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# From Energy Guzzler to Near-Zero Energy Home: Lessons from the Phased Deep Retrofit Project

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## Disclaimer

# From Energy Guzzler to Near-Zero Energy Home: Lessons from the Phased Deep Retrofit Project

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**ABSTRACT**

Monitoring results over a four-year period document phased retrofits applied to a central Florida home with very high electricity consumption, eventually ending in a home with near-zero energy use. Evaluated over a full year, the average household electricity use was reduced through a combination of efficiency measures and photovoltaic power generation by 82%. Results from the case study, and nine other deep retrofits suggest how an effective zero-energy home (ZEH) program can be implemented in otherwise poorly performing existing homes.

## Introduction

The U.S. Department of Energy (DOE) sponsored the Phased Deep Retrofit (PDR) study in 60 all-electric Florida homes, which seeks to establish annual energy and peak energy reductions from two levels of retrofit – shallow and deep. Within that project, one of the homes with very large starting energy use received extensive retrofits as a precursor to the home moving from a large user to a near zero energy home. Results from the 10 home deep retrofit segment shows savings are large enough (averaging a measured reduction of 39%) that some homeowners chose to go further by adding a solar photovoltaic (PV) generation system. This paper highlights the experience of one household over several years in moving from excessive electricity consumption to near zero energy in a hot and humid climate.

There have been many such "retrofit to zero" projects in the U.S. in the past although most in cold regions (e.g. Osser, 2012) and fewer still with detailed end-use data. An early summary prepared for the National Academy of Sciences (Parker, 2009), showcased a dozen early projects across the U.S with a good geographical distribution. More recently the work of Marc Rosenbaum in the Northeastern U.S. is particularly impressive as he transformed his home in West Tisbury, MA (Rosenbaum, 2015) and spawned many other zero energy home projects. Also the Thousand Home Challenge provides useful summaries of similar projects stretching from Maine to California (Thousand Home Challenge, 2015).

## Phased Deep Retrofit Project

Detailed audit data have been obtained from all homes including house size and geometry, insulation levels, materials, finish, and equipment. A blower door test was completed on each home. Detailed photographs were also made of home exterior, appliances, equipment and thermostat. The flow rate of shower heads was measured during the shallow retrofit, and duct testing was conducted as part of the deep retrofit.

The homes are located in central and south Florida, with varied construction characteristics. Figure 1 shows the geographic distribution of study sites over the state. There are a total of 60 sites, built between 1942 and 2006, averaging 1,777 square feet in living area, with an average occupancy of 2.6 persons. Homes were audited and instrumented during the second half of 2012. Shallow retrofits of all homes came in spring 2013 with deep retrofits of a 10 home subsample in summer and autumn of that year following analysis of the six month shallow impact at individual sites.

End-use energy data were collected to evaluate energy reductions and the economics of each retrofit phase. Monitoring included whole house power and power consumption of various end uses: heat pump compressor, air handler and resistance heat, water heating, clothes dryer, range, refrigerators, freezers and swimming pool pump. Several spare monitoring channels were used to pick up non-conventional end-uses. With all major end-uses sub-metered, the category of "lights and other" energy was arrived at my subtracting all sub-metered loads from total energy use (Parker et al. 2014, 2016).

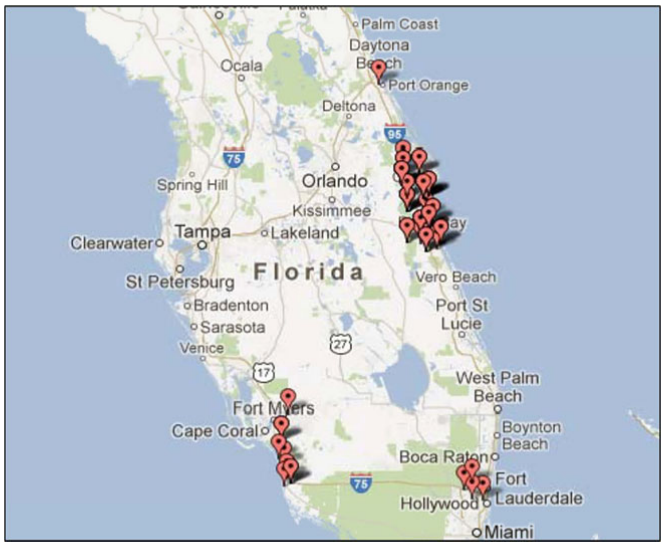


Figure 1. Geographic distribution of the Florida PDR sites.

