (green) against ambient air temperature (brown) over a four-day period in the summer 1990

Peak attic temperatures may reach nearly 120°F, although the attic cools off rapidly during the evening hours, often to a level lower than the ambient temperature because of the radiative cooling of the roof surface to the night sky. Figure 21 summarizes the average daily 15-minute garage, attic, and ambient air temperatures for the month of July while the house was almost continuously air conditioned.

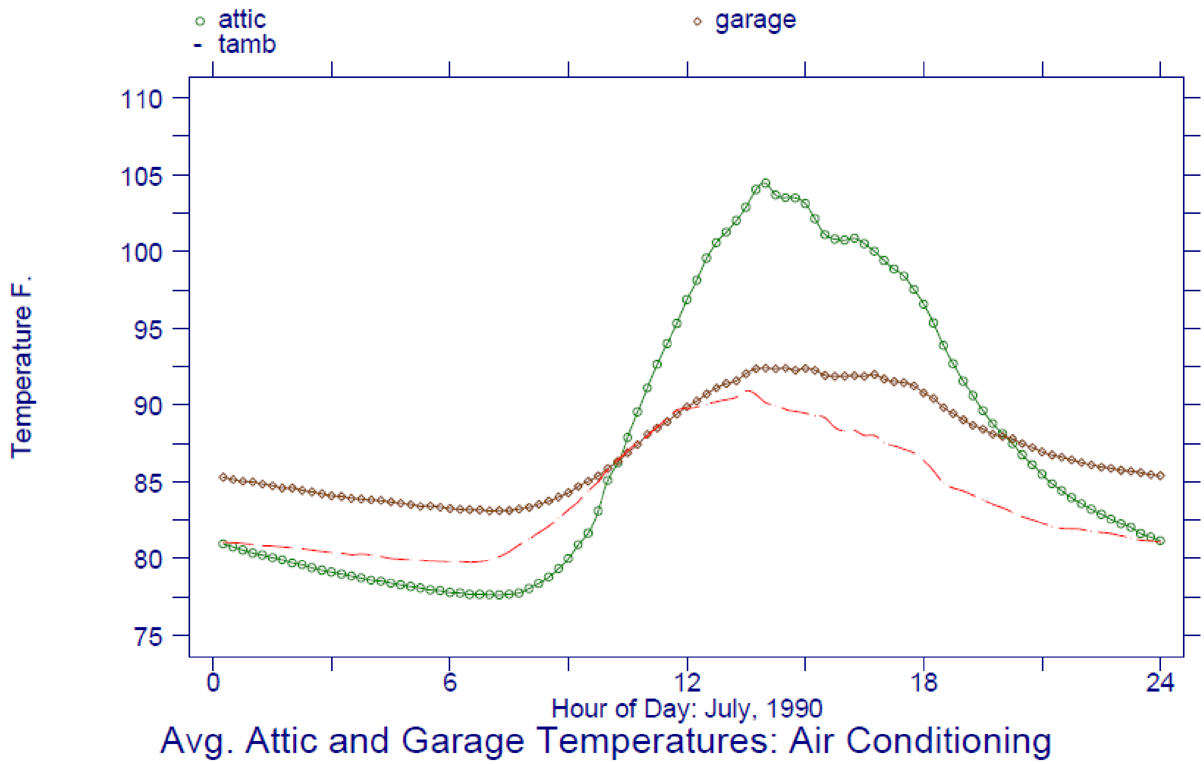

Figure 21. Average garage (brown), ambient (red), and attic (green) air temperatures when air conditioning over the month of July 1990

Table 4 summarizes the four summer months of data in 1992 on the garage and attic temperatures in the home and provides a summary of these temperatures during the utility peak demand hour. These data, as shown in Figure 21, show that the average attic and garage temperatures from 12:00 p.m. to 6:00 p.m. exceed 90°F.

Table 4. Garage and Attic Temperatures

Value	Mean	Min	Max
Garage Temperature (°F)	88.1	76.2	99.8
Attic Temperature (°F)	87.6	72.1	119.1
Ambient Temperature (°F)	84.5	72.1	98.6

Figures 22 and 23 show recent data about the temperature of the garage and how it corresponds to ambient air temperature.

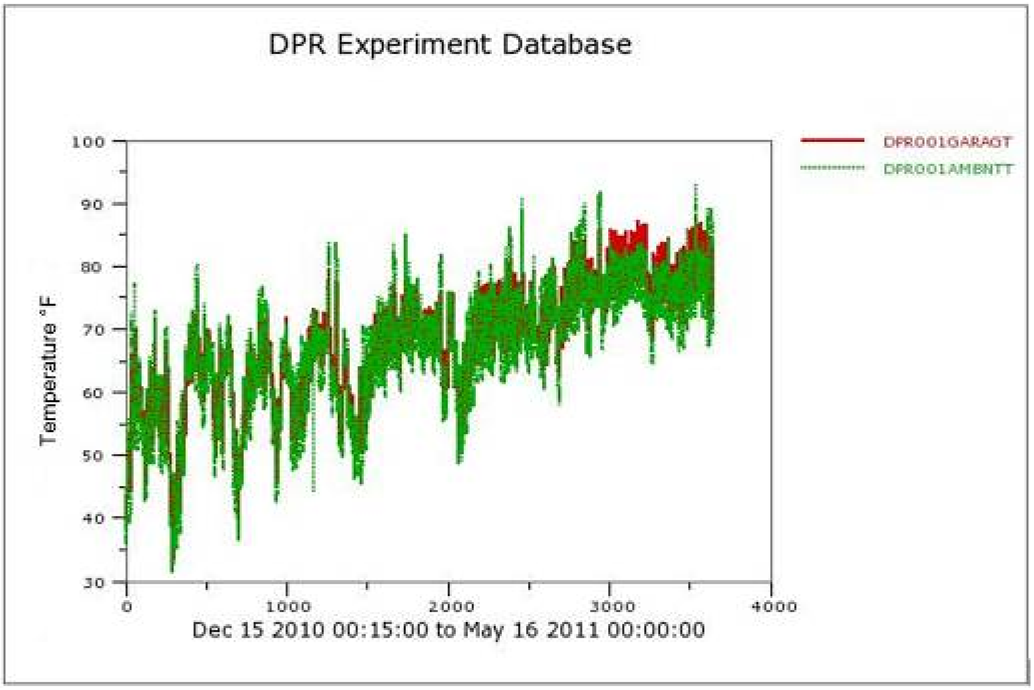

Figure 22. Measured garage and ambient air temperatures from December to May 2011. The garage temperature is shown in red and the ambient temperature is shown in green. Note similarity in temperatures, but increasing differences in April and May as the garage remains warmer.

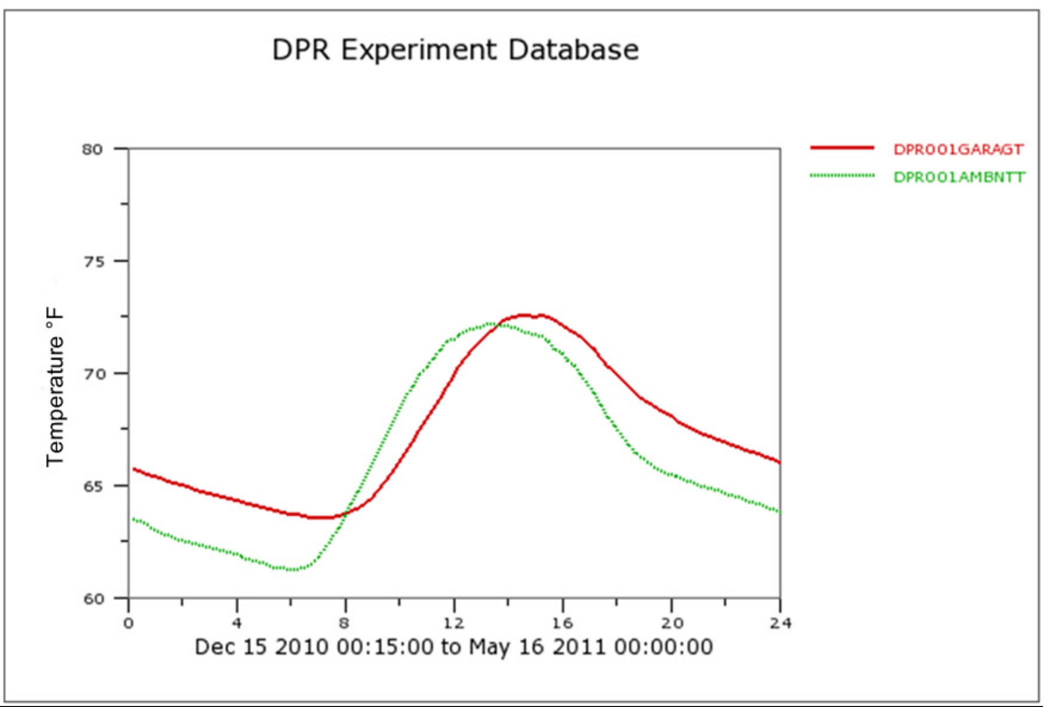

Figure 23. Average measured garage (red) and ambient air temperature (green) profile from December to May 2011. Note that the garage is both several degrees warmer than the outdoor temperature and out of phase with its amplitude by about +2 hours.

12 Floor Slab Cooling Potential

Like most Florida homes, the studied house has a slab-on-grade foundation. However, the monitored home is somewhat unusual in that the floor is not carpeted and has a terrazzo surface. Previous research has indicated that exposed floor slabs may offer some cooling season benefit for Florida homes (Fairey, Kerestecioglu, Vieira, Swami, & Chandra, 1986). Interestingly, Florida homes built after World War II—before the advent of A/C—most often had terrazzo or tile floors, likely for this reason.

Figure 24 gives an indication of the moderating influence of the ground as a heat sink during periods of natural ventilation. The ground temperature at a 2.5-ft depth varies only slightly over the daily cycle over the entire summer in contrast to the large amplitude of the swing in daily air temperatures. Figure 25 shows the distribution of living room and floor slab temperatures over a hot week-long period in June 1992 when natural ventilation was utilized. The daily cycle of heat storage within the floor slab is obvious in the plot. This indicates that the slab mass is providing a significant moderating influence on the house internal temperatures when ventilating. Figure 26 shows the slab temperature against the main zone temperature for the entire summer period. It is noteworthy that the slab temperature is lower, even during periods of A/C.

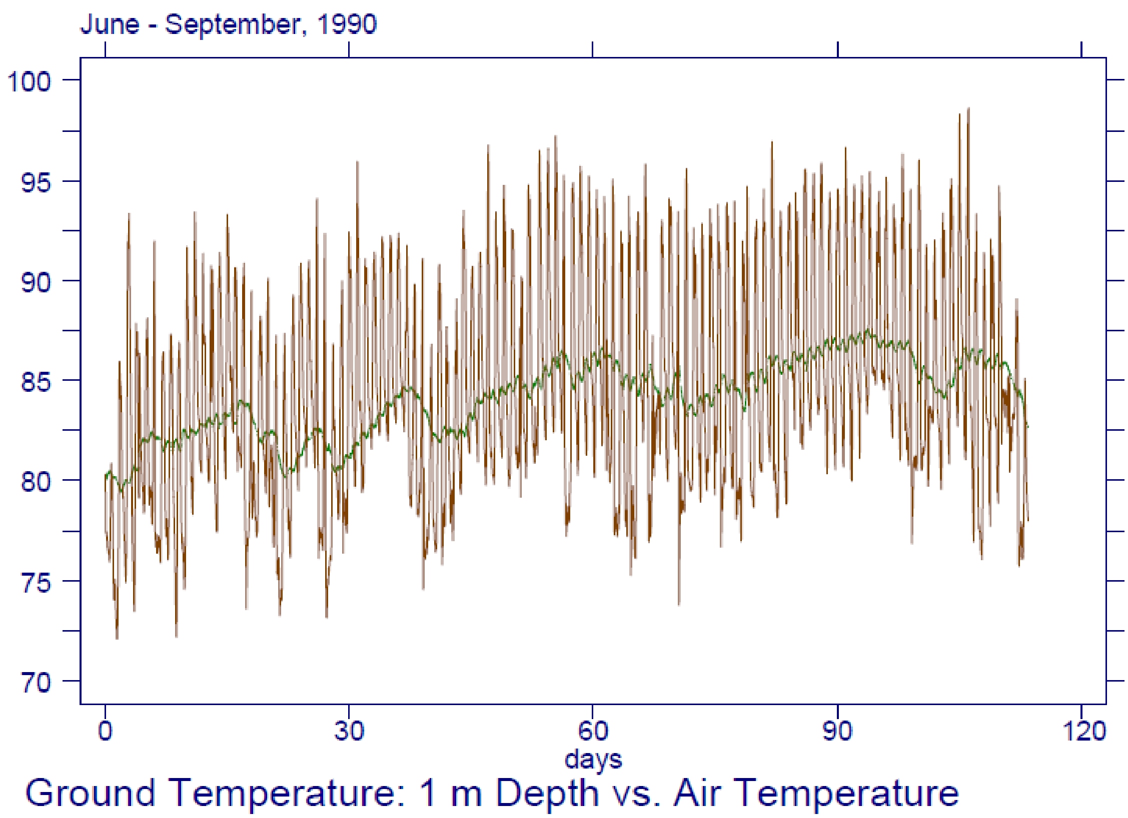

Figure 24. Moderating influence of ground temperature against ambient air temperature, summer 1990. Ground temperature shown in green against air temperature in brown. X-axis is Julian date.

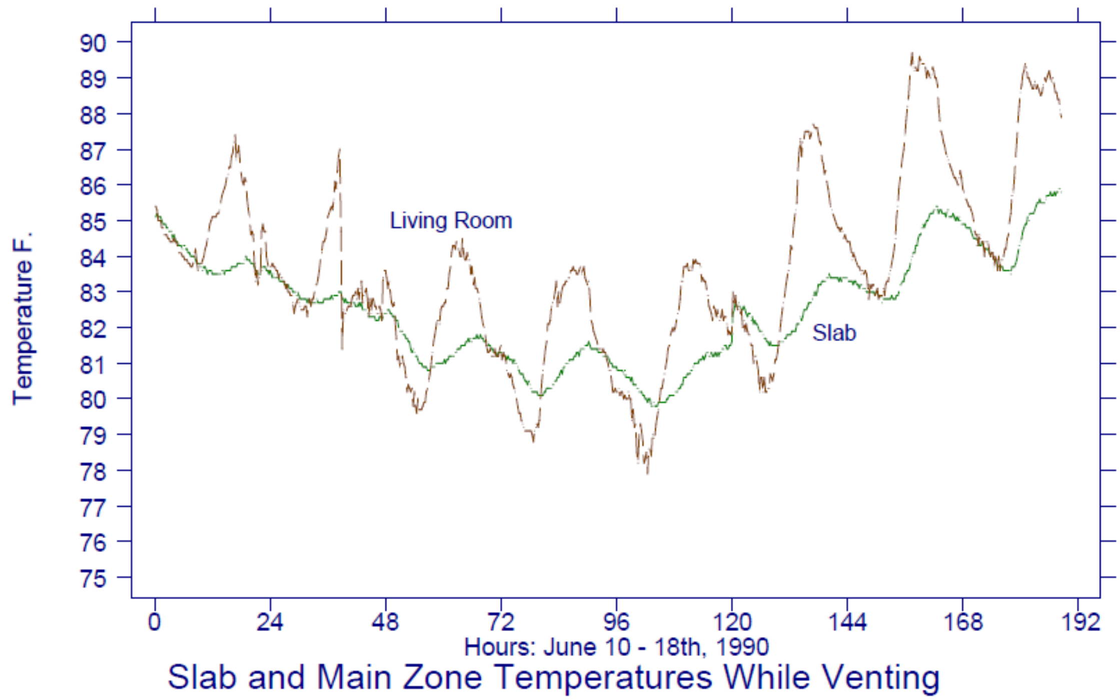

Figure 25. Interior floor slab and main zone temperatures during an uncomfortable period when natural ventilation was used: June 1990. Brown is living room temperature; slab is green.

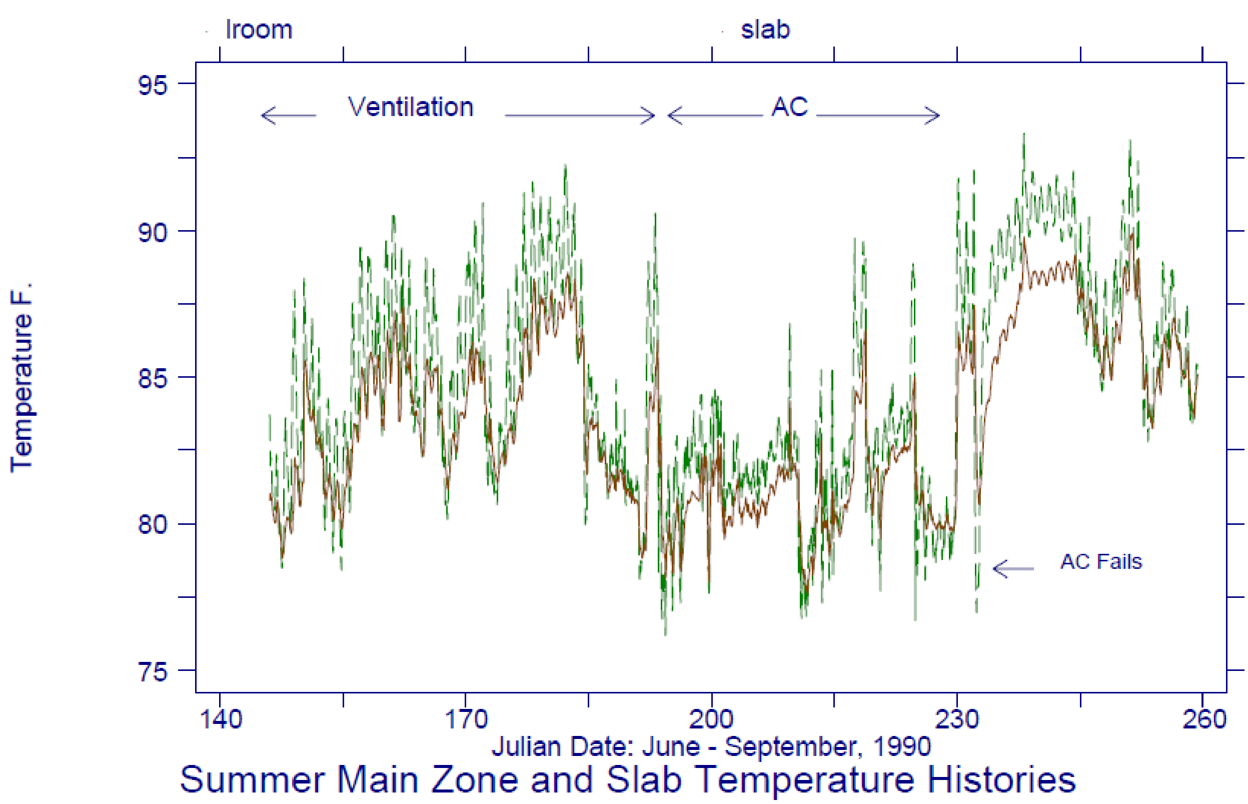

Figure 26. Summer living room (green) and slab temperatures (brown) during periods of natural ventilation and A/C

Table 5 summarizes the data about the floor slab and main zone (living room) temperatures, both while naturally ventilating and when using A/C. The data show that the floor slab surface is cooler under both conditions. Assuming 2000 ft^2 of exposed terrazzo and use of the American Society of Heating, Refrigerating and Air-Conditioning Engineers surface heat transfer coefficient (1.08 Btu/h·ft^2·°F) the data indicate an average level of cooling from the slab of approximately 3000 Btu/h when ventilating and half this figure when using A/C at an average 81°F interior temperature. It appears likely that a floor slab is adiabatic for cooling set points of 77°–80°F. This would seem to suggest that the floor slab can offer cooling potential down to 77°F with A/C, but below that point the floor becomes a sensible cooling load.

Table 5. Main Zone and Floor Slab Temperatures During Summer 1990

Value	Mean	Min	Max
Air Conditioning			
Main Zone Temp. (°F)	81.6	76.2	86.8
Slab Temp. (°F)	80.9	77.6	84.4
Ventilating			
Main Zone Temp (°F)	85.3	78.4	92.4
Slab Temp. (°F)	83.9	78.8	88.6

12.1 Detailed Monitoring in Spring 2011

During spring 2011, we used natural ventilation and a whole house fan to maintain comfort conditions. The plots below (Figures 27–29) summarize the detailed data now being collected.

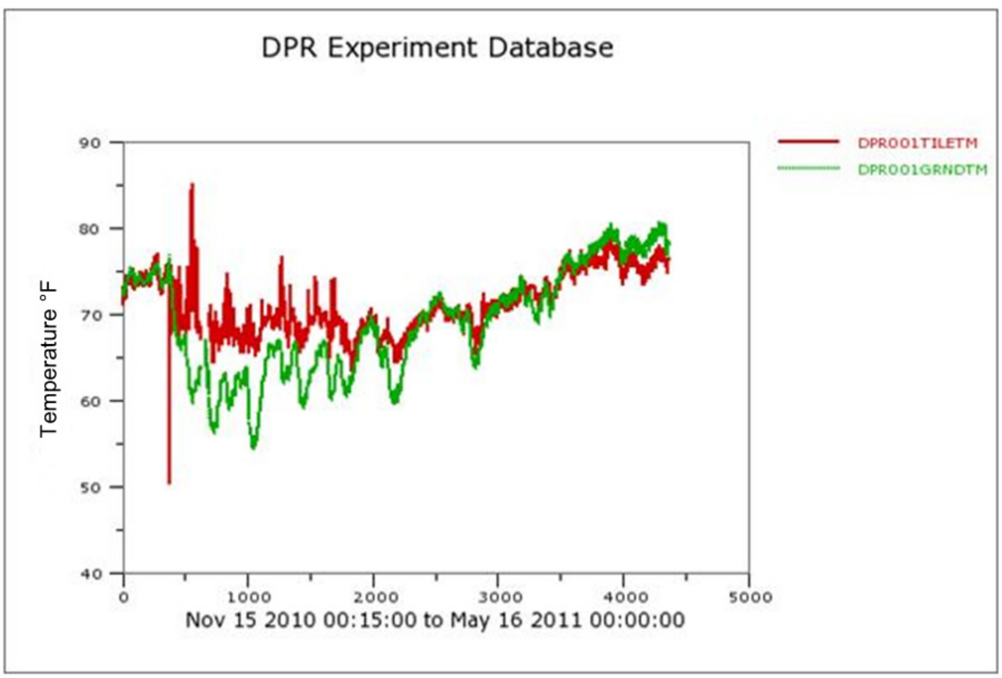

Figure 27. Measured living room tile surface temperature (red) and west house exterior ground temperature at a 1-ft depth (green) from November 2010 to May 2011. X-axis is elapsed hours.

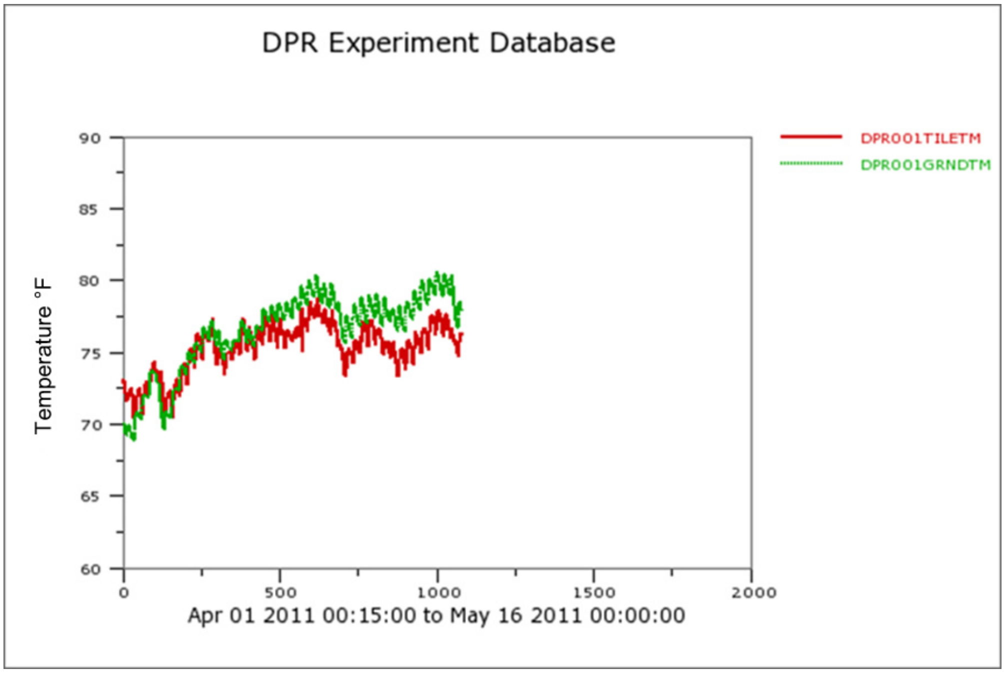

Figure 28. Tile (red) and ground temperature (green) during the spring season 2011 without mechanical cooling. X-axis is elapsed hours during period.

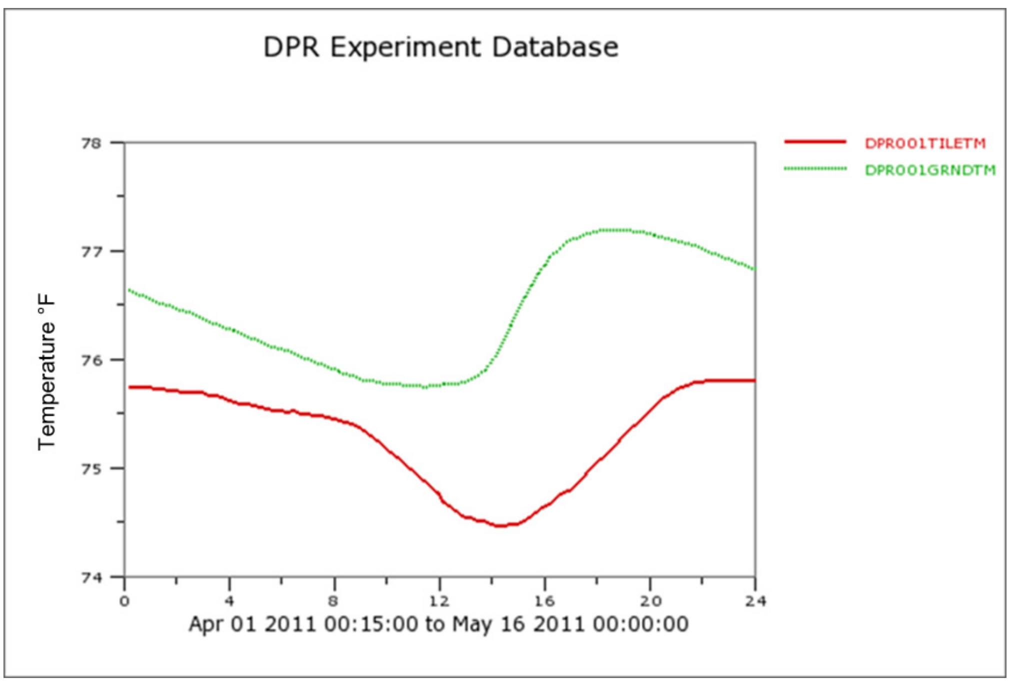

Figure 29. Average daily temperatures of tile floor (red) and ground (green) during the period without A/C. Note warming of the ground in the afternoon by sun on the ground surface on the west side of the house. Tile temperature inside is out of phase with the ground temperature.

13 Effect of Building Mass on Natural Ventilation Cooling Potential

The monitored house has concrete wall construction with a slab-on-grade foundation. This is typical for many existing Florida homes. Such a massive construction should lead to a structure that moderates the swing in daily internal air temperatures, hopefully providing a comfortable living environment without A/C when combined with natural ventilation. However, house heat gains and interior humidity made this attempted strategy quite oppressive.

Figure 30 shows a plot of the ambient air and living room temperatures over a five-day period in June 1990 during which the house was naturally ventilated. The moderating influence of the building mass is clear; the ambient temperature rises higher during the day and, at night, falls lower than the internal temperature, which varies considerably less. However, the data also show that outside nighttime temperatures are always closer to comfort conditions than the interior conditions, even with windows open. Two important reasons for this nightly difference are: (1) the delayed solar heat flux through the walls of the building; and (2) the very low wind speeds that are typical on hot summer days and the inability to flush out interior heat.

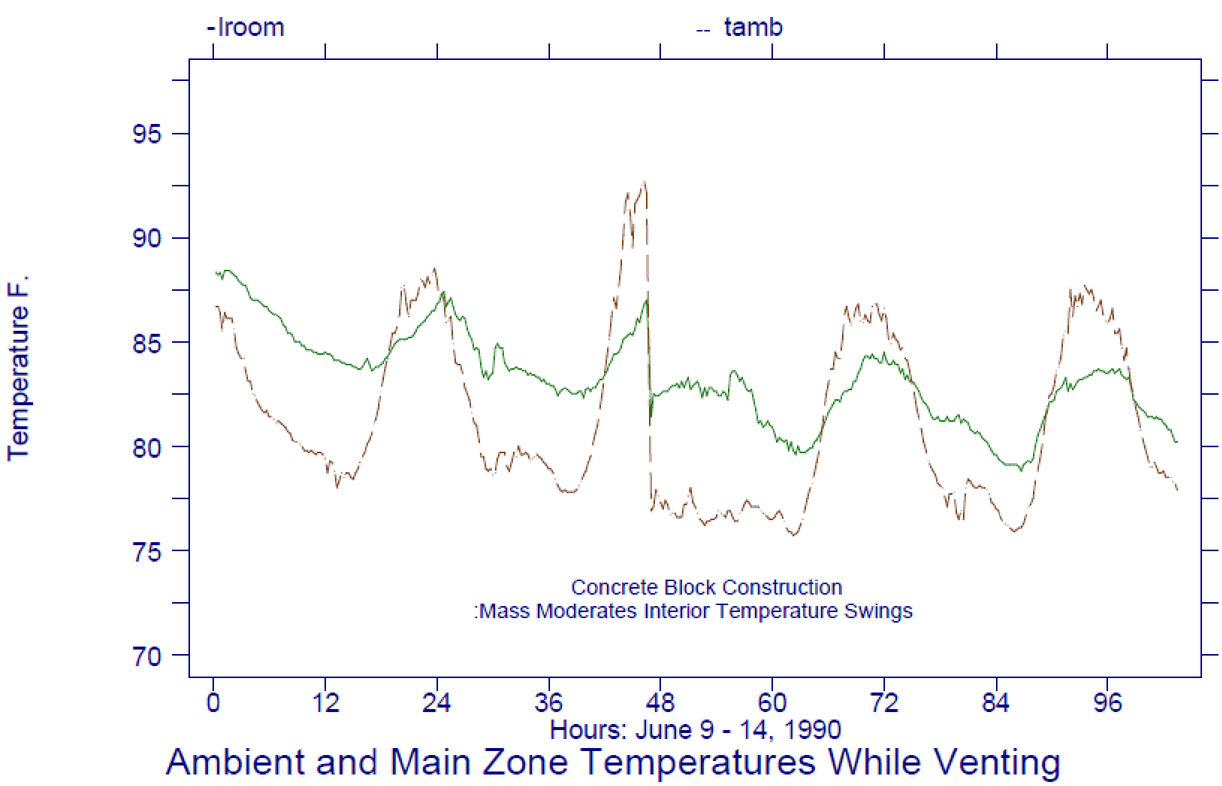

Figure 30. Ambient (brown) and living room (green) zone temperatures over a four-day period during attempted natural ventilation in June 1990

Figure 31 shows the average interior, slab, and ambient temperatures for the entire natural ventilation period in June 1991 when attempting to avoid A/C. The data show that on average the outside air temperature becomes lower than the main zone temperature at 3:00 p.m., and that substantial differences exist during the entirety of the evening hours. During this time ambient temperatures are much closer to comfortable levels. Figure 32 is a plot of monitored data from December 2010 to May 2011, also showing significant differences between the main zone and the ambient temperature during the evening and early morning hours.

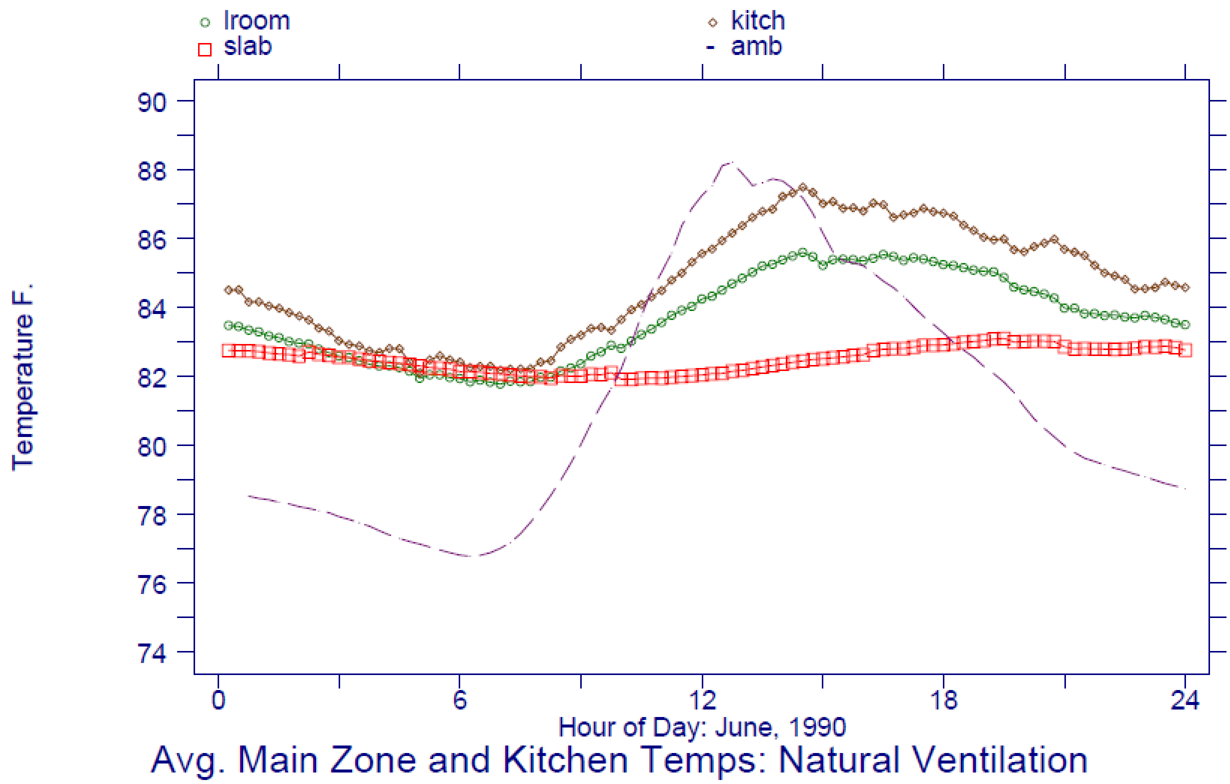

Figure 31. Average zone temperatures and ambient air temperature during natural ventilation in summer 1990

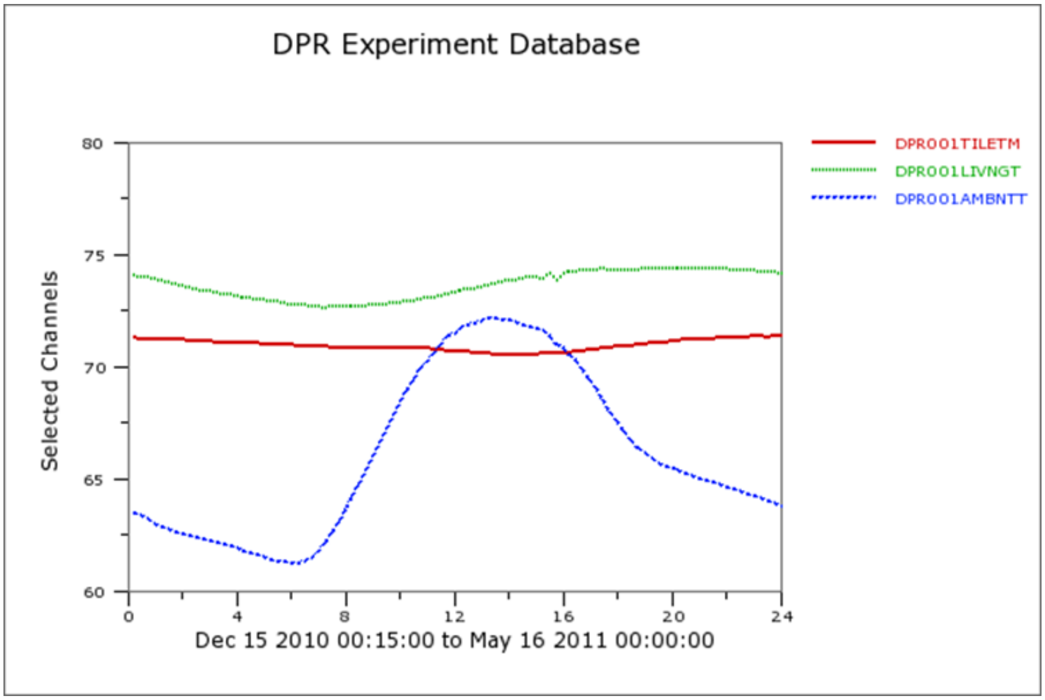

Figure 32. Average indoor (green), tile (red), and outdoor temperature (blue) profiles shown over the 24-hour cycle are plotted in a conventional fashion from December 2010 to May 2011

These results indicated that a WH fan that assisted airflow to the interior at night should provide significant improvements in comfort in high-mass Florida homes during periods when natural ventilation is utilized. Such a strategy would help to rapidly remove the accumulated heat within the building walls while helping to maintain comfort conditions closer to an acceptable level. Presumably, such forced ventilation would also extend the morning comfort conditions by removing heat within the massive construction of the house during evening hours to achieve better sensible comfort conditions early in the day.

13.1 Installation of Whole-House Fan

An experimental study was carried out in summer 1991 to investigate the natural cooling potential of a WH fan in the home (Figure 33). The house was ventilated with all windows open during the three-month summer test period (June–August). Air temperatures and relative humidity inside the home along with exterior meteorological conditions (insolation, wind speed, air temperature, relative humidity) were scanned every five seconds with integrated averages recorded every 15 minutes. The house was naturally ventilated during the first half of summer. After a significant period of pre-retrofit summer data had been collected characterizing the building's thermal response, a 24-in. WH fan was installed in July 1991. The house was then force ventilated during evening hours for the remainder of the summer to establish potential of WH fans to improve interior comfort conditions. The electrical consumption of the fan was measured at both available fan speeds.

Figure 33. First WH fan installed showing operable louvers that open during operation

Figure 34 shows the results: the operating WH fan dramatically increased our perceived comfort during nighttime hours even during the hottest part of summer. The measured electrical consumption of the WH fan (3.2 kWh/day) was less than one tenth of that used on average and during the previous summer with A/C (36 kWh/day). However, it is readily admitted that the achieved comfort conditions were quite arbitrary, with regard to both temperature and relative humidity. In particular, increased interior relative humidity was found to likely reduce the effectiveness of this strategy, because moisture and temperature levels would not suit agreed-upon standards.

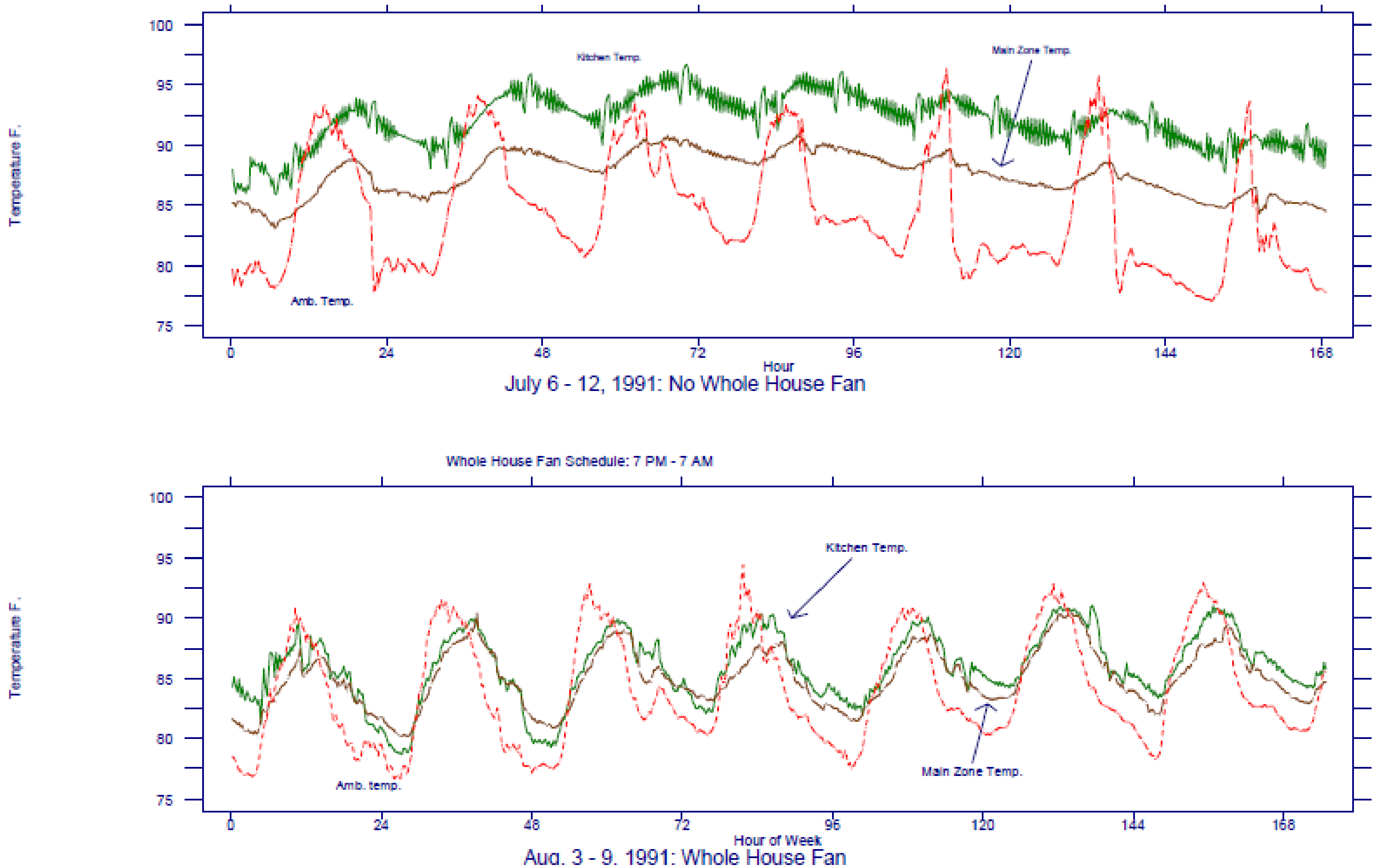

Figure 34. Two plots showing six-day periods in summer 1991 before and after a WH fan was installed to augment natural ventilation. Ambient temperature is red; kitchen is green, and living room is brown.

Measurements revealed that the building interior was 3°– 6°F cooler during the evening hours after the WH fan was operated. However, data also showed that nighttime humidity levels rose: relative humidity increased from 74% to 83% during the nighttime period when fan-powered ventilation was used. This was more fully analyzed in a more detailed report, which concluded that WH fans have limited potential in humid Florida—primarily confined to the nonsummer seasons when we generally use them now (Parker, 1992).

13.1.1 Monitoring in Spring 2011

Figure 35 shows an image plot of the tile and indoor air temperatures and how they relate to outdoor temperatures from December 2010 through May 2011. This shows that the tile surface exerts a moderating influence on the temperature indoors during natural ventilation.

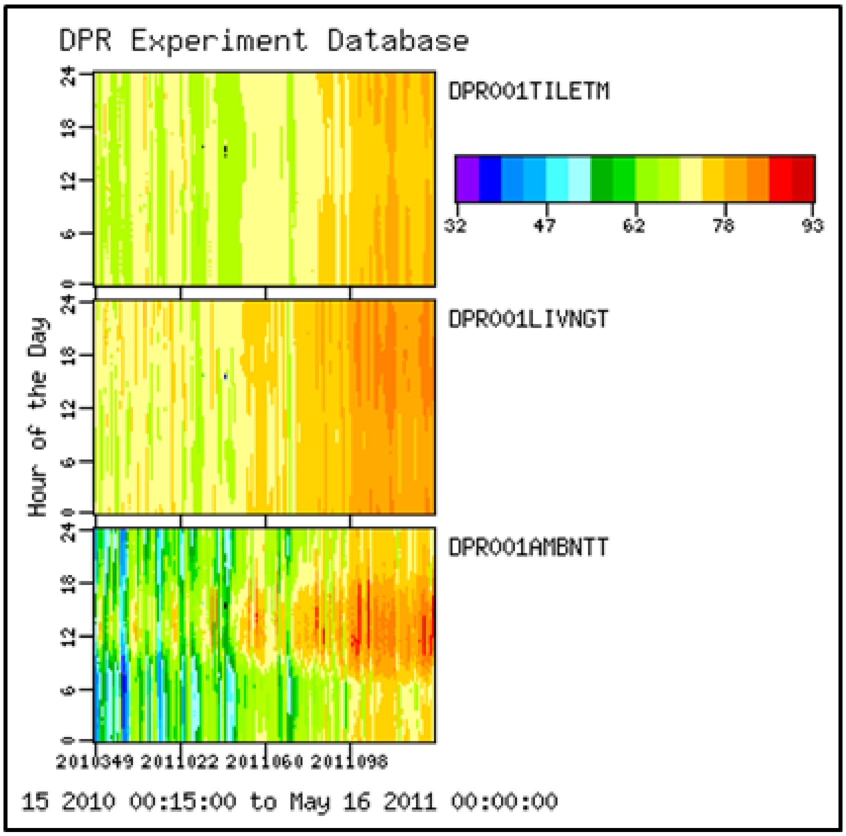

Figure 35. Image plot of tile surface temperature (top), house indoor temperature (middle) and outdoor ambient temperature (bottom) from December to May 2011. Color is proportional to temperature and X-axis is the Julian date. Note that the tile temperatures are slowly warming, with the house indoor temperatures generally warmer than the outdoor temperatures, particularly at night from internal heat gains.

Figures 36 and 37 show the temperatures and relative humidity when a new Tamarack WH fan was used in spring 2011. The new WH fan draws only about 120 W, but also provides only about 1000 cfm of airflow (Figure 38).

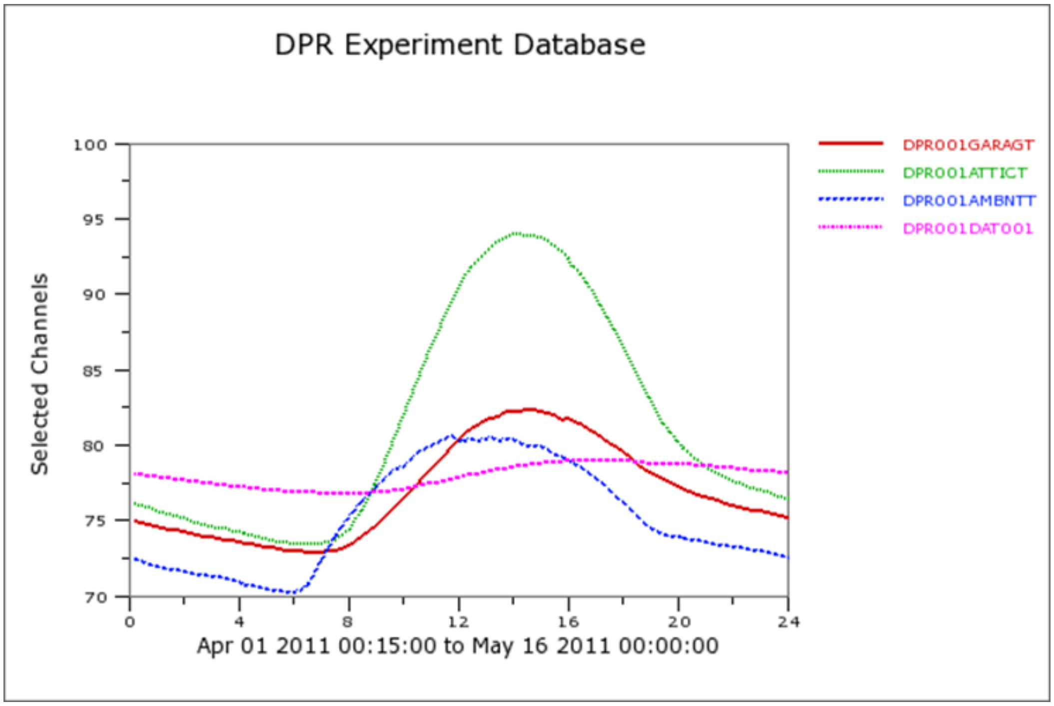

Figure 36. Average ambient (blue), attic (green), garage (red) temperatures and interior temperatures (pink) when WH fan cooling was used April 1–May 15, 2011. Y-axis = ºF.

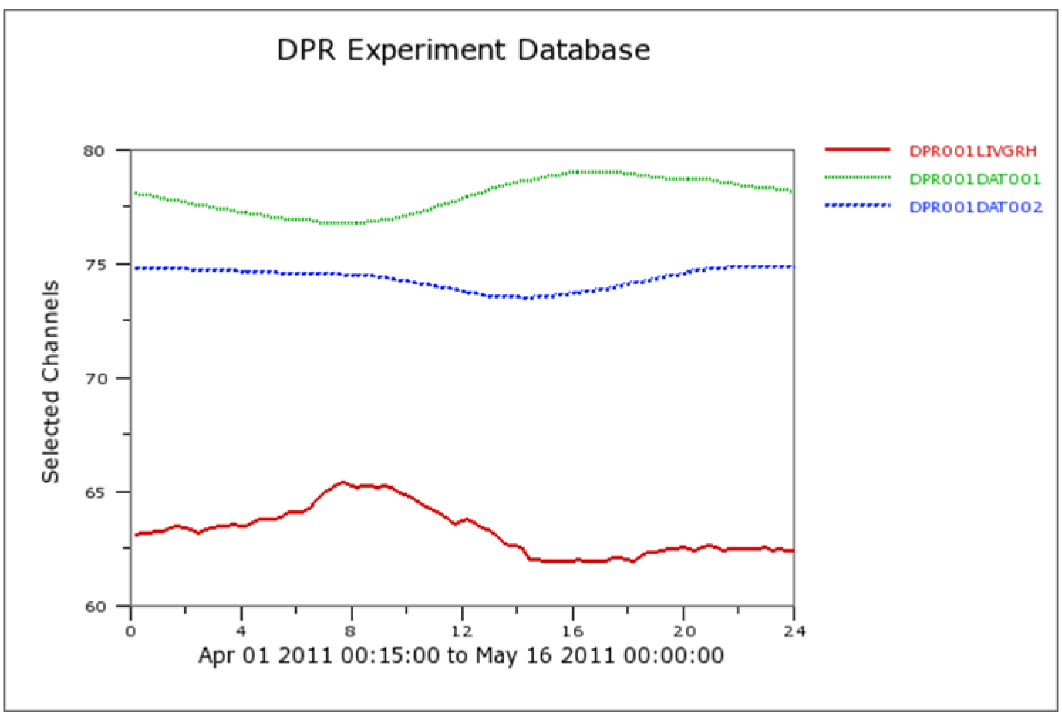

Figure 37. Average living room (green) and tile surface temperature (blue), and living room relative humidity (red) during the time when the WH fan was used for cooling in spring 2011.