## Monitored Data

A graphical summary of each site's energy end-uses is shown by the stacked bar presentation in Figure 2 for 2013. The average for the entire sample is shown by the far left bar labeled "All" in Figure 2 and illustrated in more detail by the pie chart in Figure 3. Average annual consumption across sites was 42.8 kWh/day, although highly diverse end-uses suggest a complex challenge for efficiency programs. Heating, cooling and water heating only comprised 48% of measured consumption. Moreover, difficult-to-tackle loads such as clothes dryers and home entertainment centers, accounted for 9% of use and home office, game consoles, lighting, fans and other plug loads were fully 23% of consumption.

## Shallow Retrofits

Shallow retrofits were conducted in all project homes from March to June 2013. The energy reduction measures were chosen based on ease of installation. These targeted lighting (CFLs and LED lamps), domestic hot water (tank wraps and showerheads), refrigeration (cleaning of condenser coils), pool pump (reduction of operating hours), and the home entertainment center ("smart plugs").

Most houses already had some energy efficient lighting (defined to be CFL or LED types). Indeed, one home already had 100% LED lighting, whereas six others had mostly CFLs and needed fewer than 20% of bulbs changed. Owners sometimes objected to lighting retrofits for some lamps so those were not changed. A total of 55 homes were affected by the lighting retrofit. On average, 54% of lamps were replaced with CFLs or LEDs, ranging from 5% to 96% of the home's total lighting (Sutherland et al. 2014).

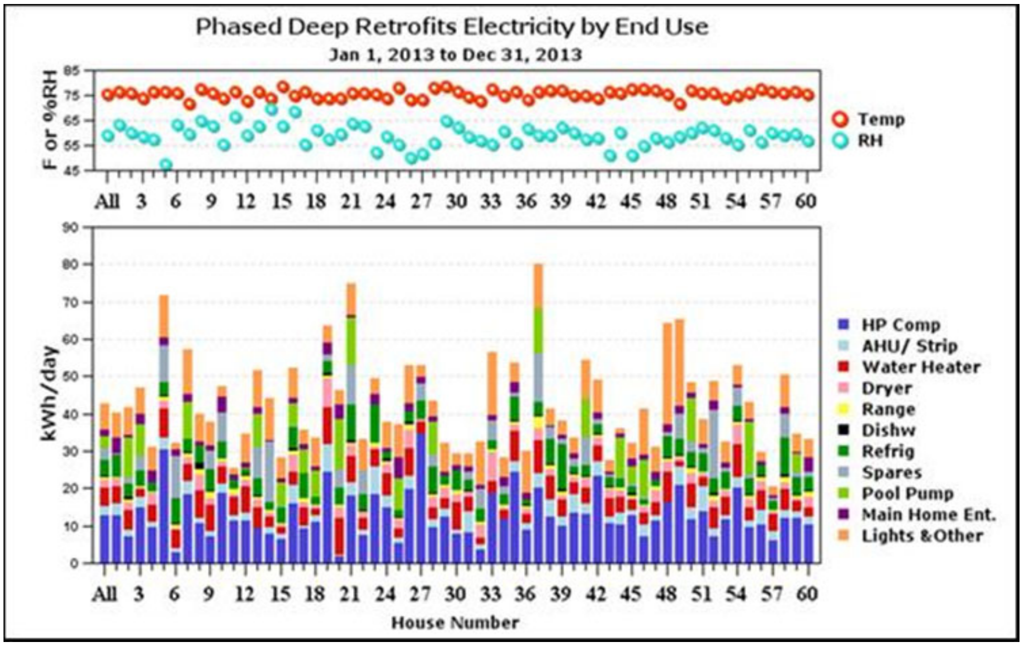


Figure 2. Site energy by end use, mean indoor temperature and RH for the entire year of 2013 in total PDR sample.

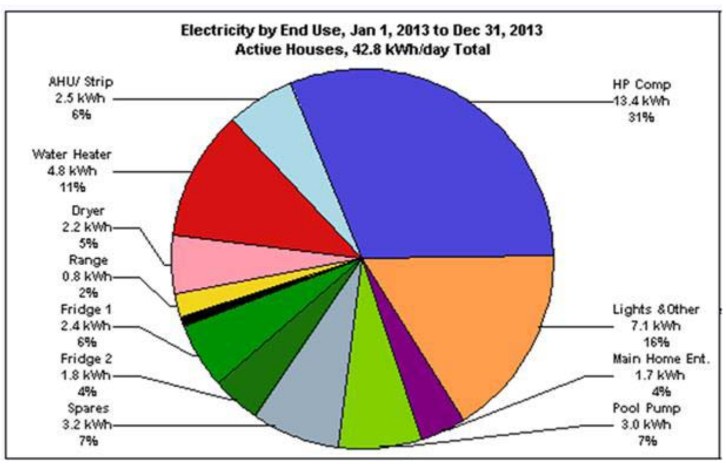


Figure 3. Average energy end-use in the entire year of 2013 in the PDR sample.