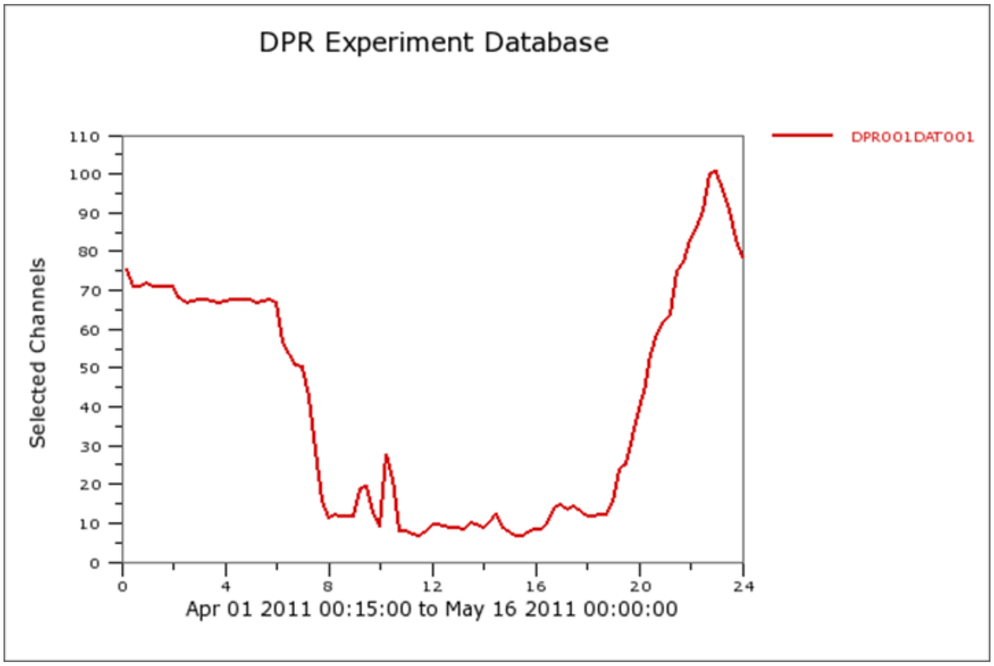

Figure 38. WH fan power (Y-axis is Watt) from April 1 to May 15, 2011 when the system was used for cooling. Note nighttime use. Average daily power was 0.95 kWh/day or 43 kWh over the six-week period.

13.2 Reflective Roof Coating

In July 1992, another experiment was conducted on the home to examine how a reflective roof coating might reduce space cooling needs (Figure 39). The aging gray shingle roof was nearing the end of its useful life and had a measured solar reflectance of 21%. The attic of the home was insulated to approximately R-19 (although uneven distribution may have degraded the actual performance to only about R-11) but the A/C was more than 15 years old and inefficient. The roof was coated with a white elastomeric coating on July 6, 1992 (Figure 40). The measured solar reflectance after coating was 73%.

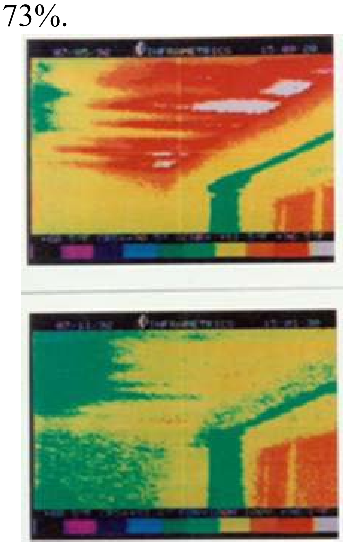

Figure 39. Thermographs taken on northeast interior ceiling on a summer afternoon before and after the roof coating. Note large change in heat conduction to the interior. Curtains over a north-facing window can be seen in the lower right.

Figure 40. A highly reflective elastomeric coating was applied over shingles in an experiment in July 1992 (a practice that is no longer recommended because of moisture-related problems)

The measured impact on A/C energy and attic temperatures, shown in Figure 41 during the week of the treatment was dramatic (Parker, Barkaszi, Chandra, & Beal, 1995). Although air temperatures and solar radiation were comparable, A/C power was reduced by an average 25% from 1690 W to 1264 W. The average electricity demand of the A/C system during the utility coincident peak period (between 5:00 p.m. and 6:00 p.m. was 2,373 W before the coating and 1,712 W after the application. This 661 W reduction represented a 28% reduction in peak power demand attributable to the coating.

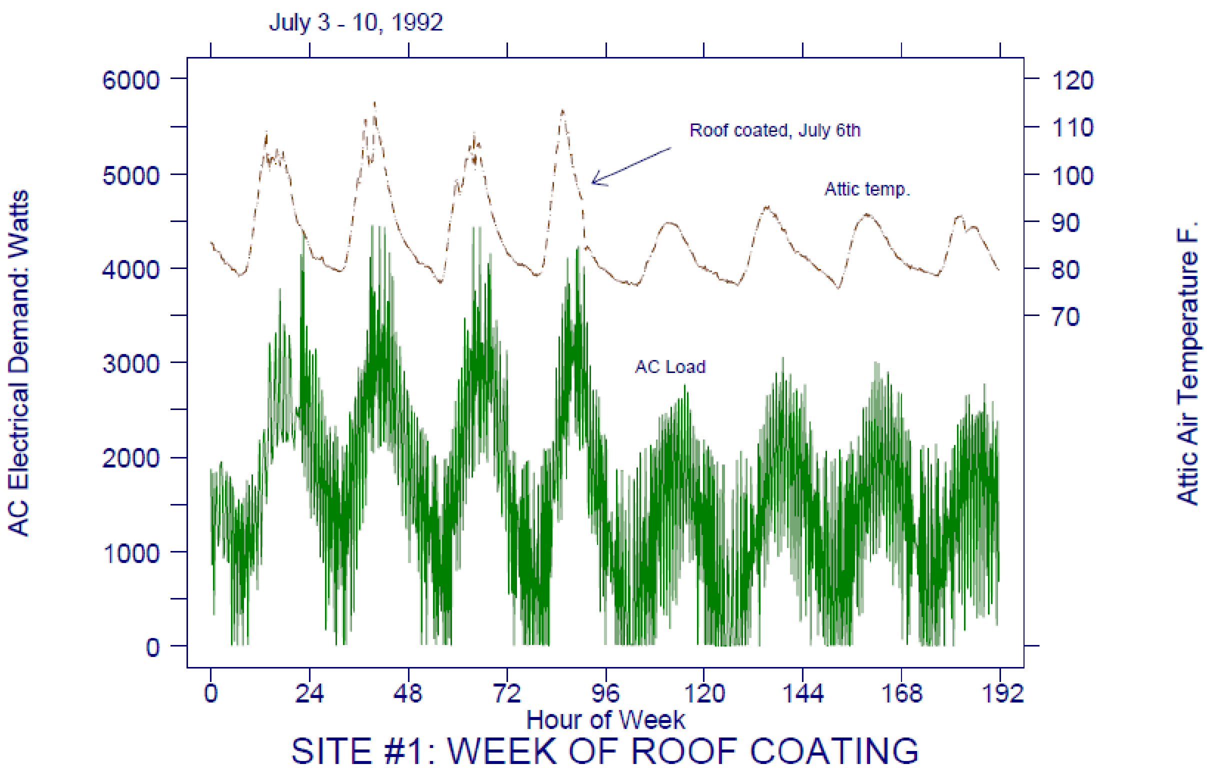

Figure 41. Measured change to attic (red) air temperatures and measured A/C power (green) from reflective roof coating done in July 1992

It must be noted that although the roof coating had a beneficial impact on cooling loads, it also had a deleterious effect on the roof, because coating a shingle roof can cause water vapor to condense under the plywood decking during evening hours because of night sky radiation. Coatings are fine for use on metal, tile, or torchdown roofing without seams, but we specifically warn that coatings should not be used on shingle roofs to prevent moisture damage.

When the home was remodeled and expanded in 1998, the coated roof was replaced by a white metal 5-vee roof (solar reflectance of 67%), which does not have this problem and has maintained its reflectance well ever since (Figure 42).

Figure 42. White metal roof after 12 years of weathering on the south exposure. The 5-vee metal panels have maintained their reflectance. PV modules are seen in the image with the solar water heater at the far end.

14 Second Phase of Retrofit Progress

In 1993, the first monitoring equipment was removed, although the retrofit process in the house went on. However, it was still possible, in a coarser way, to evaluate the impact of the various retrofits performed by continuing to collect utility records.

Within the home, the second phase of improvements continued in order to decrease energy use. Improvements have spanned a 23-year period that has included two additions to the family, adding 660 ft^2 to the home, and a host of other changes (Figure 43), both helpful and unhelpful, to reducing energy consumption.

Figure 43. During the home remodel in 1998, high-efficiency ceiling fans were installed throughout the house to help shorten the A/C season (number of weeks A/C was necessary for comfort).

The installed retrofits are summarized in Table 6 and later described in detail.

Table 6. Retrofit History for Parker Household

Date	Retrofit	Details	Cost
February 1989	Remove carpet	Expose terrazzo floor for cooling	$0*
February 1989	R-19 ceiling insulation	Add 7 in. of blown fiberglass	$254
February 1989	Setback pool pump hours	Set hours from 8 to 4 per day	$0
July 1990	Seal duct leakage	Air condition all summer	$50*
July 1991	WH fan	Natural ventilation all summer	$500
November 1991	Compact fluorescent lamps	Fluorescent lighting 80% of fixtures	$400
July 1992	White coating to roof	70% reflectance >20% A/C R	$500*
August 1992	PV pool pump	Solar power for pool pumping	$3000**
February 1993	Gas appliances	Gas heat, dryer, range, hot water	$2500***
April 1993	Separate freezer	Add garage freezer	$500
January 1994	Solar hot water[5]	4×18 ft; two tank system with gas	$1814
March 1994	Efficient kitchen lighting	Change to T8 lamps from T12s	$100
July 1995	New SEER 10 A/C	2-ton size; straight cool	$2000*
June 1998	Remodel house[6]	Add 660 ft^2 under air, skylights	NA

[5] Used 4 ft × 8 ft collector, new 40-gal tank; gas auxiliary elevated to provide 80 gal total storage

Date	Retrofit	Details	Cost
December 1999	25 ft^3 side-by-side refrigerator[7]	Current refrigerator to garage[8]	$1360R
December 2000	Hi-efficiency ceiling fans	Change six fans to Gossamer	$1200
July 2005	TED	Real time feedback display	$330*
October 2005	New E-Star LCD***** TV	Flat screen 120 W operating	$NA[9] R
March 2006	ENERGY STAR Washer	Kenmore 2706; modified EF****** = 2.0	$870R
April 2006	Locate standby loads	Use The Energy Detective and new protocol	$0*
January 2007	Tankless Gas DHW	Solar primary with tankless gas	$2178
April 2008	E-Star dishwasher	Bosch, EF = 1.14	$1500R
May 2008	Low-energy WH fan	Tamarack, HV 2000	$900
January 2009	4.095 kW PV system	5-kW SMA inverter; ESA 205 modules	$30,000[10]
October 2009	Add 820 W to PV system	PV system => 4.92 kW total	$3,800
June 2010	80-gal solar storage tank	Change from 40 to 80 gal storage	$548
August 2010	Retrofit windows	U = 0.29; SHGC******* = 0.24 windows	$13,800
October 2010	Exterior wall insulation	Add R-5 EIFS**** system to CMUs	$11,330
November 2010	Mini-split A/C	0.75-ton, central, SEER 26, heating season performance factor = 12	$1700*
	------------------------- Detailed Monitoring Begins ---------------------		
January 2011	Retrofit kitchen refrigerator	24 ft^3 unit; Guide = 463 kWh/yr	$1,900
September 2011 February 2012	*Add Plug in Hybrid Automobile*	Chevrolet Volt; 100% charge = 10.4 kWh	NA
February 2012	*Add 1.68kW to PV System*	PV System = 6.6kW; final increase	$2890

* Owner labor
** Provided free of charge for experimental research (comparable price)
*** With applicable rebates
**** Exterior insulation finishing system
*****Liquid crystal display
******Energy factor
*******Solar heat gain coefficient
R = replacement due to wear-out of equipment

[6] Included: white metal roof, sun tube skylights in interior bathrooms
[7] SEARS 5756*79, 25-ft^3 side-by-side unit, Energy Guide = 777 kWh/yr
[8] Moved kitchen refrigerator to garage and removed separate freezer at the same time
[9] Not an efficiency related investment
[10] Less $10,000 after federal tax credit

14.1 Efficient Lighting

In late 1991, we changed all the lights in the house to compact fluorescent lamps (CFLs), except for the lights in the closets, which use 25-W incandescent lamps. Typically, this involved a 15-W CFL substituted for 60-W incandescent lamps. This totaled 31 indoor lamps replaced and 13 lamps in outdoor fixtures. This provided a noticeable reduction in household electricity consumption—approximately 100 kWh/month. There were also impacts to internally generated heat, as seen in Figure 44. We also installed sun tunnel and skylights to provide daylight to the interior kitchen and bathrooms during the 1998 remodel.

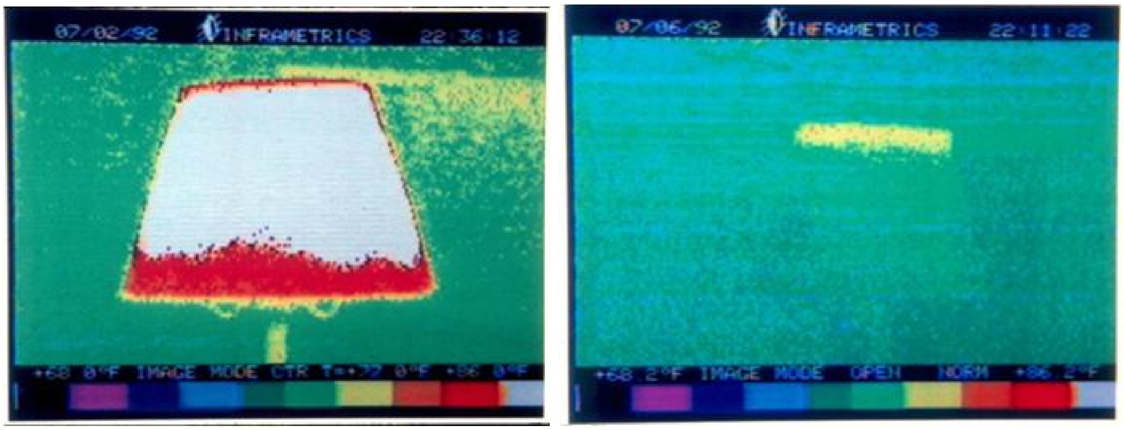

Figure 44. Infrared thermographs of a floor standing lamp with 60-W lamps (left) versus 20-W CFLs (right). With color proportional to temperature, the impact of CFLs on reducing cooling loads in Florida homes can be seen.

14.2 Conversion of Electric Resistance Loads to Natural Gas

In early 1993, we changed all possible electric resistance end uses to natural gas to reduce source energy and the associated building carbon footprint. This included replacing the heating system from the old water to air heat pump to a 78% efficient natural gas furnace. We also replaced the electric water heater (EF = 0.86) with a conventional natural gas unit (EF = 0.54) in the garage. At the same time, the electric clothes dryer was also changed to a natural gas unit and the electric range was converted to a natural gas model. We did note that the natural gas dryer actually used an appreciable amount of electricity for operation of the hot surface ignitors as well as the drum wheel and blower. Figure 45 shows the measured electricity use for the clothes dryer in operation.

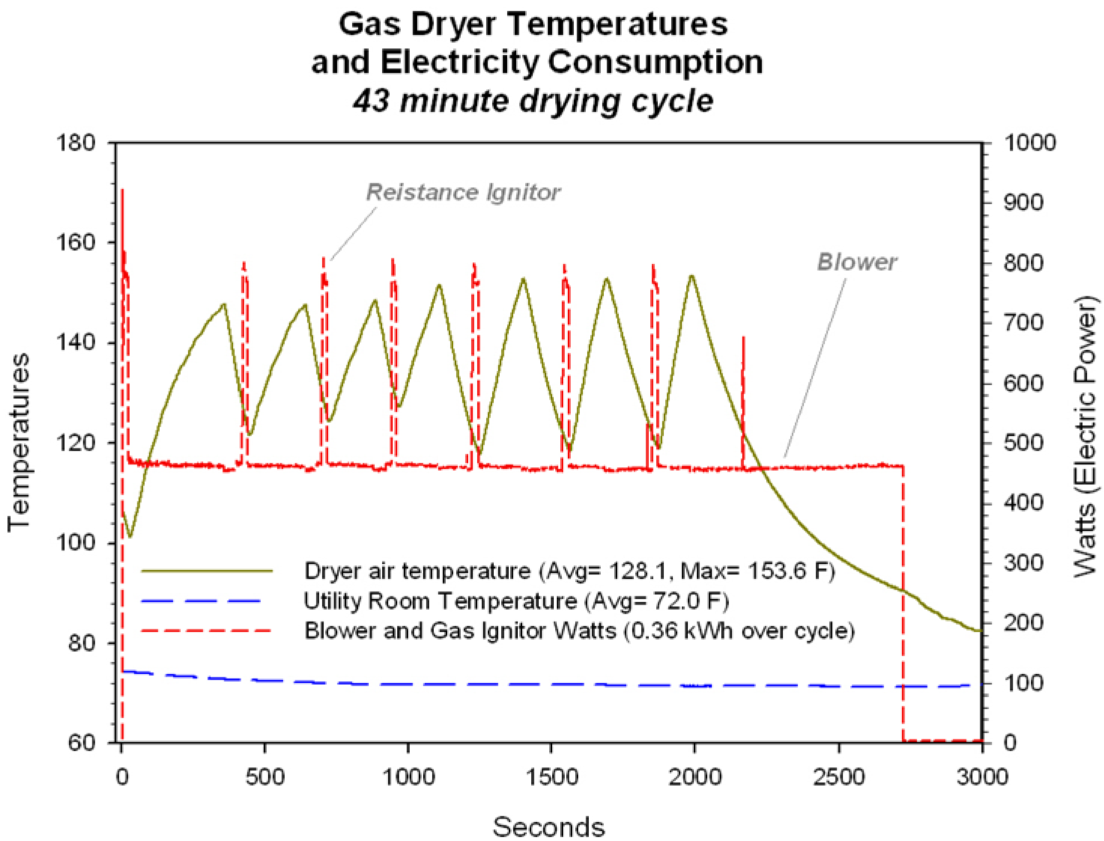

Figure 45. Measured electricity use (0.36 kWh) of natural gas clothes dryer over a single drying cycle

Figure 46 shows the natural gas range gas consumption measured from January 2011 through January 2012. This shows expected bimodal use intensity, morning and evening. With frequent cooking for a household of four (including two teenagers), the average daily use is 8.35 ft^3/day or 32.0 therms/year. Although the heat transfer characteristics of an electric stovetop are about 25%–30% better than natural gas, the offset resistance electricity use is about 700 kWh/yr.

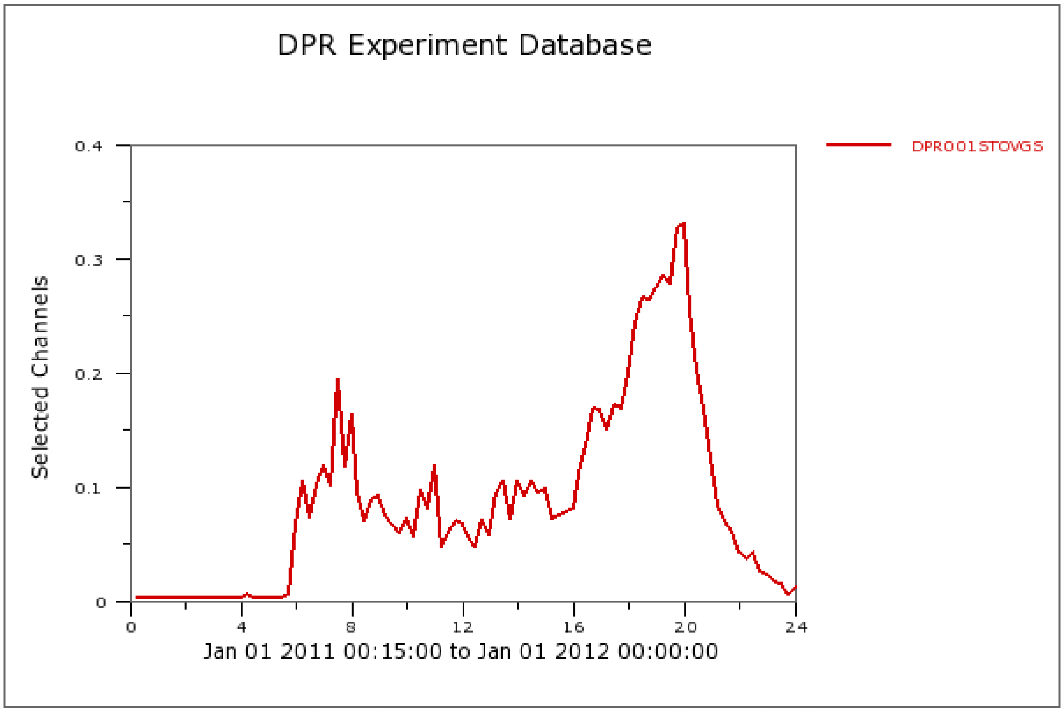

Figure 46. Average daily profile of range natural gas use (cubic feet) per 15-minute interval, January 2011-January 2012

14.3 Solar Water Heating System

Within a month of having a natural gas water heater installed, we had a solar water heating system mounted on the roof as the primary water heating system. This consisted of a used AET 4 ft × 8-ft collector, pumped by two 5-W PV modules mounted in parallel and a small El-Sid direct current (DC) pump (Figure 47). Storage consisted of an 80-gal tank that was plumbed such that it convectively circulated to the elevated auxiliary 40-gal natural gas tank whenever the 40-gal storage exceeded the temperature of the water in the natural gas tank (FSEC, 2006). This effectively provided 80 gal of storage for the solar water heating system. The system provided about 50% of annual water heating required, although this was reduced by the inefficient auxiliary tank.

Figure 47. 4 ft × 8 ft solar collector. System is PV pumped by two 5-W PV modules mounted in parallel.

14.4 Tankless Gas Auxiliary Water Heater for Solar System

In January 2007, the standard gas water heater was removed and replaced by a tankless gas Rinnai R-28 water heater. It has a claimed heating efficiency of 81% (although data from FSEC's hot water systems laboratory suggest these numbers are optimistic by about 10%). Still this is considerably better than the EF = 0.54 gas storage tank that it replaced. The standby power of the unit with its electronic controls is about 4 W. Electric power during hot water draws is about 40 W.

Figure 48 shows the installed configuration. A key innovation is the tankless gas water heater, which is located above the solar storage such that the hot water naturally migrates to the heat exchanger in the tankless unit based on thermal buoyancy (the tankless auxiliary is elevated relative to the solar primary tank). Because the tankless heater is fully modulating, it does not come on if the hot water inside the unit is in excess of the set temperature. We have this set to 120°F on its electronic key pad.

Figure 48. Tankless water heater elevated above 80-gal storage tank (lower right)

As seen in the data in Figure 49, this system resulted in a noticeable drop in natural gas consumption, which was apparent in the monthly data. We estimate that approximately 70% of annual water heating needs are met by the solar water heater in combination with the tankless auxiliary.

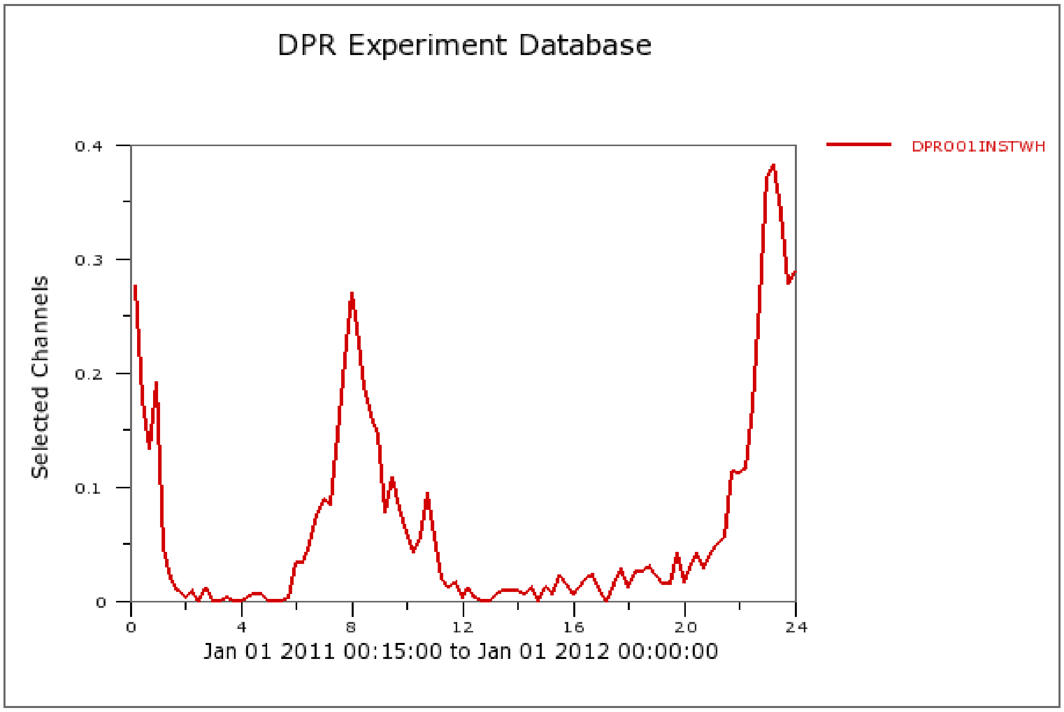

Figure 49. Auxiliary gas consumption of tankless gas water heater when the solar system could not meet the load between January 2011-January 2012; average daily use is 6.34 ft^3/day or 24 therms/year). This is the average for the entire period. Y-axis is cubic ft per 15-minute interval.

Figures 50–53 show various performance indices for the solar water heating system.

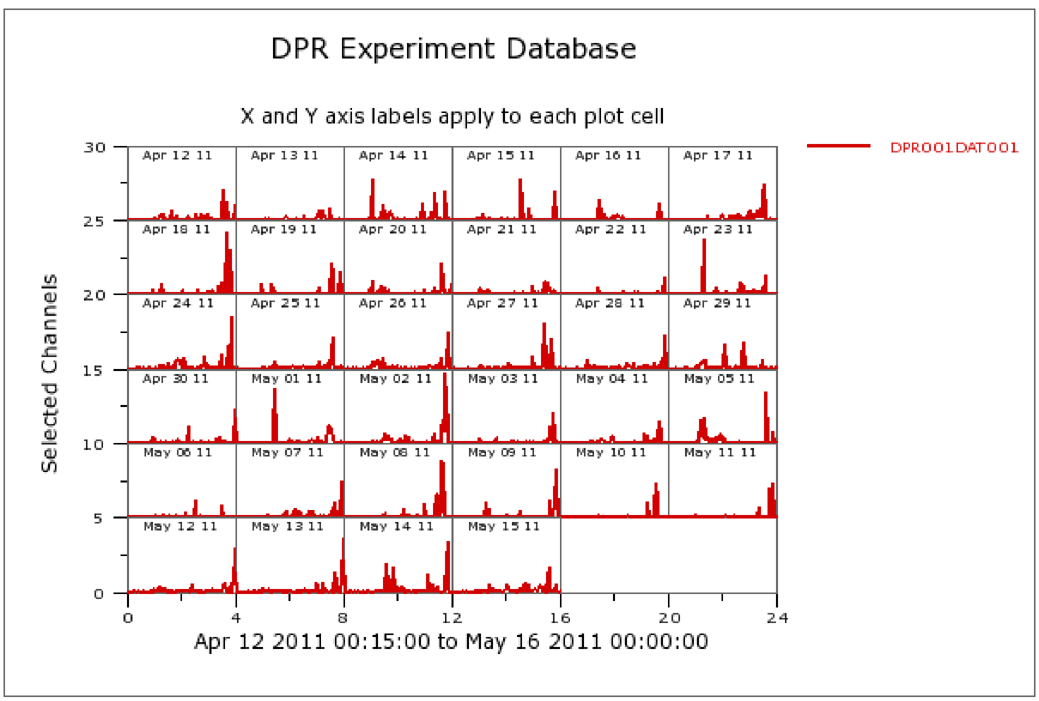

Figure 50. Measured daily hot water gallons used each 15-minute interval on calendar plot from April 12 through May 15, 2011. Provides an indication of the large day-to-day variability.

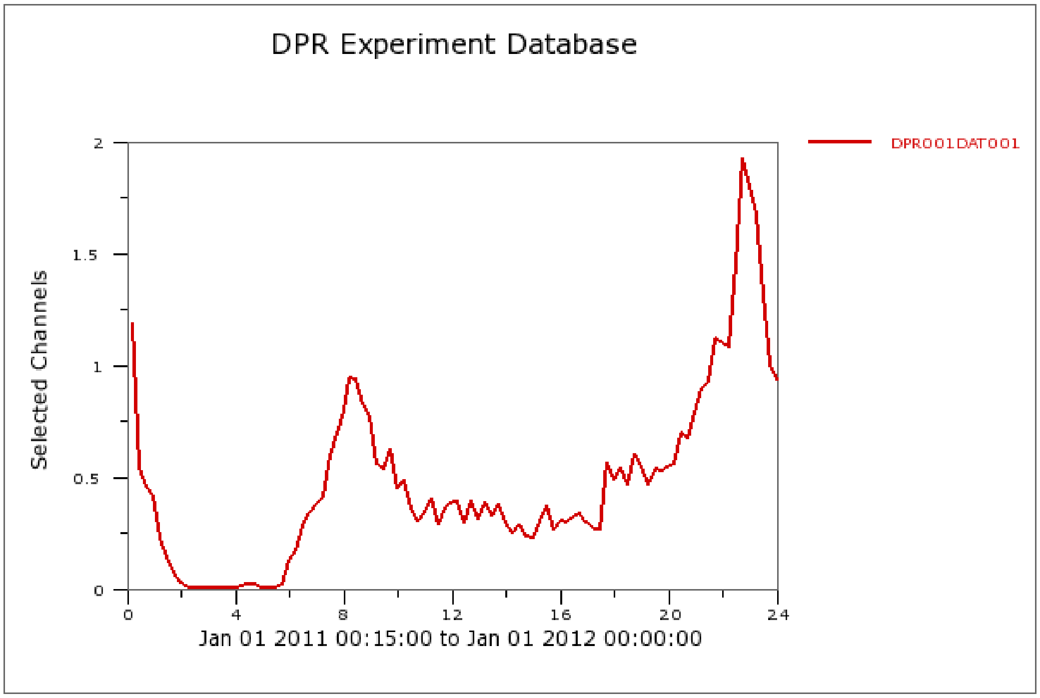

Figure 51. Measured average daily hot water gallons used on a typical day in 2011. The Y-axis is gallons per 15-minute interval. Average consumption for the four-person household was 46 gal/day over the year. The use pattern reflects two to three showers at night and hot water use associated with morning meal preparation and one additional shower.

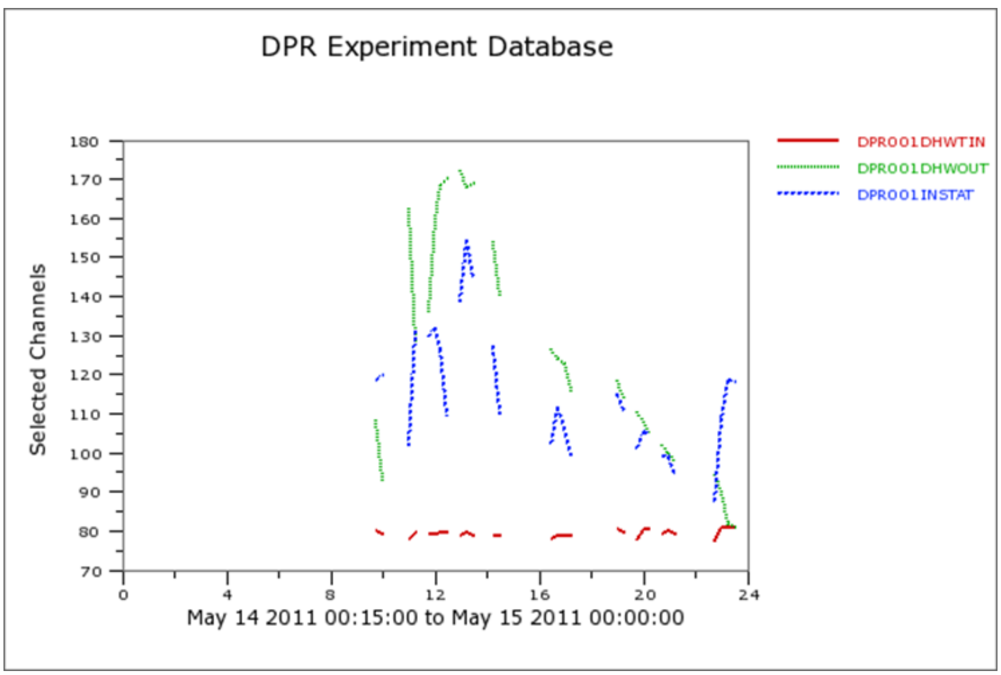

Figure 52. Thermal performance parameters of the solar water heating system during draws on May 14, 2011. Inlet water temperature (red) is about 78°F. Output from solar storage tank is as high as 170°F. Output after tankless gas water heater (blue) shows considerably lower temperatures. Gas use in last evening hot water draw as the tankless auxiliary must make up for an insufficient delivery temperature (see Figure 53).

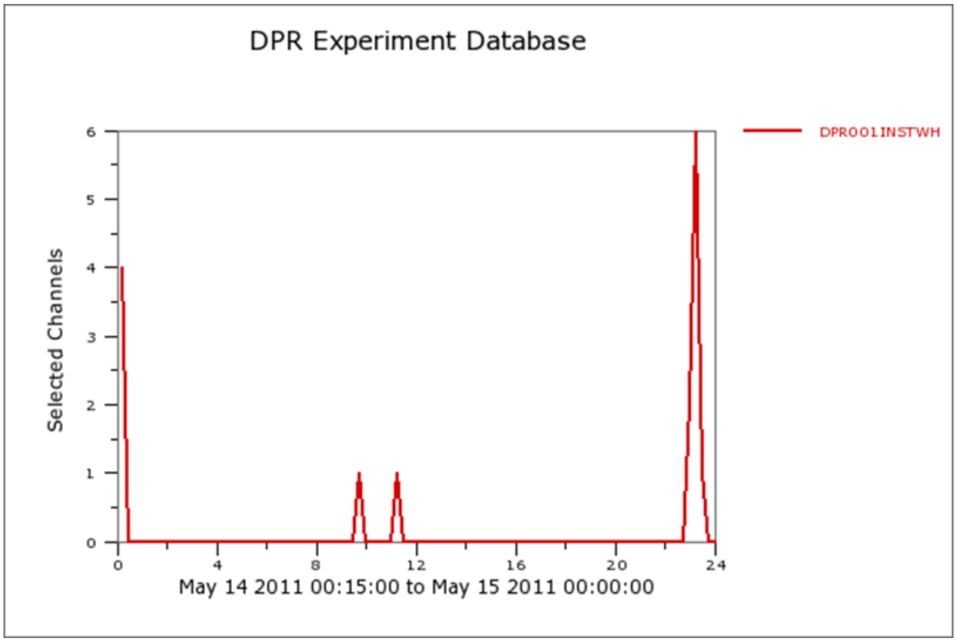

Figure 53. Tankless water heater gas use on May 14, 2011 corresponding to the solar system performance shown above. Y-axis is cubic feet of gas recorded during the 15-minute interval.

15 Remodel and Progress Toward Reducing Energy Use

15.1 Occupancy Changes and Remodel

In 1998, after the births of two children, one in January 1994 and another in November 1996, we undertook a large-scale remodel of the home. This entailed adding approximately 660 ft^2 of conditioned floor area (a third bedroom and an office). These changes, both adding household members and 50% more conditioned floor area, could be expected to increase energy use. However, at the same time, we made some improvements to reduce consumption:

- In the home remodel in 1998, new roof trusses were added that featured a standard 19-in. overhang on the east, west, and north faces of the home (see Figure 54). However, on the critical south orientation, a 3-ft overhang was specified. This prevents the large glazed dining room porch from receiving sunlight in all months but winter. This substantially reduces cooling loads and improves room comfort.
- We added two solar tube tubular skylights to the interior bathrooms and added a conventional solar control north-facing skylight (using solar control Azurlite glass) in the kitchen to reduce interior daytime lighting needs.
- We added low-sone Fantech FR150 fans to the kitchen range hood and both bathrooms to allow removal of warm moist air from these areas.
- The newly added sections of the house had R-4 insulation added to the interior of the concrete block walls. R-19 fiberglass batts were added to the attic floor above the new additions.
- Soon after the remodel, we installed high-efficiency ceiling fans (Gossamer Wind series) on-off manual wall switches that allow fans to be easily deactivated. A total of six ceiling fans were changed out. This was done in December 2000.

Within the second phase of retrofits, we pursued many actions to reduce energy loads in the home, most of which are summarized in Figure 93 (Section 16).

Figure 54. Three-foot overhang on the south face of the home and resulting shading pattern shown at noon on June 10, 2011. Note that the windows, walls, and foundation are fully shaded.

15.2 Television and Home Entertainment

Like most homes, the household has a television as well as a home stereo and associated components. When we moved into the home, this consisted of a Sony 27-in. tube television with a measured power demand of approximately 5 W (depending on picture). In 2006, the tube television failed after having reliably operated since 1988. Given the picture quality of flat screen televisions, we desired to obtain such a model for its replacement. Even with test data not typically being published, we found that the Sony Bravia series of LCD TVs had low power use (approximately 125 W depending on picture), as well as low power in standby mode (<1 W). Table 7 lists components of the revised home entertainment center after upgrading. We also used a Valhalla 2100 power analyzer to carefully measure power of both the new television and various other components used with it.

Table 7. Entertainment-Related Miscellaneous Electric Loads

Component	Active (W)	Power/Standby (W)
Sony Bravia 37-in. LCD television	150	1
Scientific Atlanta, DVR	35	26
Sharp stereo receiver (100 W output)	65	3
Sony CD* player (5 CD changer)	10	3
DVD** player	17	8
Self-powered sub-woofer	15	12

*Compact disc
** Digital video disc

We were able to verify that the power use of the television met the published specifications, but did also learn that the DVR used with it to obtain digital cable images and to record programs for later viewing consumed nearly 35 W when on and 26 W when off! Unfortunately, we also learned that there was no reliable way to turn off the DVR without sacrificing its functionality. This problem continues today.

We were, on the other hand, able to use a power strip with the television, DVD player, and audio system and sub-woofer that turned these items off when not in use. This was manually operated (in an imperfect fashion), but reduced the standby power of these combined elements by 20 W during times when the systems were unused—a saving of more than 100 kWh/yr.

15.3 Home Computers

Like many homes, the household has multiple computers. One of these consists of a desktop machine used for word processing with few other connected peripherals other than its monitor. The other machine, however, is used extensively in the home office and has a printer, cable modem, speakers, a monitor, and wireless router operating. Through detailed monitoring, we discovered the components other than the central processing unit, the cable modem and router, still consumed 25 W when the computer was not in use. Although the computer can be shut down, it was found that the computer and components were frequently left on when not in use.

To address this energy waste, in mid-2006, we installed a motion-controlled power strip (Wattstopper Isole) that can shut down the unneeded components when not in use. When someone leaves the room for more than 30 minutes, the peripherals are automatically turned off. The office occupancy sensor reduced home office loads by 25 W per nonuse hour on average (0.3 kWh/day reduction). Based on use patterns, we estimate that this measure saves about 100 kWh/year. As the motion control device sells for about $90, the payback is approximately 7 years. In the last year, two additional laptop computers have been added to the household (one for each teenager in high school), although these have not been measured.

Figure 55 and 56 show the power of other plug loads such as computers, lighting, and minor appliances in recent detailed monitoring:

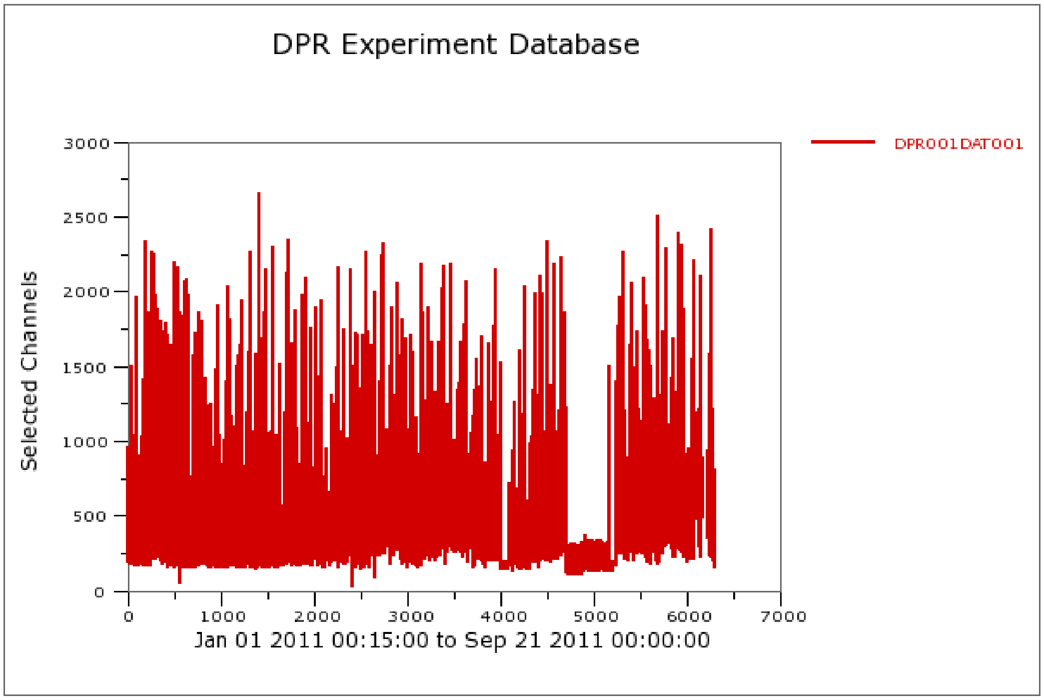

Figure 55. Measured other electricity use from lighting, television, stereo, kitchen small appliances, computers, ceiling fans, and plug loads from January 1 to September 20, 2011 (before the plug-in hybrid was added to the loads). Y-axis is Watts every 15 minutes. Home vacancy during August 2011 is quite apparent.

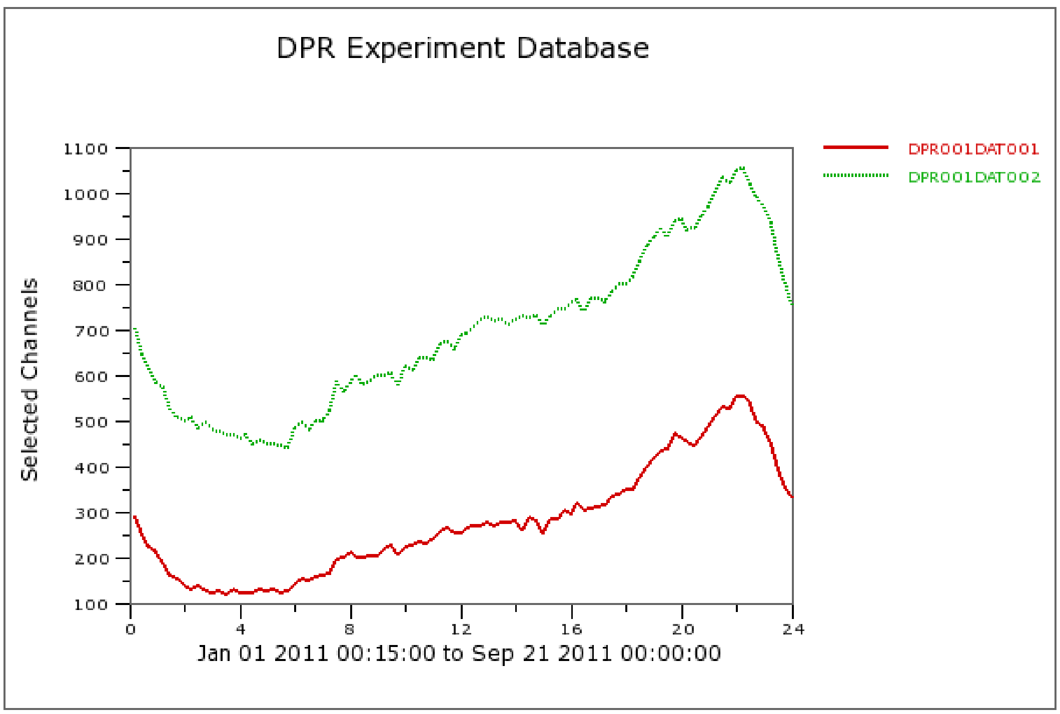

Figure 56. Average measured other electricity use from lighting, small kitchen appliances, computers, TV, ceiling fans and plug loads from January 2011 to September 21, 2011 (red). Total house electric power (green) shows that "other" is the largest component of total consumption use (6.6 kWh/day compared with total of 16.6 kWh/day). The load shape of total looks much like that of other since other is the largest component of the home's total electrical loads.

15.4 Real-Time Energy Feedback

In mid-2005, we installed a real-time electricity use feedback (The Energy Detective) device (Figure 57). This allowed us to monitor real-time household power and to track how well we were doing relative to power consumption.

Figure 57. The Energy Detective real-time energy feedback device

In April 2006, we used the feedback device with a protocol to locate approximately 90 W of phantom loads that were being wasted. This included power use in the entertainment center, the home office, rechargeable tools in the garage, an unused transformer, and a potter's wheel inadvertently left on. The protocol allows isolation of household loads through a two-person audit procedure with circuit breakers and plugs used to isolate all house-specific electricity end uses (Parker, Hoak, Meier, & Brown, 2006). The monthly electricity consumption (see in Figure 92) shows a measurable saving from this intervention at about the same time that the ENERGY STAR clothes washer was installed. The relatively low level of reduction seen on the installation of the device compared with actions shown at April 2006 suggests that feedback will be most productive when linked to actions to reduce energy, such as replacement of aging appliances, identified though using the devices as a diagnostic tool.

15.5 ENERGY STAR Clothes Washer

With a four-person household, a considerable amount of laundry is done each week. In March 2006, the existing clothes washer in the home, a Whirlpool LA5668, (modified energy factor = 0.817) failed. To replace it, we purchased a high-efficiency Kenmore 2706 clothes washer (modified energy factor = 2.00), see Figure 58. Using established methods that use manufacturer's data and DOE label information, it is possible to determine energy and operating characteristics of the washer. The energy use of the washer itself is quite small, 0.25 kWh/clothes wash cycle for the original washer and 0.09 kWh/cycle for the new unit.

Figure 58. Kenmore 2706 ENERGY STAR washer

The larger impacts, at least theoretically, are from hot water use. The original clothes washer theoretically used 17.6 gal of water of hot water per wash. The new ENERGY STAR washer uses approximately 5.5 gal per wash. Potentially, this would substantially reduce hot water energy use. However, in our case this is less influential on energy use, because given the high inlet water temperatures in Florida, we generally do a cold water wash.

With a four-person household with two teenagers, we do approximately six loads of laundry per week, as seen in the associated clothes dryer gas consumption calendar plot in Figure 59 for the month of April 2011. Thus, the electricity saved by the new machine is too small to be observed.

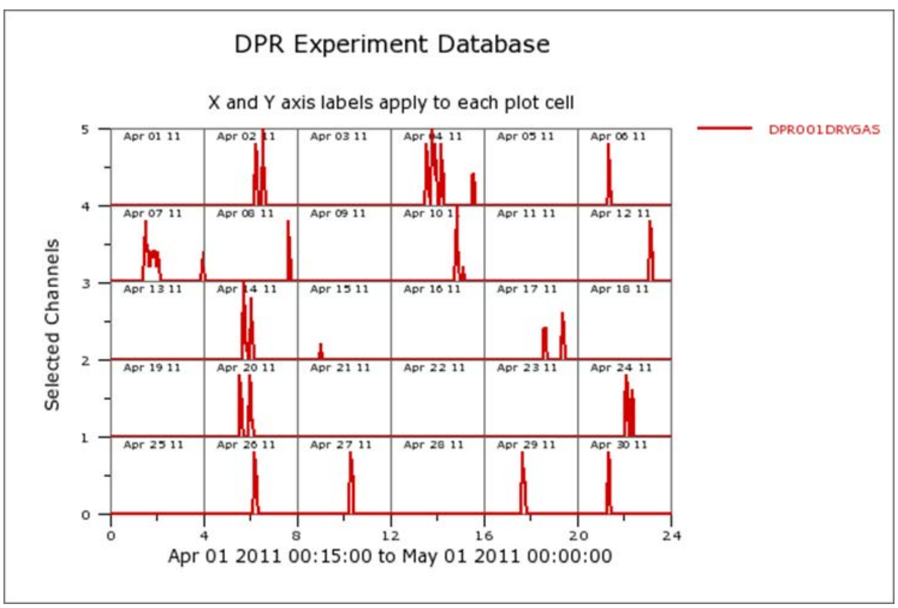

Figure 59. Calendar plot of measured clothes dryer gas use in the month of April 2011 showing day-to-day variability. Y-axis is measured cubic feet of gas used per 15 minute interval. Note that often two loads are done in a single day.

Although a vertical axis washer, the new Kenmore Oasis machine has a very high spin rate to removed excess moisture, which could reduce clothes dryer energy. Based on test data for the two machines, the original and ENERGY STAR washers would produce clothes for the dryer with a remaining moisture content of 0.5 and 0.37, respectively. Indeed the first thing noted using the new clothes washer was the faster time to dry a load of clothes coming out of the new machine. Figure 60 shows the typical gas use of the clothes dryer during a typical drying cycle.