We made an effort to reduce domestic hot water energy in two ways: (a) reducing use with low-flow showerheads and (b) reducing storage thermal losses by insulating tanks piping.

Many homeowners were particular about their showerhead and rejected this measure. Parker et al (2014, 2016) describe the energy savings results for the full sample of shallow and deep retrofits.

## Phased Deep Retrofit Site 19: Description and Shallow Retrofit

Site 19 is a 2,554 square foot, single-story home built in 1988 with three occupants (3 adults), of which one daughter is home periodically. Construction is slab-on-grade with CMU walls and average 10.6 foot ceilings. Windows are double glazed, some untinted with metal frames and others with solar control glass and vinyl frames. Home air tightness as originally tested was typical: 6.51 ACH @ 50 Pa pressure. Existing systems included: 5-ton, HP system with the original 1988 condenser (compressor was replaced in 1997); manual thermostat; 50-gallon electric water heater; and R-19 fiberglass batt ceiling insulation.

The shallow retrofit at Site 19 was performed on April 17, 2013 and involved replacing incandescent lamps with CFL or LED lamps (there were 89 audited lamps in the home) and also wrapping the hot water tank and replacing two shower heads. The total lighting load was changed from 3.394 kW to 1.529 kWh—a reduction of 55% in lighting wattage. The achieved savings is the quantity produced for fixtures given their operating hours which may vary substantially from the lighting load reduction. Evaluating consumption before and after the changes showed no immediately obvious reduction to lighting and plug loads, in fact an increase as shown in Figure 4, although this seems due to the daughter returning home with a constant load of about 60 Watts added just before the shallow retrofit went in [we hypothesize a desktop computer]. So adjusted, the lighting retrofit saved ~0.65 kWh per day or about 240 kWh/year.

Also as a result of the shallow retrofits, daily average water heating energy use dropped from 13.3 kWh/day to 11.8 kWh/day (11% savings), as shown in Figure 4, after the hot water tank and pipes were wrapped (R-3.0 insulation wrap) and two showerheads replaced.

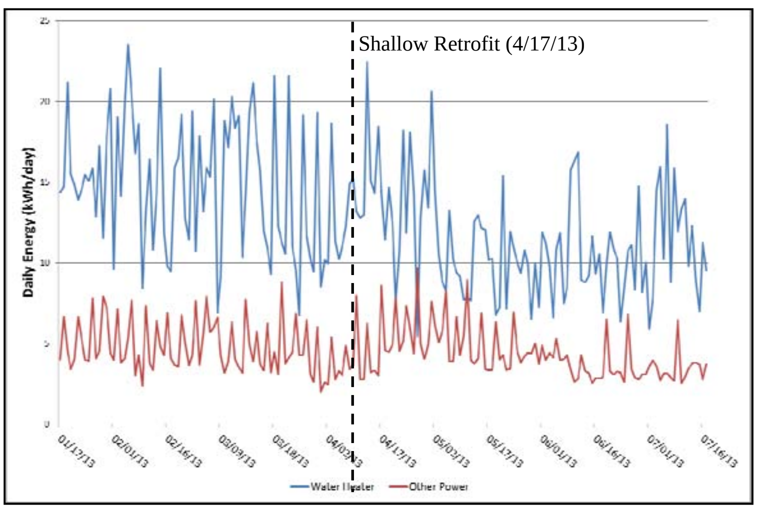


Figure 4. Hot water energy (blue) & lighting/plug loads (red) pre & post retrofit.

Deep retrofit measures at the site included: (1) high-efficiency heat pump; (2) duct sealing; (3) passive return air pressure relief in the master bedroom; (4) smart thermostat; (5) heat pump water heater; (6) ceiling insulation upgrade to R-38 using blown-in fiberglass with knee wall insulation upgrade as appropriate; and (7) ENERGY STAR clothes washer and low-energy clothes dryer installations. Deep retrofit measures began August 26, 2013 with the HVAC system install and concluded November 18, 2013 with final appliance installations.