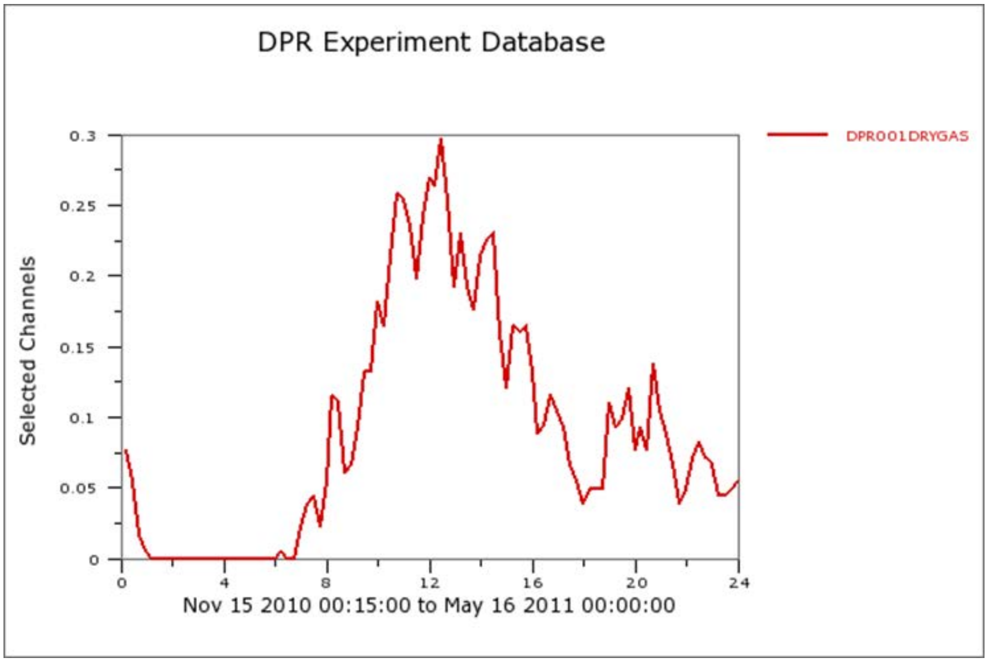

Figure 60. Average cubic feet of gas used each 15 minutes for clothes drying (January-December 2011). Shows greatest laundry activity around noon time. Average = 7.3 ft^3/day or 28 therms/year).

Consequently with the monthly gas consumption data shown in Figure 94 (Section 16), a small reduction in gas use is suggested by the new clothes washer. This may reflect reduced dryer runtime with the new washer. Impacts to gas consumption associated with reduced hot water use are likely minimal, because most is solar heated.

15.6 Energy-Efficient Dishwasher

In April 2008, we substituted a very high-efficiency dishwasher (Bosch SHX98M09; EF = 1.14), as shown in Figure 61, for the existing Kenmore 665-1658220 unit. Extensive experiments were done on the existing dishwasher and the new model (Hoak, Parker, & Hermelink, 2008). The existing dishwasher with an EF of 0.49 had a measured per-cycle machine electricity use of about 0.74 kWh, whereas the new ENERGY STAR model had a measured energy use of 0.35 kWh. We found that savings were increased by about 0.1 kWh/cycle if the dishwasher was run at midday when the solar water heater was providing the hottest water.

Figure 61. Installation of new ENERGY STAR dishwasher

As the household dishwasher is used approximately six times a week, expected energy savings should amount to approximately 122 kWh/year or about 10 kWh/month. A small discernible reduction in electricity use can be seen in Figure 93 (Section 16). There were also measured reductions to the amount of hot water used per cycle: 6.7 gal for the standard unit versus 2.3 gal per cycle for the high-efficiency unit. However, this impact could not be observed in the overall household gas consumption.

15.7 Window Replacement

The existing windows in the house were subject to air loss, thermally uninsulated, and admitted a large amount of heat to the interior from radiation. The original windows were single-glazed awning units with aluminum frames (Figure 62) that had begun to mechanically fail so that they were difficult to close and did not seal well. The situation is similar to that encountered in many older Florida homes, but had been put off for years because of the high cost of replacing windows.

Figure 62. Poorly fitting single-glazed awning windows with aluminum frames before retrofit

In the third week of August 2010, the windows in the home were replaced with high-efficiency low-e solar control double glass with vinyl frames and argon fill (Custom Window Systems: U = 0.29 Btu/ft^2-°F, SHGC = 0.24), shown in Figure 63. The windows were installed starting August 16 and completed on August 20.

Figure 63. New high-efficiency solar control low-e windows on the south side of the home installed in August 2010. These casements open fully for ventilation.

Sixteen glazing units totaling 306 ft^2 of glass were replaced. Three bids were solicited, with the lowest bid being selected. The overall cost was $13,800 ($45/ft^2), although the net cost was $1500 less because of the applicable federal tax credit. Analysis of daily A/C data on days pre and post with similar weather revealed approximately a 20%–25% reduction in cooling from the retrofit (Figure 64). This is greater than the 15% seen in an earlier study in two Florida homes (Anello, Parker, Sherwin, & Richards, 2001). We believe this was due to the large change in the building leakage characteristics from replacing the old leaky windows (McIlvaine, 2010). [11]

[11] An initial analysis of data from this cost-effective, high performance residential retrofits for affordable housing in the hot humid climate project shows that homes replacing windows were made 15% more airtight than those that did not replace windows. A key initial finding is that retrofitting windows reduces building air leakage by about 2 ACH(50) or about 14% more than whatever else was done in a sample of 41 audited Florida homes.

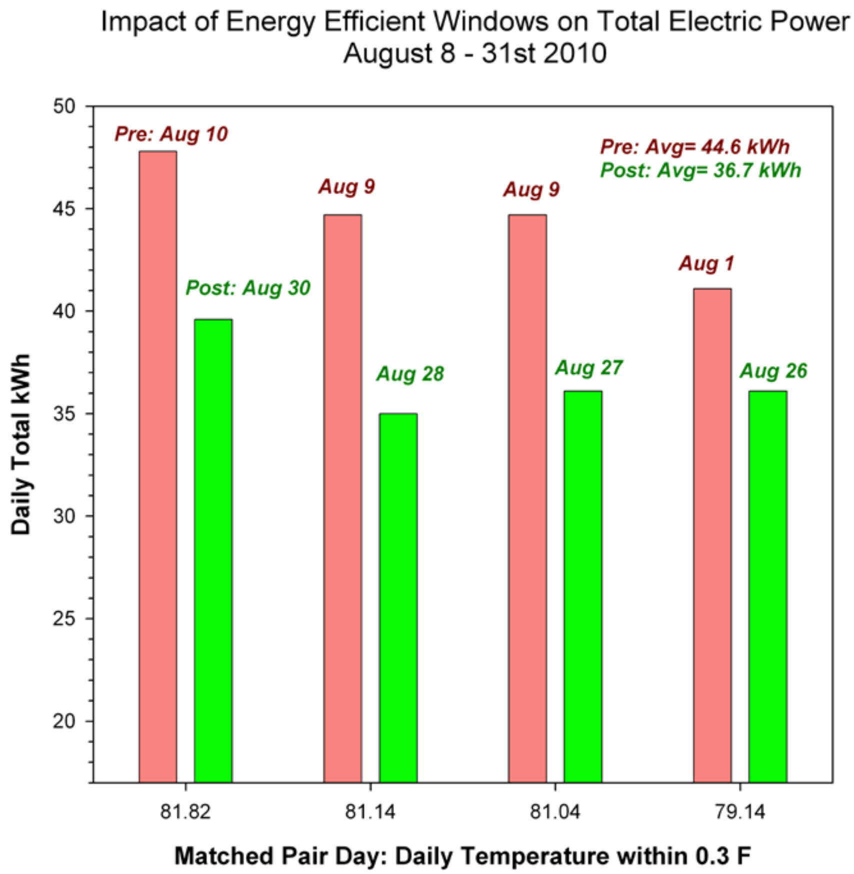

Figure 64. Measured household total electric power before and after retrofit to energy-efficient windows. Thermostat was set to a constant level; non-A/C loads averaged about 16 kWh/day. Savings appear to be approximately 8 kWh/day.

This reduction in air infiltration was verified by a blower door test, which found measured leakage of the home had dropped since the window retrofit from 24.4 ACH (very leaky) to 11.4 ACH at a @ 50 Pa pressure. Although this is still relatively leaky (average household leakage in Florida homes tends to average about 10 ACH), auditors were able to determine that the remaining leakage sites consisted primarily of two bathroom fans, an undampered kitchen range hood, two lighting recessed cans in the kitchen, and leakage from the front door and another door to the garage.

15.8 Wall Insulation Retrofit

The concrete block walls were insulated to R-5 on the exterior with an EIFS system in September–October 2010. Figure 65 shows the wall insulation retrofit in progress. The final system consisted of a vinyl stucco coat over fiberglass mesh and the 1 in. of expanded polystyrene. The final coating R-value is likely around R-5.5 Btu/ft^2-h-°F.

Figure 65. Exterior EIFS wall insulation retrofit in progress. Insulation consists of 1 in. of expanded polystyrene on the exterior covered by fiberglass mesh and vinyl texture stucco.

The total cost of the improvement was $11,300 to cover a gross wall area of approximately 1,830 ft². The net area less doors and windows was 1,398 ft², so the net cost was approximately $8/ft².

Data analysis of the impact of the walls on heating and cooling loads will have to await data from winter and summer 2011. Simulation analysis indicates only a 5%–10% saving in space conditioning energy, which is similar to previous FSEC research done on such systems (Barkaszi & Parker, 1995).

As shown in the gas consumption data in Figure 94 (Section 16), the measured average natural gas consumption prior to 2007 was 225 therms/year. However, after the installation of the better windows and insulated walls, the consumption over the last 12 months has totaled 107 therms—a reduction of 52%. As shown later, measured electricity use for the mini-split was only about 200 kWh. Although it is misleading to attribute this to the walls alone, it can be confidently concluded that the combination of the wall insulation with the better windows and the very efficient mini-split allowed a large reduction in household natural gas consumption.

15.9 Photovoltaic-Powered Pool Pump

About 20% of Florida homes have swimming pools. Pumping represents a significant proportion of the overall energy use and cost of operation. The average pool pump in central Florida uses about 4,200 kWh/year (Parker, 2002). Pumps are frequently oversized with narrow piping and small filters. They also may be operated more frequently than necessary. The average pool pump runs about 8 h/day. A detailed experimental study of 120 pools by Florida Atlantic University in 1981 found that pool pump operation no more than 4 h/day resulted in no degradation in pool clarity or increase in algae formation (Messenger & Hays, 1982).

When the home was first occupied, pool circulation was reduced to 4–6 h/day depending on the season. The ¾ horsepower (hp) pump drew about 1 kW in operation such that 120–160 kWh of monthly electricity was used to circulate the pool.

In an effort to totally eliminate this electricity end use, it was substituted with a PV-powered ½ hp DC pool pump (ETA Engineering 90 Volt DC pump). The pump runs as long as the sun is up each day from a dedicated 450 W of PV (six 75-W modules), shown in Figure 66. The system works very well compared to the ¾ hp A/C pump that was removed. It fully operates the automated pool cleaning system (Figure 67). The addition of the system produced a noticeable drop in total household electric power, as seen in monthly electricity consumption in Figure 93 (Section 16).

Figure 66. 450 W of solar modules powers pool pump directly. Solatube on white metal roof can be seen in the background. Array shown before installation of larger 4.9-kW PV system.

Figure 67. PV-powered pool pump in operation with the automatic pool cleaner operating during daytime. This retrofit saved at least 2000 kWh/year.

15.10 Very High-Efficiency Mini-Split

Fairly large cooling costs were experienced in the summer of 2010. Cooling was provided by an aging 10 SEER, straight cool split system with attic ducts and associated losses (Figure 68). In October 2010 this was supplemented with a centrally located Fujitsu 9000 Btu/h SEER 26/heating season performance factor 12 mini-split heat pump (Figure 69). The evaporator is located centrally in the living room of the home with the outdoor unit located on the exterior of the west side of the house.

Figure 68. Attic ducts, while sealed, are only insulated to R-6 and a major source of heating system heat loss in winter and cooling season heat gain in summer. Using the mini-split allows the duct system to be largely abandoned in place without these losses for space conditioning.

Figure 69. Outdoor unit of Fujitsu 9RLS mini-split heat pump as it appeared during the installation of the wall insulation retrofit. The outdoor unit is located outside the west garage.

The system cost was only $1700, including line-set, and all equipment and was owner installed. Professional installation would have cost about twice this amount. Performance specifications are shown in Figure 70.

Features | Specifications | Dimensions | Downloads

SYSTEM	9RLS	12RLS	15RLS
CAPACITIES:			
Cooling BTU/h	9,000	12,000	15,000
Outdoor Design Temp F° DB/WB	95/75	95/75	95/75
Heating BTU/h	12,000	16,000	18,000
Outdoor Design Temp F° DB/WB	47/43	47/43	47/43
SEER	26	25	21
EER Clg/Htg	17.3/15	14.5/13.3	12.5/12.3
HSPF	12	12	11
Power Supply (V)	208-230	208-230	208-230
INDOOR UNIT:			
Noise Level db (A) *Cooling* *Hi*	46	46	46
Med	42	42	40
Lo	34	34	33
Quiet	24	24	25
Noise Level db (A) *Heating* *Hi*	46	46	46
Med	42	42	40
Lo	34	34	36
Quiet	24	24	26
Weight (lbs.)	24	24	18
OUTDOOR UNIT:			
Max Fuse Size (A)	15	15	20
Running Current Clg (A) *Rated*	2.6	3.9	5.2
Running Current Htg (A) *Rated*	3.7	5.5	6.4
Weight (lbs.)	88	88	89
REFRIGERANT PIPING:			
Max Ht. Difference (ft.)	49	49	49
Max Total or Combined Length (ft.)	66	66	66
Discharge Vapor Line (O.D.) inches	1/4	1/4	1/4
Suction (O.D.) inches	3/8	3/8	3/8

Figure 70. Specifications for the Fujitsu 9RLS mini-split heat pump

The system draws only about 600 W under full load (roughly twice that of the blower alone for the central A/C system and furnace). Rated capacity is 9000 Btu/h in cooling mode and 12,000 Btu/h in heating mode. Its EER at the 95/80/67 condition is 17.3/Btu/W and at 47°F in heating mode is 15 Btu/W.[12]

The system became operational in November 2010. With the addition of the EIFS and high performance windows, it was possible to use the centrally located mini-split for heating and not utilize the natural gas furnace in winter 2010–2011. Figure 71 shows average heating power use of mini-split heat pump from November 2010 through March 2011. If room temperatures were too low, the air handler and blower could be used to provide distribution. Cooling performance will await data in the summer of 2011.

[12] www.fujitsugeneral.com/wallmounted9-12RLS_specs.htm

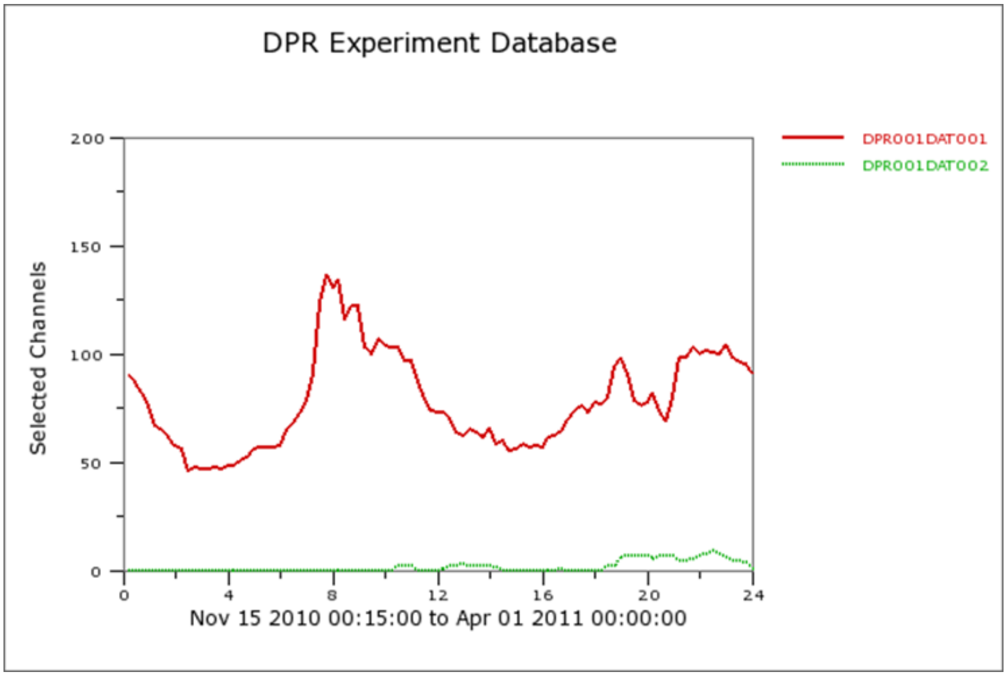

Figure 71. Mini-split heat pump (red) and central air handler power (green) (for distribution) from November to March 2011. Y-axis is average Watts. The mini-split and air handler were used only for heating over this period, consuming only 196 kWh for heating and the air handler for periodic distribution only used 4 kWh more.

Based on recent changes, it is anticipated that gas consumption will be reduced by approximately 100 therms/year and annual electricity consumption will be reduced by 1000 kWh. However, so large was the change in the interior thermal environment from the wall insulation and the installation of the better windows that the household planned to use the single living room high-efficiency mini-split to accomplish all heating during winter 2010–2011.

15.10.1 Variation in Room-to-Room Temperatures

In autumn 2010, portable temperature loggers were deployed in each room of the home prior to the use of the mini-split heat pump. One idea was to see, with the better wall insulation and windows, if it might be possible to avoid using the natural gas furnace for space heating. The attractiveness of this is apparent. Approximately 100 therms/year are used for space heating. We found that it was possible to use the mini-split heat pump in this fashion without unduly sacrificing comfort in the main living zone. However, one question that arises is what difference will be seen in the temperatures of individual rooms when using this strategy.

Figure 72 shows the measured variation in room-by-room temperatures in November and December 2010. Note that in early November, the house was floating, with no space conditioning and the room temperatures were fairly consistent, typically with less than 6°F difference from one room to the next. The higher temperature seen in the dining area comes from its large glazing fraction facing south, which tends to run warmer in daytime in winter.

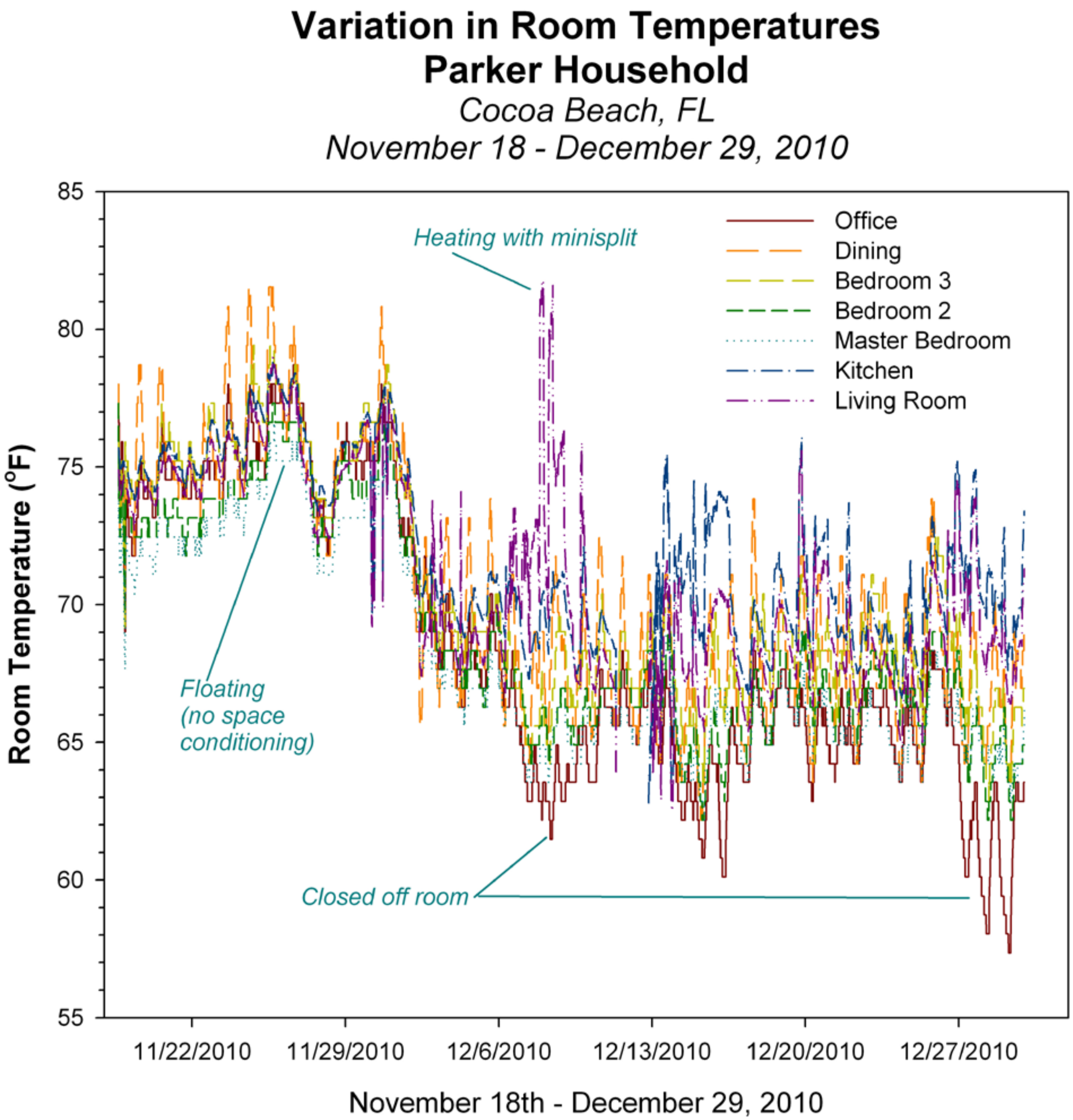

Figure 72. Measured room-by-room temperatures in home during space heating with mini-split heat pump in November and December 2010 showing the degree of variability

When space heating begins in earnest at the end of the first week in December, the temperature spreads apart with the highest temperatures seen in the living room zone where the mini-split indoor unit is located. A large office area was closed off on the southeast corner of the house to see how a closed door would influence space temperatures. Note that even ignoring the closed off room and the living room space, temperatures vary by 7°F or more from one space to another. Although this seems high, experiments this summer and next winter using the central system and the mini-split for various periods will allow further evaluation of how room-to-room temperatures are influenced by central system operation and what portion is intrinsic to the natural thermal zoning that occurs when the system is not operating.

15.10.2 Summer Cooling Experience with the Mini-Split System

In the summer of 2011, the centrally mounted high efficiency mini-split heat pump was extensively used to augment household space cooling. These systems use an outdoor unit connected to an indoor evaporator unit directly by refrigerant lines. As there is no duct system, there are also no duct leakage and duct conduction losses. Moreover, fan power is much reduced as the indoor evaporator unit needs much less fan energy for effective cooling than would be required for a central air handler. The Fujitsu 9RLS (Figure 73) has a rated SEER of 26 Btu/Wh against the 10 Btu/Wh for the aging central A/C. The system also does not have duct losses such that the theoretical efficiency may be up to 20% greater than a central system.

A series of tests were run where the central A/C system was operated for a week and compared to the mini-split operating in the periods immediately before and after its use. In this way, it was hoped to compare the energy use of the two approaches.

Figure 73. SEER 26 Fujitsu mini-split heat pump. The outdoor unit is located on the west garage outside face. The indoor unit is located inside the central living room, adjacent to the garage in the house.

Although millions of mini-split units are in use around the world (they are particularly prevalent in Asia), the systems do not provide ducted air to all rooms as with a central A/C system. However, the quality of the cooling may be adversely affected by using a single mini-split as these systems are commonly intended for use in cooling only two rooms or so, with multiple units used to cool a home. Another configuration is to use a single outdoor condenser with multiple indoor "heads" or evaporator units. [13]

A useful question to be answered was how the energy and room-by-room temperatures varied with a central system versus the mini-split. This was examined through A/B switch tests in the

[13] These are called multi-split units, although they typically have lower efficiencies than the single dedicated mini-splits. Current maximum efficiencies tend to be 20-22 Btu/Wh.

cooling season in summer 2011. Most of the summer, the mini-split was used for cooling, while during one week, we used the central cooling system with temperature distribution and power use compared.

From July 3-9, 2011, the central system was used for cooling rather than the mini-split A/C. The average temperature during this period was 82°F during this time (range was 75.8°–91.5°F). The average temperature at the thermostat was 79.1°F during this week long period. Measured central A/C power was 20.7 kWh/day of which 3.5 kWh per day was for operating the air handler. The average temperature maintained at the central hallway thermostat was 79.1°F.

Although the mini-split system was used for cooling for much of the summer, we examined the data to locate a week where the outdoor temperature was similar to the time during which the central system was used. A good match was found from July 10-16th where the average outdoor temperature was 82.3°F (73.8° - 93.6°F)—slightly warmer than the period where the central system operated (Figure 74). The average measured temperature at the central hallway thermostat was 79.3°F—very close to that maintained with the central system. The average mini-split A/C power over this period was 8.9 kWh per day—a 57% reduction over that with the central system.[14]

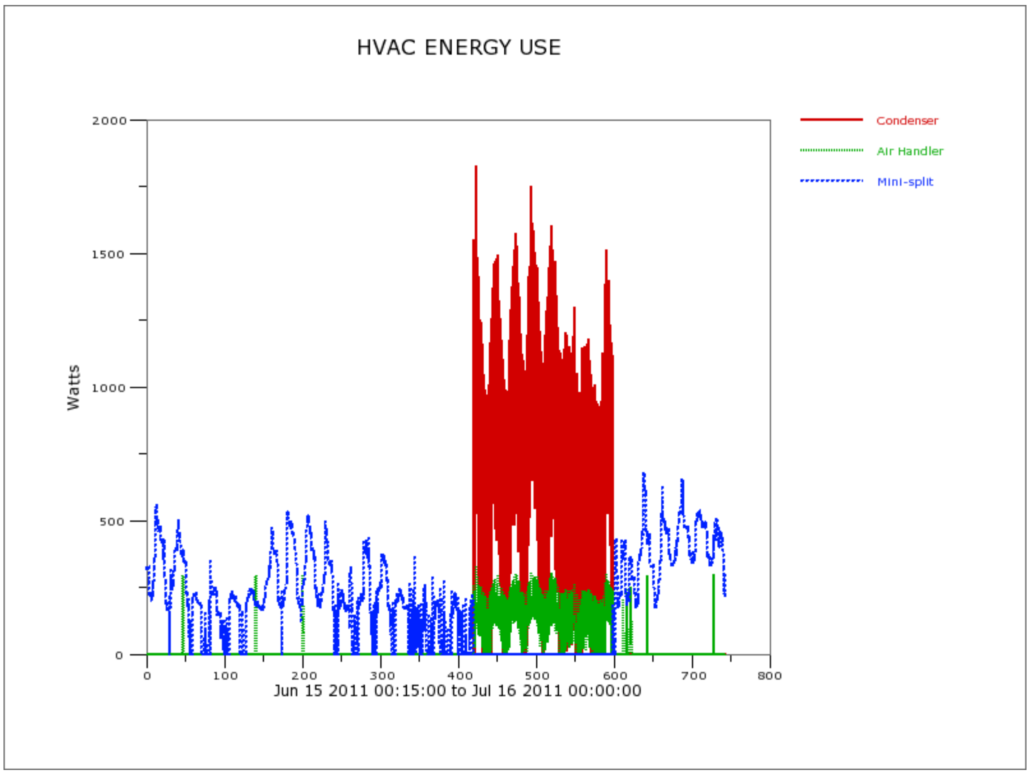

Figure 74. Measured mini-split (blue), air handler (green) and central A/C system (red) power from June 15 - July 16, 2011. The central system was used for a week-long period for a comparison. Y-axis is Watts; x-axis is elapsed hours during the period.

[14] Comparison of the ratio of the nameplate SEER ratings (26 vs. 10 Btu/Wh) would indicate a 61% reduction, such that this level of energy savings is not unexpected.

A key question in this comparison, however, is what the distribution of temperatures in rooms in the house might be like. We had two standard interior temperature probes with the project data logger which showed interior temperature and relative humidity in the living room and at the hallway thermostat. Relevant data is shown in Figure 75 below.

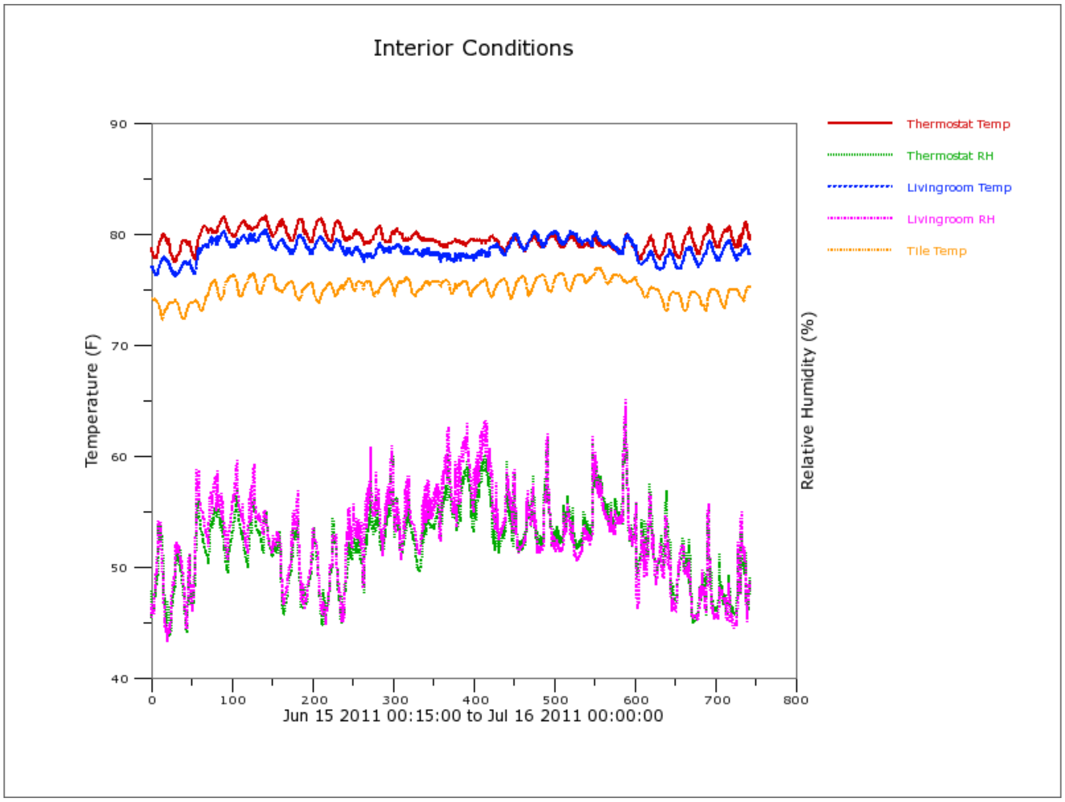

Figure 75. Temperature (blue) and relative humidity (pink) in the living room and at the hallway thermostat (red and green) during the periods where the central and mini-split heat pumps were providing comfort. Central A/C seen operating from observation 430-610. Mini-split operating at other times. X-axis is elapsed hours during the period.

Note that the data does show tighter temperature control by the thermostat during the time where the central system was operating—not unexpected since the thermostat controls the central A/C system. However, it does not seem to produce lower interior relative humidities, which are actually lower at other times when the mini-split is operating. Although the central system may have a greater moisture removal capacity, it must be noted that the central system with its large air handler likely depressurizes portions of the building envelope leading to additional air infiltration from the outside that is not produced by the mini-split system.

However, these two temperatures do not show how temperatures might vary in more distant rooms and bedrooms. To address this question, a series of portable data loggers were deployed in each room of the house during the tests. The recorded data revealed how temperatures varied across rooms vs. those measured during the periods with the central system operating. Figure 76 shows how temperatures in individual rooms varied during the two periods.

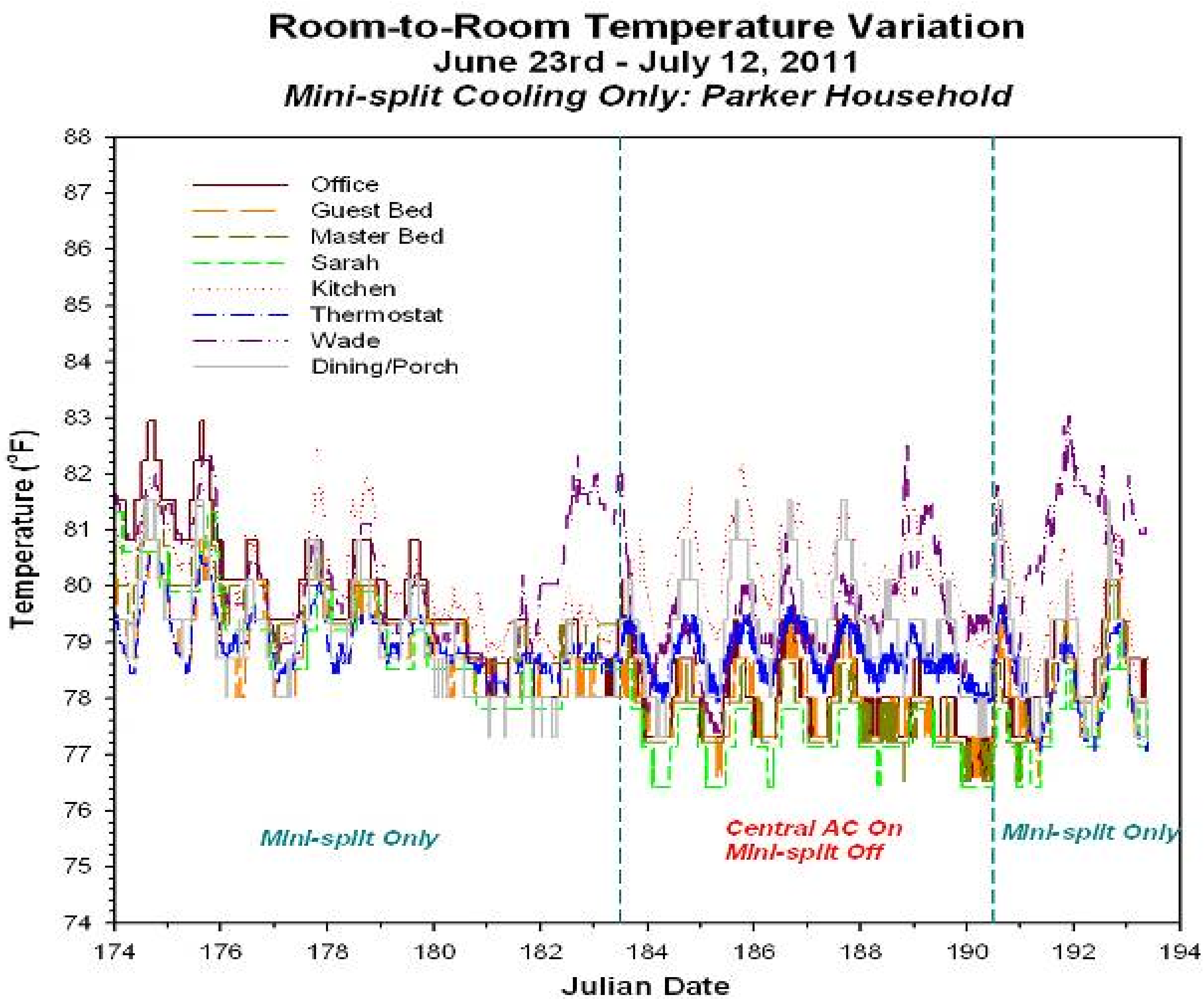

Figure 76. Comparison of room-to-room temperatures where the central system was used, versus that with the mini-split heat pump in the early summer of 2011. The x-axis is the Julian date from June 24 – July 13 on both sides of the central A/C operation.

A key observation is that while the room-to-room temperatures vary considerably during the mini-split operation, they also vary appreciably during the central A/C operation. In fact, the room-to-room temperature variation with the central A/C looks just as high as when the mini-split was operating!

The idea of a single interior thermostat setting, typically invoked in almost all computer simulations, looks to be contradicted by the collected data. The room of the author's son (Wade) shows the greatest excursions as he frequently leave the door closed and has a good amount of heat generating computer equipment leading to high temperatures. Curiously, the dining room, which is served by a large ceiling register with the central system, is not better controlled in its temperatures than with the mini-split operation.

Later in the summer, the mini-split system was operated continuously, albeit at an elevated thermostat setting when the family was away for an extended vacation. During this time of continuous mini-split operation, a ceiling fan was used in the central room to see how air temperature distribution in adjoining rooms would be influenced. Also, after occupancy was resumed on August 8, the mini-split was used with the central fan operating to assist distribution of the cooled air. Results are plotted in Figures 77 and 78.

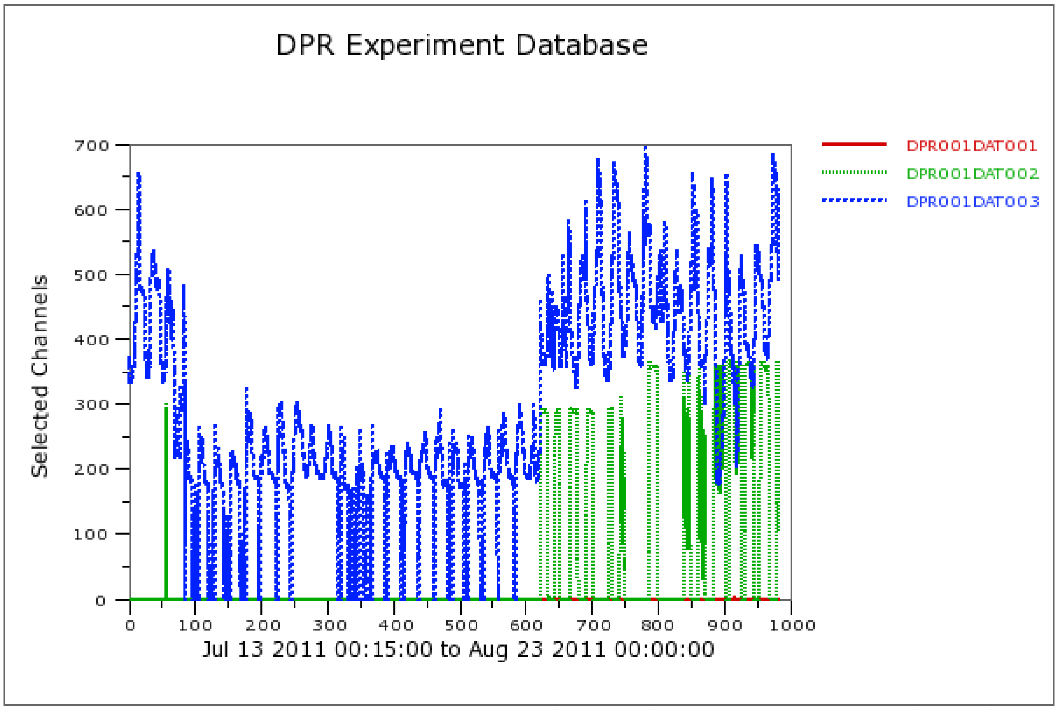

Figure 77. Measured cooling power of mini-split A/C (blue) and central blower (green) during the second half of summer from July 13- August 23, 2011. The home was unoccupied from July 15 (obs =90) until August 8 (obs= 625). During the occupied period, the central blower was operated often during evening hours to help equalize temperatures. X-axis is elapsed hours.

The data showed that while mini-split cooling consumption was quite low, using the central blower to even out room temperatures substantially increased cooling energy as the blower energy was nearly equal to that of the mini-split itself. Figure 78 below shows the room temperature distributions during this same period of testing.

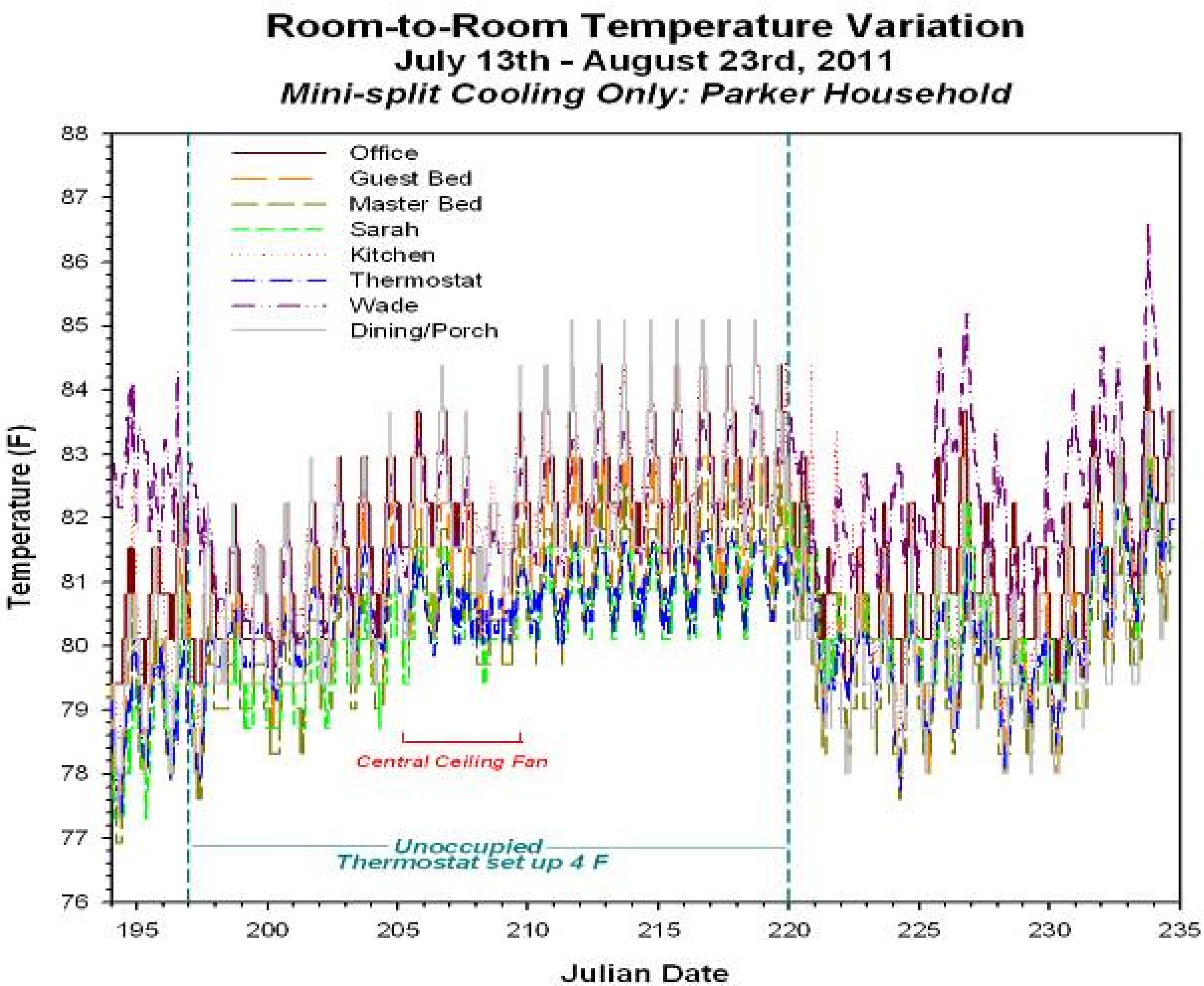

Figure 78. Plot shows the room-by-room temperatures from July 14 through August 23, 2011. During this time, the home was unoccupied for a period of time and the mini-split thermostat was set up to 82°F. All rooms were open. During a week long period, a central ceiling fan in the living room was operated to help distribution of cooled air.

Results showed that the ceiling fan did appear to reduce variations in proximate room temperatures during the unoccupied period. Use of the central blower greatly elevated overall cooling energy use, but only slightly seemed to reduce room-to-room temperature variation. The later data after occupancy for the later part of the summer also clearly shows that closing the door (Wade), can result in poor room temperature control with a central mini-split even with the central blower operating.

Review of the data for the entire summer of cooling revealed that the energy use of the mini-split system was less than half that for the central system. Also, examination of the use of the mini-split used with a central blower at night to even out temperatures revealed lower savings, but still a reduction in cooling energy use of approximately 30%. Figure 79 shows the measured cooling energy in kWh per day over the entire summer of 2011 by the varied cooling strategies in use.

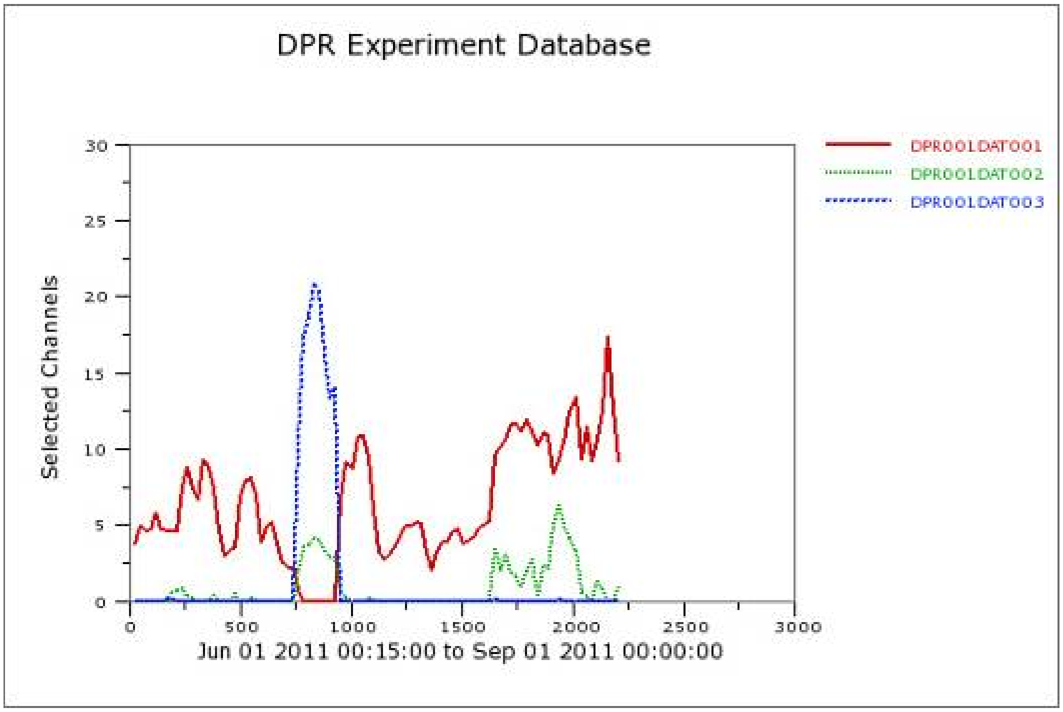

Figure 79. Measured daily cooling kWh from June 1-September 1, 2011. The red trace shows the measured energy use of the 3/4-ton mini-split. The blue line shows the measured two-ton Central AC condenser power during the week-long comparative test period with the central system vs. the mini-split. The green line is the central air handler blower which always operates when the central system runs and was also used in August of 2011 to even out the room-to-room temperature distribution. Note how using the mini-split vs. the central system cuts daily cooling energy use by more than 50%.

The measured daily electricity use in kWh for the condenser, air handler and mini-split A/C are shown during several distinct experimental periods during the cooling season in 2011.

The data indicate that using the blower to even out temperatures with mini-splits may be a limited strategy—not surprising since duct leakage and conduction are again made a significant part of the overall cooling load.

This may indicate that use of small interior duct systems for mini-splits such as being installed in California may be a better means to provide cooling distribution where perhaps two or three mini-splits can be used per household with small low-pressure drop ducts used to provide sufficient cooling distribution.

15.11 Addition of Plug in Hybrid Automobile

On September 26, 2011, a Chevrolet Volt plug-in hybrid automobile (Figure 80) was added to the house electrical loads. The idea was that the excess electricity production from the site PV system could be used to create a situation where not only the house electricity use brought to zero, but also the energy normally used for commuting to work with the primary household automobile would be eliminated as well.

Figure 80. 2012 Chevrolet Volt with an estimated driving range of 35–45 miles on the 10.4 kWh battery

The automobile includes a 16 kW DC battery, of which 10.4 kWh is available for daily use. Based on the author's driving in the fall of 2011, the 10.4 kWh of battery can be expected to provide an all-electric range of 40-46 miles per day, depending on weather (temperature and wind), use of A/C and driving speed. (The one time the car was driven to battery exhaustion, the recorded electric range was 49.4 miles.) The typical daily commute to work along with side trips and so forth typically amounts to 24 miles on weekdays. Driving on weekends and out of town periods require much lower driving time. This means that approximately half of the battery capacity would be used on the average weekday and something less than that overall, including times with less driving.

However, the 120 volt 1.2 amp alternating current charger used is less than perfectly efficient and during charging the car's battery system uses additional energy to thermally condition the battery to extend its useful life. A dedicated circuit at the home recorded the amount of electricity used for charging the car each day and the on-board computer on the car was used to record the daily DC power consumed. We found that the ratio of on-board electricity use to that used the charge and condition the car's battery was about 1.28.

The daily charging, along with periods of inactivity can be seen below in Figure 81.

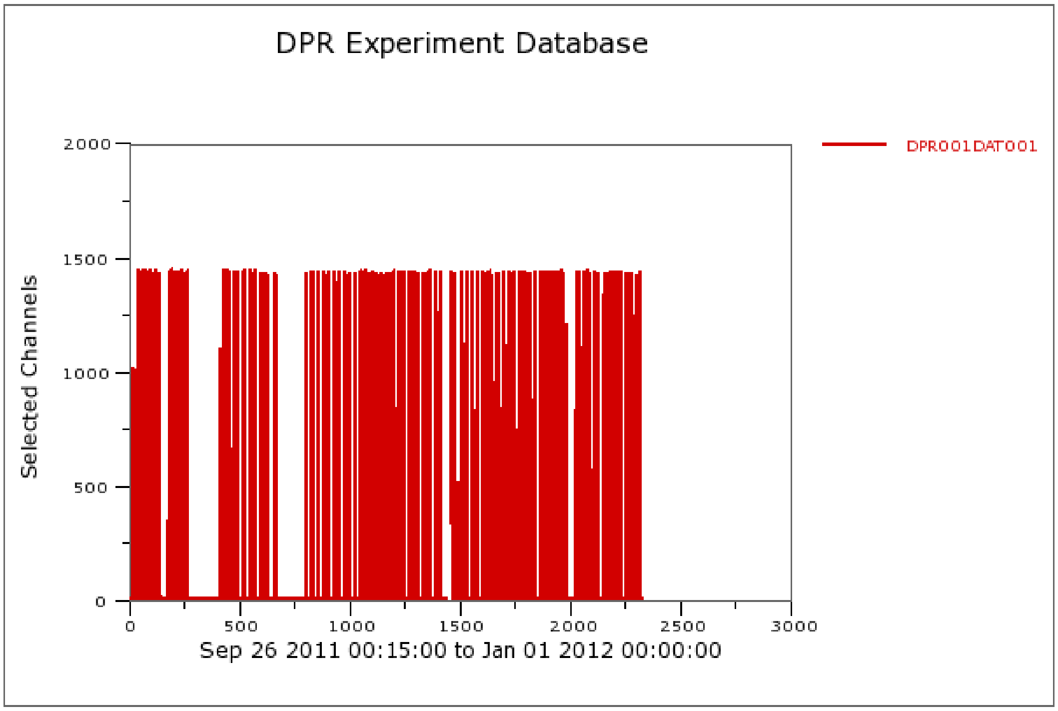

Figure 81. 15 minute data for loads from plug-in hybrid automobile recorded from September 26–December 31, 2011. The 1.2 amp 120 volt charger has a charging electric load of approximately 1.44 kW. Y-axis is 15-minute Watts; x-axis is elapsed hours.

The second calendar plot in Figure 82 reveals much more about the nature of the square-wave of the electrical demand associated with charging from day to day.

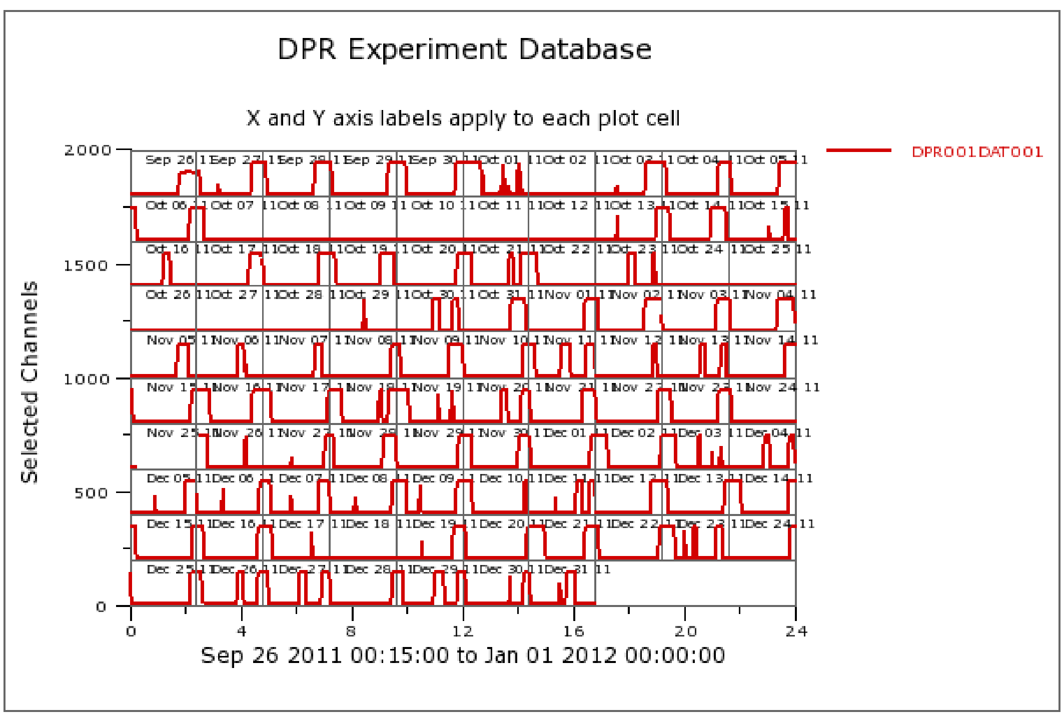

Figure 82. Calendar plot of the power draw for the charging of the plug in hybrid automobile from September–December 2011. The top value of the y-axis in each plot is 2000 W.

Even more revealing was the average daily demand profile over the 24-hour period. This is shown for September–December 2011 in Figure 83 and for September 2011 to June 1, 2012 in Figure 84.

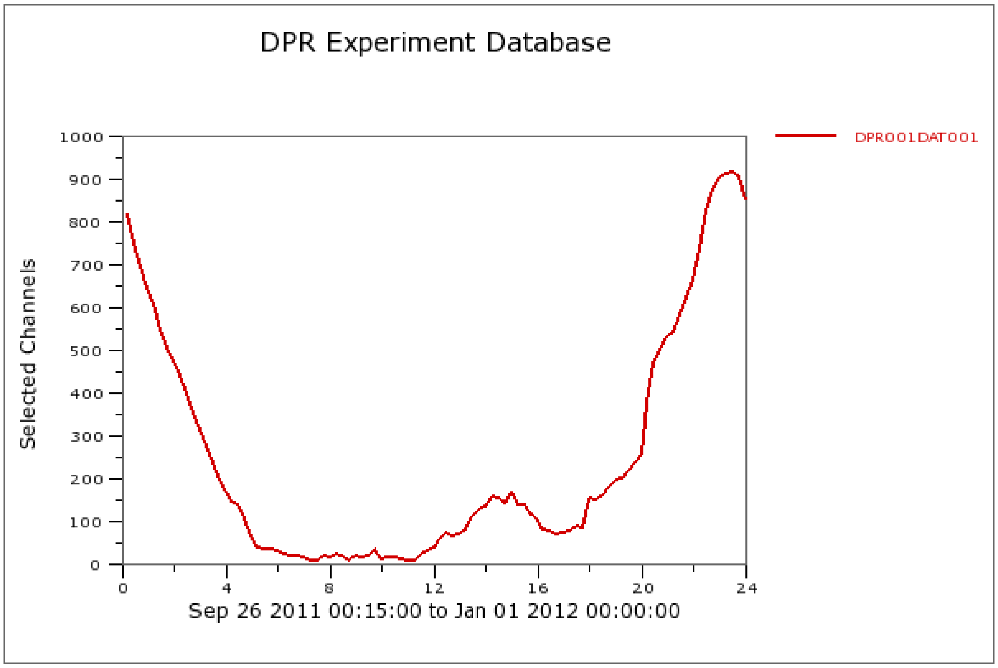

Figure 83. Average power demand profile for charging the plug in hybrid automobile in the autumn of 2011. Total daily average electricity use was 5.9 kWh per day. Note the nighttime nature of the demand profile even though no time-related preference was used for charging. The small elevation around 3 PM relates to weekend use. Y-axis is average Watts during the 15-minute period.

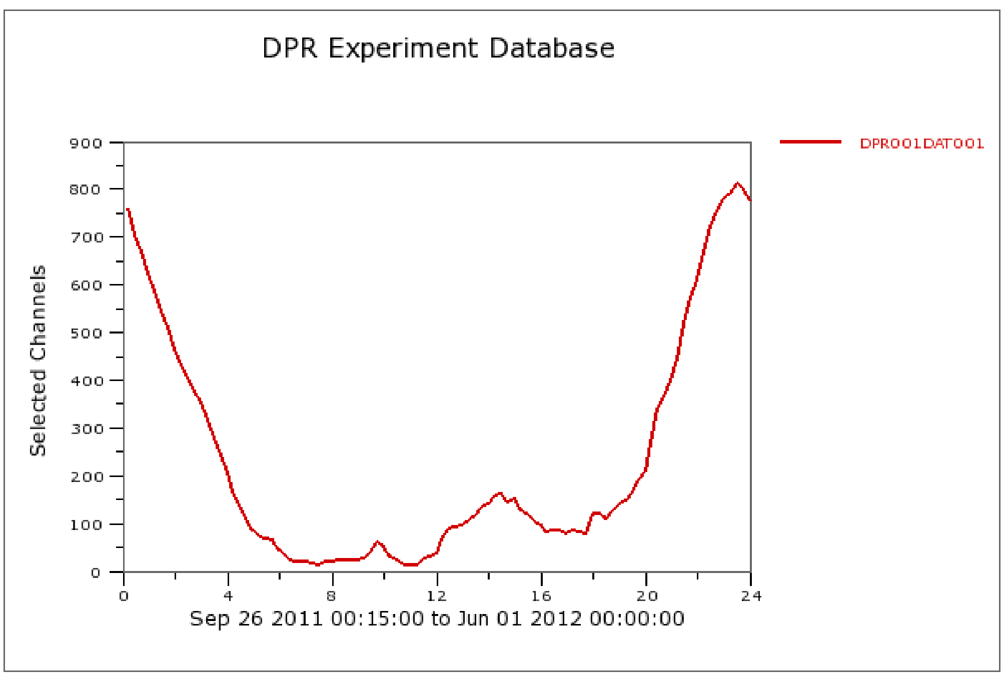

Figure 84. Average power demand profile for charging the plug in hybrid automobile from September 26, 2011–June 1, 2012. Total daily average electricity use was 5.6 kWh per day.

Total electricity use for charging the car over the available analysis period was 5.6 kWh per day with which the car was driven a total of 5,593 miles. Total gasoline use over this period was 31.9 gallons—almost all of which was used for a single trip 1,200 mile trip on February 12-15, 2012. Prior to this single trip on February 11, the car had been driven 2,803 miles with a use of gasoline of only 0.7 gallons. (The gasoline use was only to monthly condition the back up gasoline generator each month). Total home electricity to charge the car during this time was 833 kWh. Thus, our data shows the car will travel about 3.4 miles per kWh of home energy used to charge the car when operated in pure electric mode. (This measure includes all charging related losses).

Figure 85. On board display on February 2, 2012 showing 2,609 miles driven with only 0.7 gallons of fuel consumed. At this point, 776 kWh had been used at home to charge the car which had been operated in all electric mode, with gasoline only used for monthly maintenance starts.

The total performance at which time the report was written on June 1, 2012, indicated, a total traveled distance of 5,655 miles with 31.9 gallons of gasoline used and 833 kWh. The total of all-electric miles since ownership were 4,544, with 1,373 kWh used to charge the car over the total analysis period. This amounts to an electric fuel economy of 0.302 kWh per mile. When used on the long trip in non-battery mode, (with the gasoline electric generator used), the automobile showed a fuel efficiency of 35.1 miles per gallon.

In summary, the addition of a plug-in hybrid to the household loads in September 2011 has shown an average increase in electricity use of 5.6 kWh per day for a typical 24-mile daily weekday commute. The automobile shows about 3.4 miles achieved for each kWh of electricity used for charging. With the expansion of the PV system in 2012, all of the electricity used to charge the car is overcome by site-generated electricity.

15.11.1 Economic Impacts

Since the primary automobile in U.S. households are driven about 11,000 miles per year with an average fuel economy of about 24 miles per gallon of gasoline, the annual cost is about $1600 at a fuel cost of $3.50/gallon.

Similarly, the cost of utilities at 20,000 kWh for a home like the one studied would be about $2400 a year. Thus, the combination of reducing both home utility costs and a primary automobile transportation costs to zero would have the effect of reducing annual household energy related expenditures by about $4000. The impact of this additional money being spent within the region would likely have large beneficial effects to the local economy since the multiplier effect is larger for non-energy related purchases. However, these impacts are beyond the scope of this study.

15.12 Photovoltaic System

The attempt to reach a zero energy existing home required renewable energy generation. As one of the most expensive elements in the overall project, it was carefully planned. After evaluating multiple bids, at the end of January 2009, we installed a 4.1-kW PV system, although the net metering did not go in until the following month. Figure 86 shows the south face of the house during the retrofit with its PV system in January 2009. The original system consisted of 20 south-facing Evergreen ESA 205 modules grid connected to an SMA-6000 inverter located on the east side of the house (Figure 87). In October 2009, we added another 820 W (4 modules) to expand the capacity to 4.92 kW (Figure 88). Average power production since the system was increased has averaged about 20.3 kWh/day. Figure 89 shows a calendar plot of power produced by the PV system in April 2011.

Figure 86. Installation of 4.1-kW PV system in February 2009

Figure 87. SMA 6000-W inverter is located on the east side of the home with the utility bidirectional meter. A ventilated enclosure was built to protect the inverter from sun and rain.

Figure 88. South roof of the home showing 4.92-kW PV system, 450-W PV pumping array, and solar water heating system (far left).

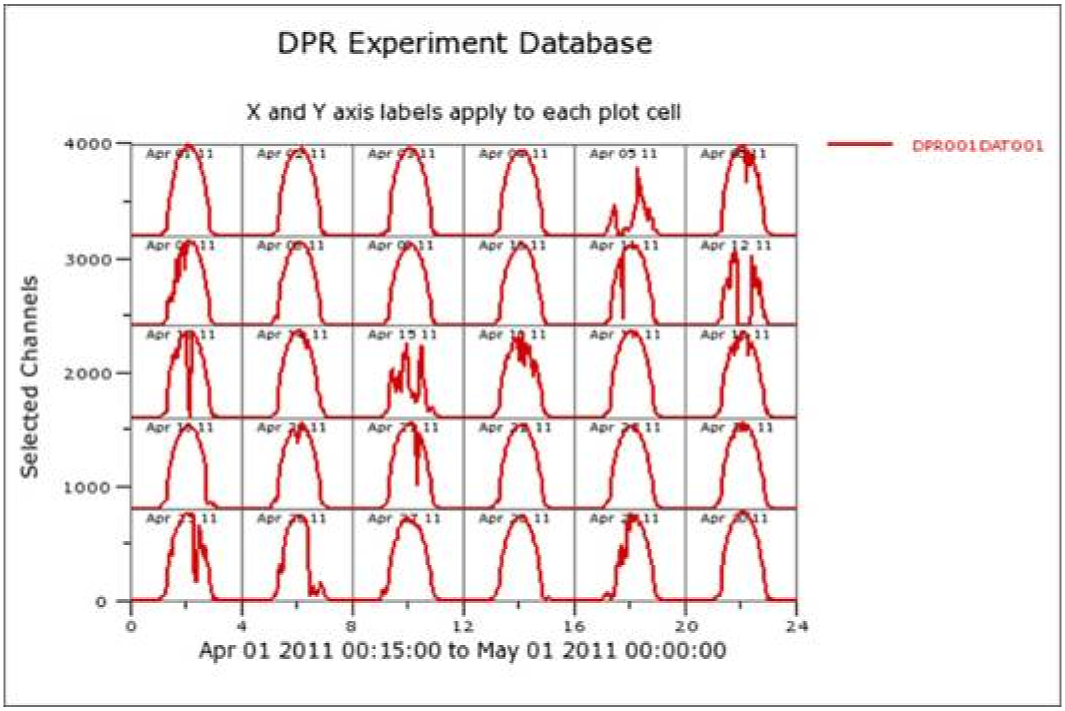

Figure 89. Calendar plot of daily PV power generated in the month of April 2011. Average daily output was 24.7 kWh/day. Y-axis is W power generation (0-2000 Watts).

More interesting, the image plots for the widening PV output band clearly show the changing day length over the analysis period (Figure 90).

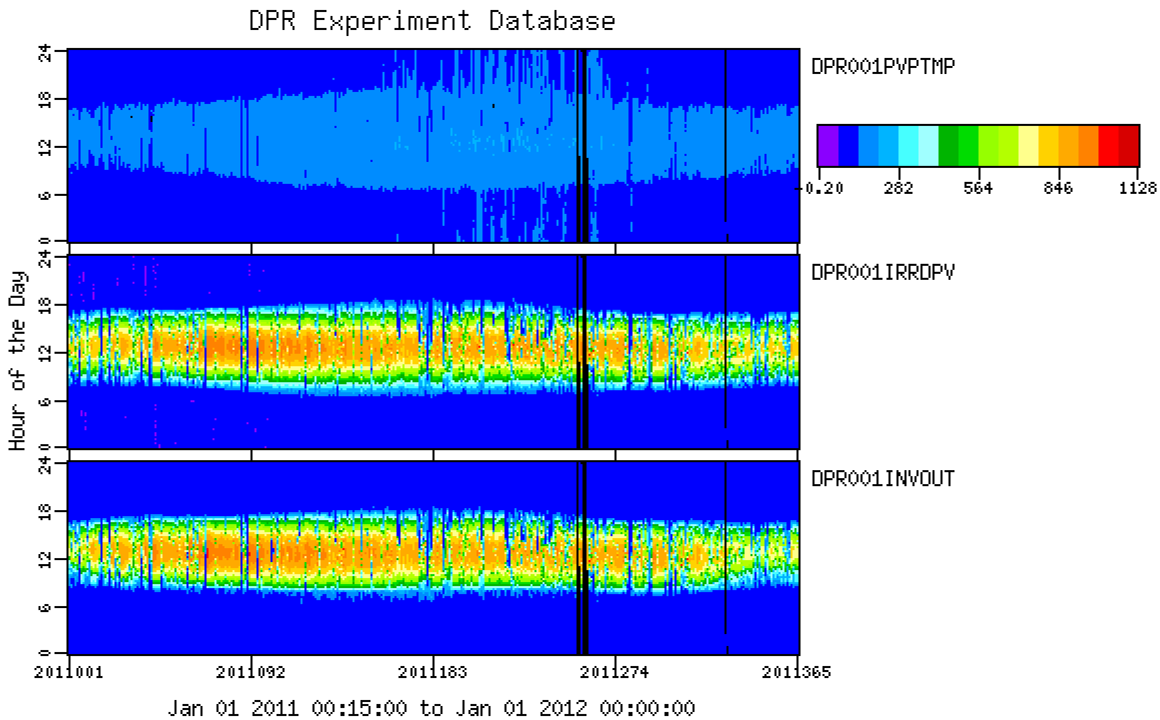

Figure 90. Image plots of the PV module temperature (top), W/m^2 irradiance (middle) and Wh/15 minutes for the PV system from January-December 2011 (bottom).

Figure 91 shows how the plane or array irradiance (IRRDPV) closely corresponds to the inverter power output (INVOUT) every 15 minutes. In Figure 90, the PV module backside temperature is also shown with the obvious finding that module temperatures increase as summer nears.

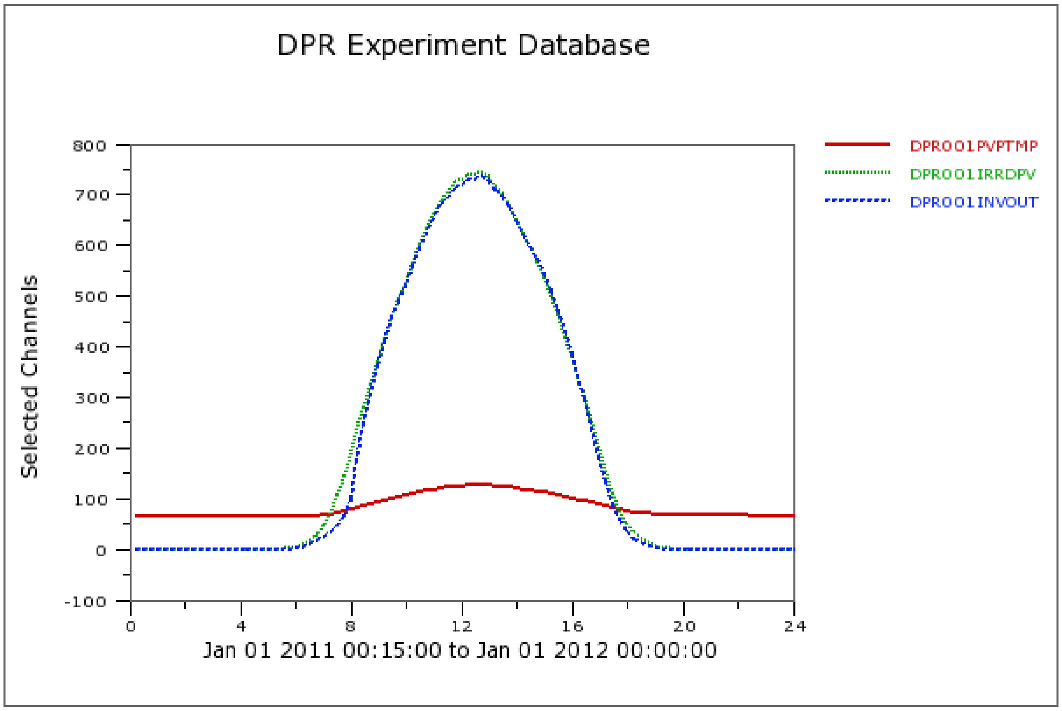

Figure 91. Annual PV output summarized over a daily cycle. Note the array irradiance (green) and the inverter output (blue) every 15 minutes is virtually identical for the 4.92-kW array. This means that power output for 15 minutes is well predicted by array irradiance (W/m^2) * 4 kW. Note that inverter efficiencies appear somewhat better at maximum output but somewhat lower on morning startup. The PV array panel temperature is shown in red in degrees.

15.12.1 Expansion of Photovoltaic System

In February of 2012, the south-facing PV system was expanded a second time to its final configuration. This was done so that a zero source energy household budget could be maintained by producing the extra 6 kWh per day required to charge the plug-in hybrid automobile.

A total of eight 210 W modules were added, expanding the configuration to 6.60 kW—the maximum possible with the existing inverter. The connection was altered to a two-string arrangement that may reduce inverter efficiency slightly due to the lower system operating voltage. Figure 92 below shows the plotted PV output in W from January 2011 to May 2012 with the increased power output from the expansion clearly visible.

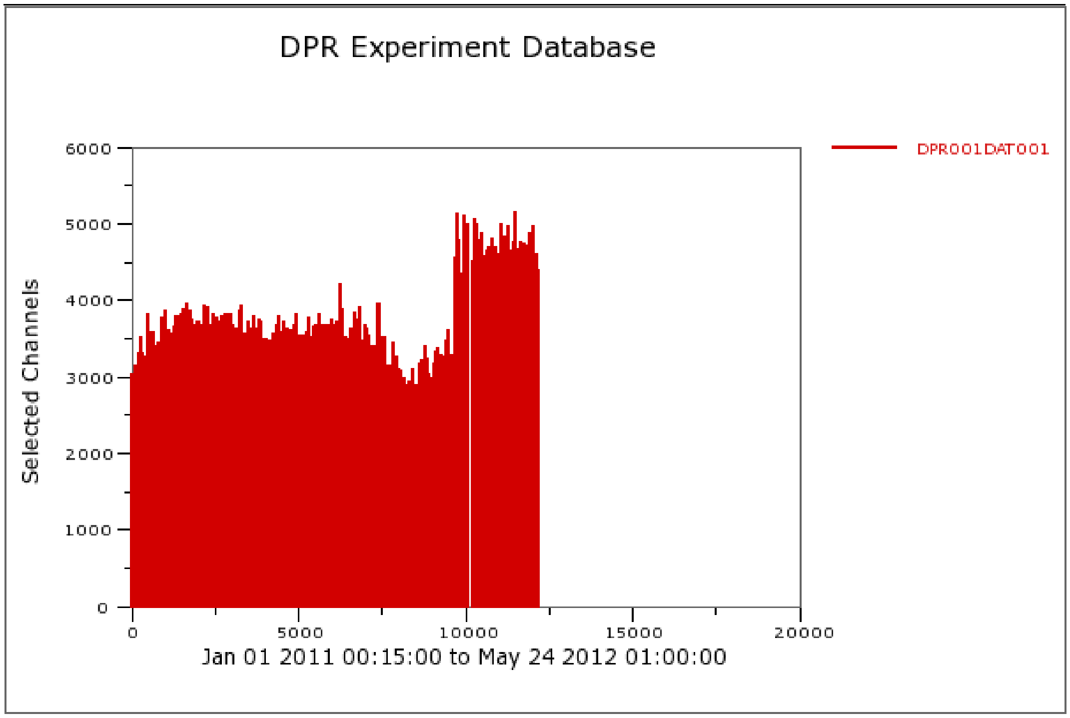

Figure 92. Plot of 15-minute output of solar PV system from January 1, 2011 to May 24, 2012. The PV system was expanded from 4.92 kW to 6.60 kW on February 8, 2012. Y-axis is AC Watts. X-axis is the elapsed 15-minute periods.

By way of comparison, the daily PV output from the rooftop system was 23.02 kWh per day from February 8–May 24, 2011. With the larger system over the same timeframe, the output of the 6.60 kW system was 29.27 kWh. Allowing for variation in weather, and slightly lower inverter efficiency, the 27% increase in the daily output is closely proportional to the increase in size of the array (34%).

16 Combined Retrofits

16.1 Long-Term Utility Records: Electricity Consumption

More than 20 years of utility data were collected for the home and then used for retrofit analysis. Figure 93 illustrates the monthly electricity consumption, which totaled 9,774 kWh from April 1990 through March 1991. The data clearly show increased electrical consumption associated with A/C in the months of July–September. The electrical base load, including hot water use, initially appeared to be about 600 kWh/month.

The figure also shows the annotated 23-year history of electricity use at the Cocoa Beach home. Monthly recorded kWh, as well as the 12-month moving average, are shown. The figure also shows the various retrofits and changes that we made to the building and to the family. Some of these changes reduced energy use, but some changes also increased consumption.

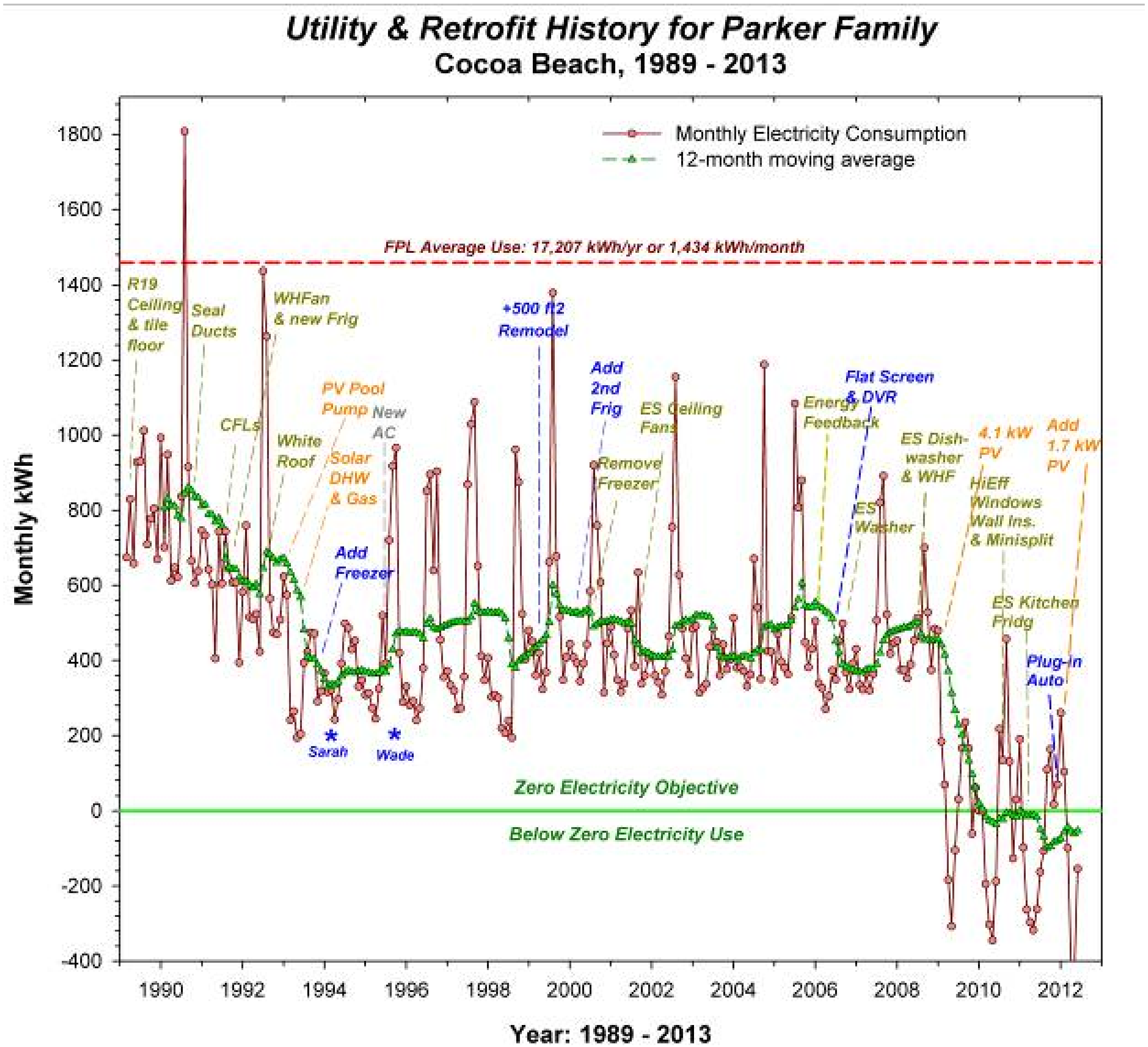

Figure 93. Changes to electricity consumption over the 23-year occupancy of the home

Each of the retrofits is superimposed on the plot of the month-by-month electricity consumption (red) over the entire history of house ownership. The green triangles show the moving 12-month average, which takes out much of the seasonality of the data.

With the addition of the PV system, the moving 12-month average has reached zero electricity and below. Since installation of the PV system, and subsequent improvements, the household has not had an electric bill other than the cost for connection and tax. This totals $6.98/month. Moreover, at the end of 2010, the household received a credit from Florida Power & Light Company for $7.50 to compensate for the 190 kWh leftover credit at the end of the year.

Figure 94 shows the same type of presentation for natural gas, but only with the retrofit items shown that are expected to have an impact on that fuel use.

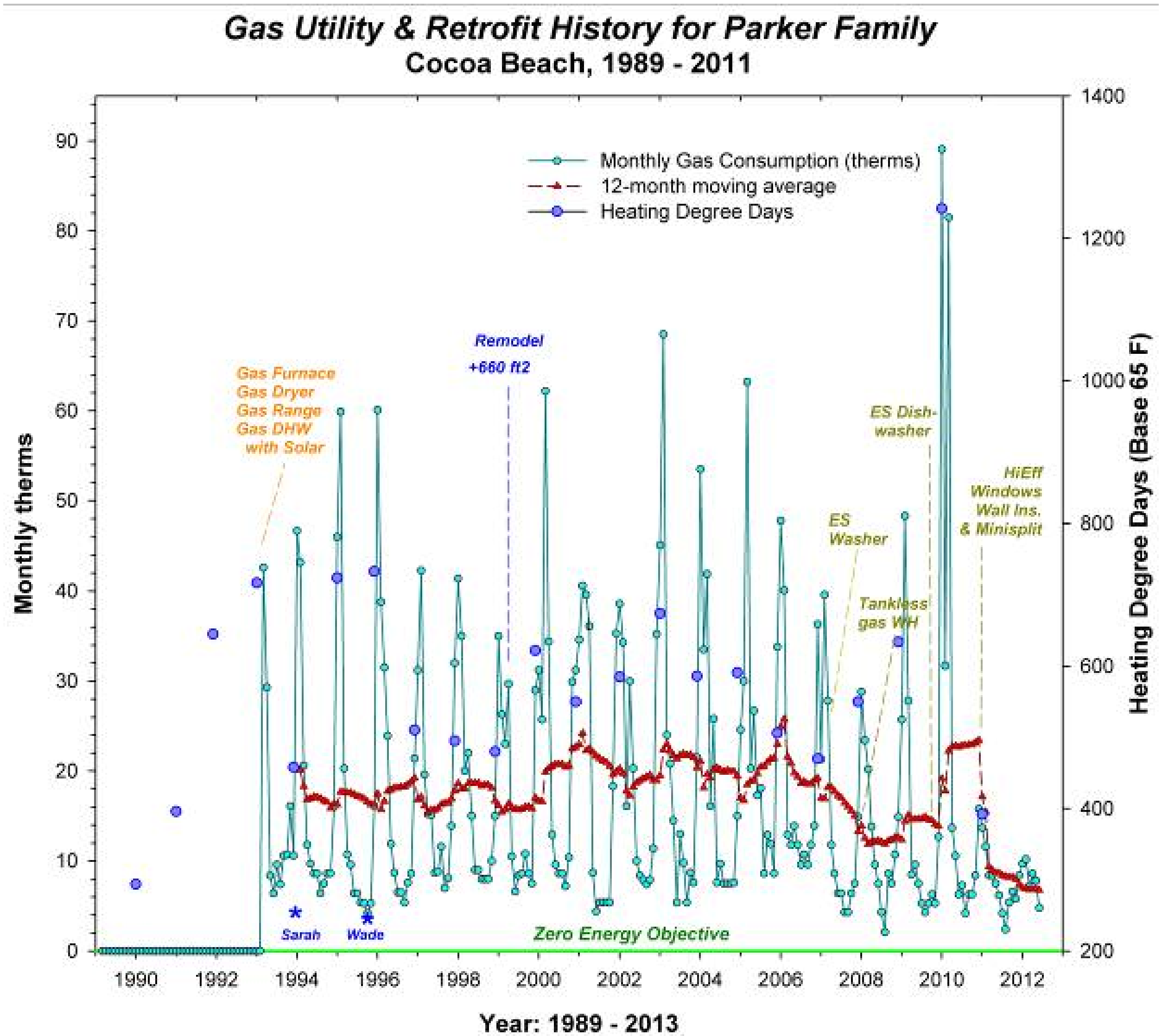

Figure 94. Changes to natural gas consumption over the 23-year occupancy of the home. Natural gas was installed in February 1993. The red triangles are the 12-month moving average.

16.2 Changes to Natural Gas Consumption

Figure 94 shows a similar presentation on how natural gas consumption has varied since gas was added to the home in February 1993. This was done in hopes of dropping the household electricity consumption as well as total source energy.

The following end uses were changed from electricity to natural gas all in the same month:

- Water to air heat pump to natural gas furnace (AFUE = 78%)
- Electric water heater to solar water heater with EF 0.54 natural gas storage water heater
- Electric clothes dryer to natural gas clothes dryer
- Electric range to natural gas range/oven.

Heating degree days are also shown on the plot as space heating is a major end-use of natural gas—particularly as seen in the cold winter of 2010.

16.3 Reduction in Source Energy Use

As seen in the analysis, natural gas was substituted for the following end uses in 1993:

- Water heating (with solar)
- Clothes drying
- Space heating (gas furnace)
- Range and oven.

Because electricity typically takes more energy to produce a unit of energy, it is useful to examine how source energy changed with the retrofits. Here, source energy use per month is given in million Btu. The conversions are according to the Building America analysis methods (Hendron, Anderson, Christiensen, Eastment, & Reeves, 2004, August) to reflect the following multipliers:

- Electricity: kWh * 3413 * 3.365 = source energy electricity MBtu
- Natural gas: Therm * 100,000 * 1.02 = source energy natural gas MBtu

The sum of these two items is plotted in Figure 95. Note that no large reduction is seen from the substitution of natural gas. Part of this is explained by timing. Two additional family members were added very soon after this change, with known increases to clothes washing (uses more hot water), clothes drying, as well as cooking. Thus, source energy consumption rose from 1993 to 1999 after remodeling that added 50% more conditioned floor area as well as a second refrigerator. From 2000 to 2006, consumption remained relatively stable, but with a drop seen from the addition of energy feedback and an instantaneous gas water heater. Much larger reductions are seen recently as the PV system was added, as well as better windows and wall insulation that have allowed most space heating to be accomplished with a single central mini-split heat pump.

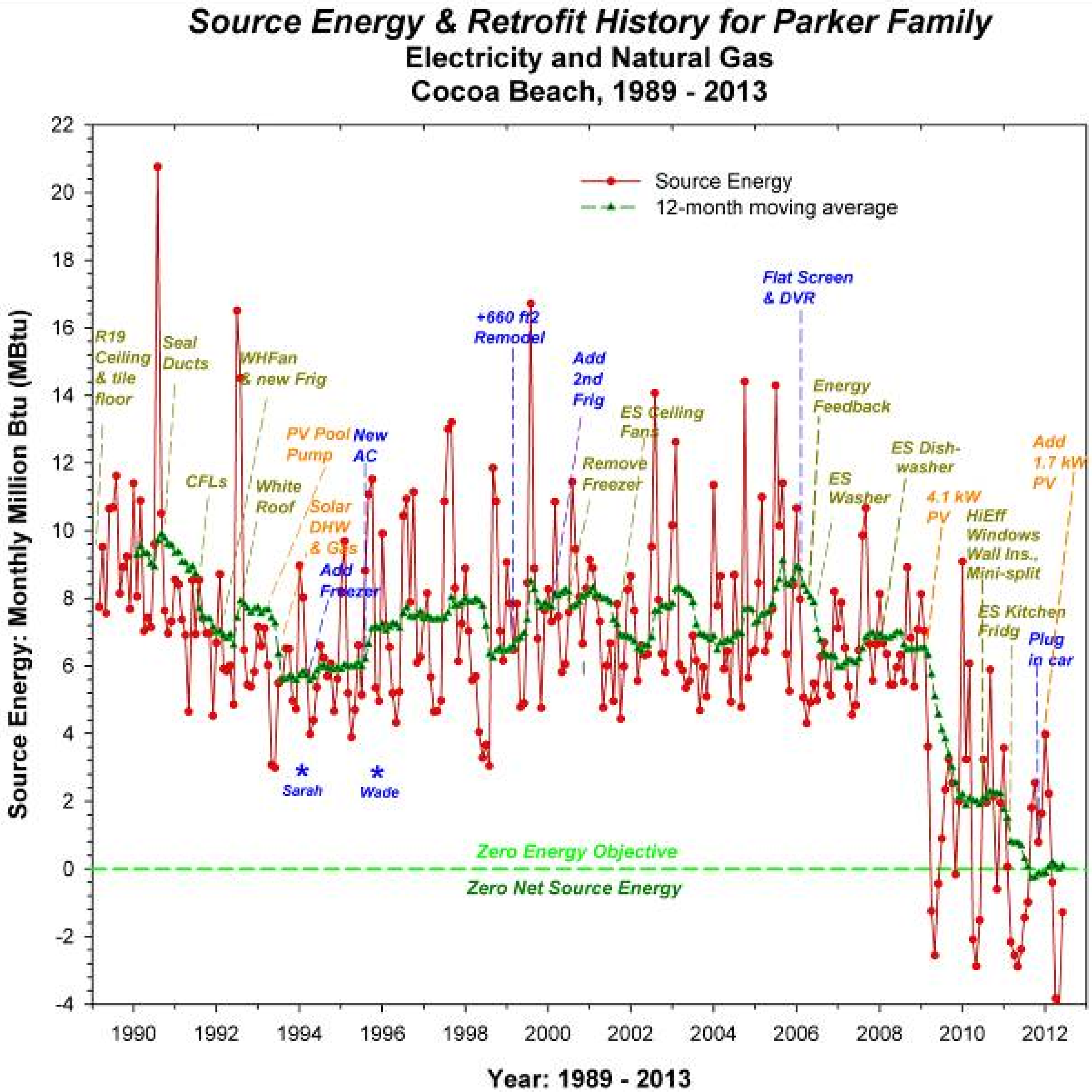

Figure 95. Changes in source energy use over the 23-year period of home occupancy. Green triangles are the 12-month moving averages. Source energy use has dropped by about 90% over the period.

16.4 Net Energy Use Since Installation of Photovoltaic System

In 2009, the 4.1-kW PV system produced 6,052 kWh in 11 months (approximately 18 kWh/day), which was 98% of household electricity consumption. Net electricity use in the year was 112 kWh. Annual natural gas use in 2009 was 155 therms for heating, hot water, cooking, and clothes dryer, but true zero energy remained the primary target. Total source energy use in 2009 was 17.1 MBtu. Figure 96 shows recent data about how the PV power production profile compares with the house electricity demand from January through December 2011.

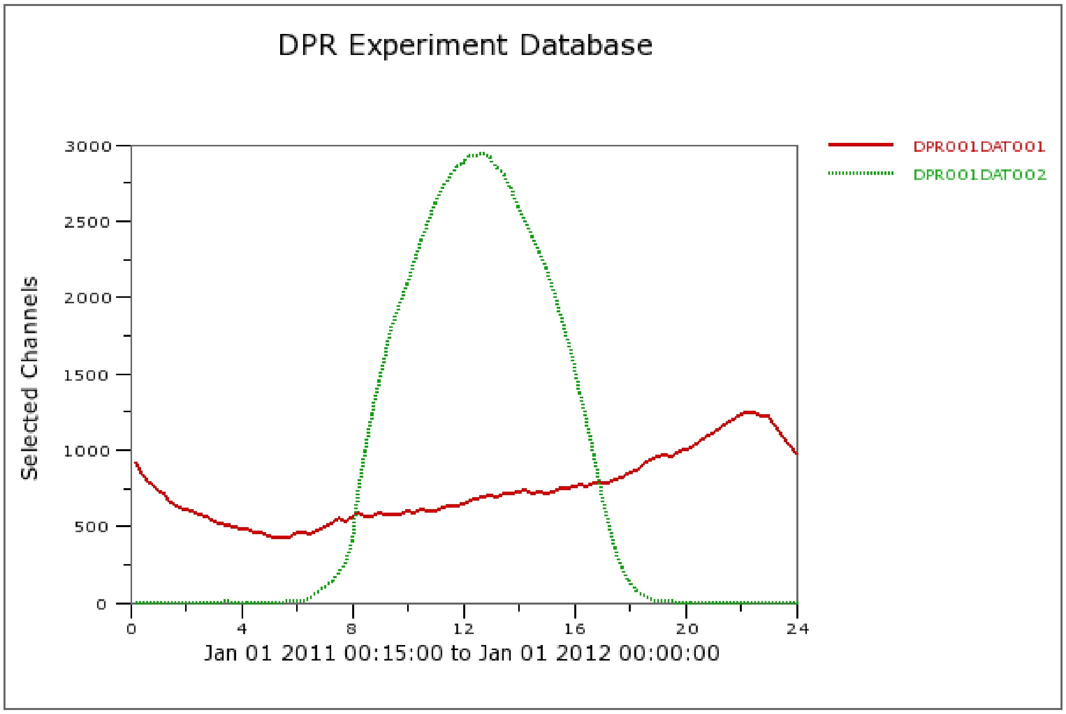

Figure 96. Total house power (Watts in red) against total PV output (green) from inverter (January–December 2011). House power averages 17.6 kWh/day; PV output averages 19.7 kWh/day.

In 2010, the output of the 4.92 kW system totaled 7,415 kWh (20.3 kWh/day), which was 190 kWh more than the house used (7,225 kWh). Summer 2010 featured considerably greater A/C than the previous year from an aging A/C. Also, natural gas use increased to 205 therms during 2010—stemming from a much colder January and February with considerable space heating before installing the insulation. Total source energy use in 2010 was 20.7 MBtu. This compares to about 230 MBtu (20,000 kWh) for a house of the same vintage with a pool in Florida.

In 2011, the output of the PV system totaled 7,197 kWh (19.7 kWh/day), which was 766 kWh more than the house used (6,431 kWh or 17.6 kWh/day). This level of surplus was achieved even after a plug-in hybrid car was added in September 2011. Electrical charging of the car used 568 kWh over the balance of the year. Most of the drop in electricity use came from the better windows, insulation and mini-split A/C, which reduced A/C use significantly. Experiments were also run showing the large differences in the energy use of the mini-split A/C vs. the central system as well as the room-to-room temperature achieved.

Given the sharp drop seen in natural gas consumption in winter 2011 with the improved windows and wall insulation allowing the use of the mini-split for all space heating, gas consumption in the preceding 12 months was cut to only 84 therms versus 221 therms in previous years.

Figure ES-2 shows that the 12-month moving average of source energy consumption in the home had been reduced by 90% to only 1 million Btu/month. Compared to average homes of the same type and vintage, the reduction is more than 95%. *In 2011, the home achieved zero net source energy (in fact, a -0.39 million source Btu surplus) in the calendar year. The additional 766 kWh* *offset the natural gas use when the comparative generation effectiveness to produce the offset electricity is considered*.

16.4.1 Data Sharing Website

Since the installation of the detailed monitoring system in November, the 15-minute data acquired are shared on the Infomonitors.com website: www.infomonitors.com/dpr.

A summary of the data on the Infomonitors site from November 15, 2010 to May 15, 2011 is shown in Figure 97. Note that during this period, the house produced 907 KWh more than it used.

Nov 15 2010, 00:15 -To- May 16 2011, 00:00 EST		
Total Electric Energy Use	**Peak kW**	**kWatt-hrs**
Consumption from utility	3.4	2635.4
PV production	12.1	3542.7
Fed back to Utility	12.5	2755.1
PV used by house	2.3	787.5
Net purchased electricity	3.4	-907.4
Selected Electric Energy End Use	**Peak kW**	**kWatt-hrs**
House consumption	5.4	3422.9
A/C Condenser	0.0	0.0
Air Handler	0.3	4.9
Mini-split Heat Pump	1.7	259.6
Kitchen Refrigerator	0.7	341.2
Garage Refrigerator	1.0	526.4
Whole House Fan	0.9	72.5
Lighting, plug loads and other	2.6	1430.6
Gas Consumption (ft3)	**Avg**	**Total**
Instantaneous DHW	0.1	473.3
Clothes Dryer	0.1	395.0
Range/Oven	0.1	507.0
Furnace	0.0	0.0
Indoor Conditions	**Avg**	**Min/Max**
Thermostat Temp (F)	74.2	-7.3/ 84.5
Thermostat RH (%)	60.0	4.6/ 79.2
Tile Floor Temp (F)	71.2	43.7/ 85.1
Weather Conditions & Other	**Avg/Total**	**Min/Max**
Ambient Temp (F)	65.7	29.5/ 293.8
Ambient RH (%)	74.8	24.4/ 100.0
Horz. Plane Irradiation (wh/m2)	808927.9	-7.7/ 1009.1
PV Plane Irradiation (wh/m2)	892462.4	-6.8/ 974.1
Ground Temp @ 1ft (F)	69.1	54.4/ 80.6
Garage Temp (F)	66.8	26.2/ 87.6
Hot Water Consumed (Gal)	7973.0	0.0/ 28.0

Figure 97. Half year data summary for November 2010–May 2011

17 Challenges to Efficiency and Future Retrofits

Existing homes present special challenges to achieving zero net energy relative to new structures, because certain features are difficult to alter. For instance, the case study home had a 10-SEER A/C with a standard blower that operates at a lower efficiency because of its age and difficulty achieving proper airflow. It also has a sealed duct system that is still located in the attic, leading to conductive losses in both heating and cooling modes. The installed mini-split allows existing homes to cut duct-related losses and engage in zoning of the house. The old central system may later be replaced with a higher efficiency unit that will then be run in a series of A/B flip-flop tests with the centrally located mini-split. This can potentially provide useful research to the Building America effort.

Other appliances that continue to waste energy:

- The home entertainment center has a DVR that draws 25 W and cannot be turned off without defeating the programmable recording capability. This remains a non-addressable electrical load that is responsible for approximately 220 kWh/year in consumption as well as waste heat released to the interior.
- Garage refrigerator that is using 3.4 kWh per day compared with modern refrigerators which should use less than 2 kWh per day for the same service. This will eventually be replaced.
- A clothes dryer that, while modern, has low efficiency.

17.1 Initial Comments About Retrofit Process, Cost Effectiveness, and Repeatability

It must be pointed out that within the overall project, the retrofits were not done in an optimal order or even with optimal selection based on some economic criteria. Often the improvements were made as a way for the author to learn what kind of difference the installed measure might make, even at the risk of unknown performance. Measures were installed based on convenience, available funds, or the breakdown of conventional equipment. Thus, the retrofit process was inherently arbitrary and not necessarily cost effective.

It must be said, however, that the overall process has provided a number of lessons learned and has provided information to bracket energy savings and measure costs. Although up until now, there has not been an attempt to establish the specific savings of the various measures installed, we intend to explore this in the final report. This process will be one of considerable uncertainty, however, as the point at which improvements are most efficient can have a large impact on the achieved savings.

Similarly, replacing components on burnout (replacement) can have considerably differing economics. Thus, we may depend on simulation analysis to help with this evaluation, which will also be necessarily approximate.

17.2 Opportunity for Addressing Refrigeration in Florida Homes

Based on FSEC's monitoring experience, replacement of older, inefficient refrigerators may offer a significant savings potential in existing Florida homes. Approximately 20% of Florida homes have second refrigerators. The monitored garage unit in the studied house used 1.240 kWh in 2011 (nearly 25% of the total annual consumption in the studied house). Moreover, given the monitored performance of the refrigerator in 1992 and then again in 2011, degradation of performance of even efficient refrigerators can be expected. Meanwhile, the larger but newer refrigerator in the kitchen used only 604 kWh during 2011—half as much as the garage unit.

Two experiments found that cleaning of refrigerator coils was associated with about a 10% reduction in refrigerator energy. Although this maintenance did not account for the observed degradation in performance, it did agree closely with previous field experiments showing similar improvements to performance. This suggests routine cleaning of refrigerator coils every two years could produce measureable improvements to performance. One practical adoption would see future refrigerator models include an indicator lamp indicating the need for coil cleaning after a compressor runtime of approximately 5000 hours.

18 Conclusions

When the author moved into a 1958-vintage home in 1989, the structure was grossly inefficient, lacking basic ceiling insulation. Statistics show that with a family of four in a home built before 1960 with a pool, the average electricity use in Florida is about 20,000 kWh/year (Parker, 2002). Using a combination of operational strategies, appliance, and envelope improvements, it has been transformed from an average dwelling to a very near zero energy home (Figure 95). Figure 98 shows the home as it appears today. Its net use of electricity has been less than zero for the last 12 months. Moreover, natural gas consumption has dropped sharply from thermally improved windows, added wall insulation, and the use of a mini-split heat pump for heating. The excess generation of electricity from the PV system (766 kWh) in 2011 has allowed the home to reach a net zero energy performance level based on offsetting electricity use elsewhere to compensate for the site natural gas consumption. Considering source energy, in 2011, the home produced a -0.39 million source Btu surplus, even after a plug-in hybrid automobile was added in late September of that year (which added about 6 kWh per day to the energy budget). A small expansion to the photovoltaic system in 2012 promised to continue the home's status as having reached zero net source energy when all fuels are considered.

More significantly, the home now not only produces enough electricity to cover all its energy needs, but also enough to cover the daily commute to work using the plug-in automobile. The approximate annual energy savings for utility electricity and the end to gasoline consumption for the main car is estimated at approximately $4000 per year.

Figure 98. Home as it appears today from the northern exposure

In summary, based on the experiences in this single case study, zero energy existing homes appear very feasible in existing Florida homes. Moreover, the fact this has been accomplished in one home indicates that many thousands of homes could achieve similar results with appropriate will and resources. The ability to reduce home energy-related expenditures by $4000 annually while circulating these funds in the local marketplace could have large and significant effects on the local economy if such a circumstance was achieved for the majority of the public.

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