**Cooling Energy Savings**

The home's existing SEER 10, 5-ton York heat pump was replaced with a 5-ton two speed SEER 16 Carrier heat pump. Ducts were tested and sealed and a Nest learning thermostat was installed. Normalized duct leakage averaged 0.09 $Q_{n,out}$ prior to sealing and 0.05 post. Figure 5 displays daily HVAC retrofit savings analysis at Site 19. Post-retrofit savings averaged 47% (19 kWh/day) as evaluated by regression results applied to the entire period. There is a large reduction in cooling energy use from week pre to week post (76.8 kWh to 37.9 kWh/day). Figure 6 shows the change in interior temperature after the combined retrofit on August 26, 2013. The occupants maintained a slightly higher indoor temperature with the Nest learning thermostat.

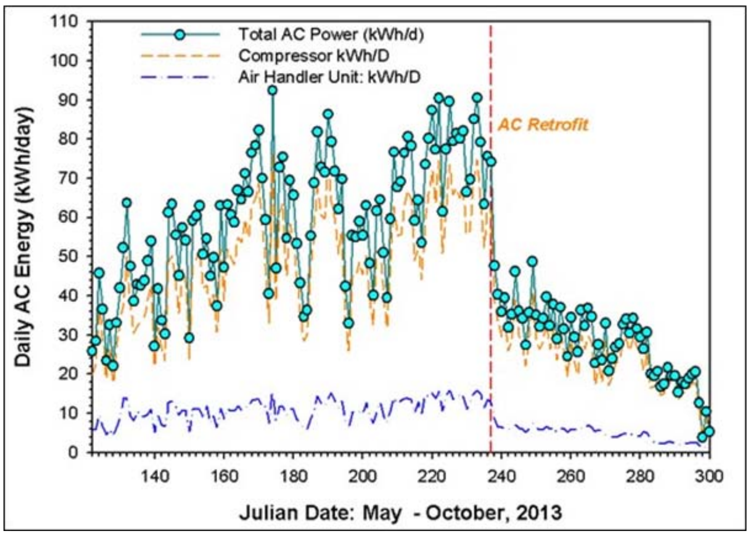

Figure 5. Site 19 AC energy: pre and post retrofit, May – October 2013.

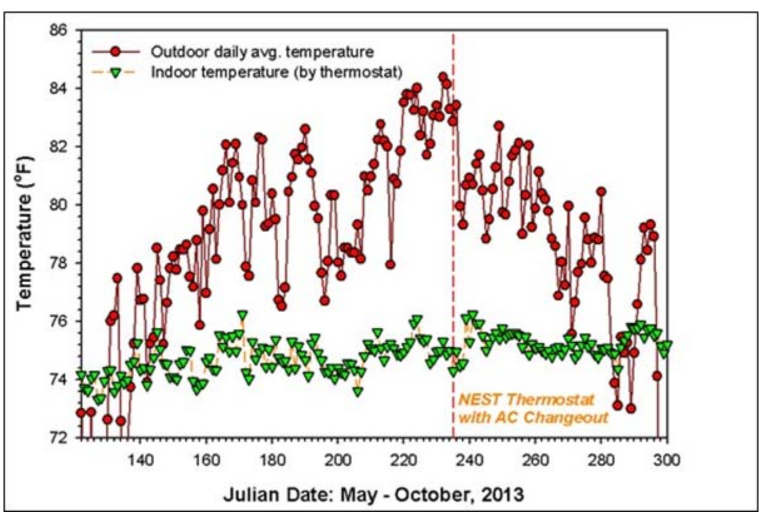

Figure 6. Average indoor & outdoor temperature May – October, 2013.

To evaluate weather-related influences, we used the pre and post daily air conditioning data and then determined daily cooling kWh as a function of the average daily air temperature (Figure 7) using quadratic regressions. At a daily average outdoor temperature of 80°F, the regressions indicated the air conditioner used 61.0 kWh/day pre-retrofit and 30.8 kWh/day after – 30.2 kWh/day savings or a 47% reduction. This represents the HVAC retrofit overall savings including: AC change out, duct sealing and Nest learning thermostat installation. Through examination of pre and post interior temperatures we attempted to separate out the savings attributable to the learning thermostat. In the month before the retrofit, the occupants maintained an average temperature 75.1°F; in the month after the retrofit, the interior temperature rose to an average of 75.4°F. Differences in regression against outdoor temperature shown in Figure 7 and another regression that examined changes to cooling use against the outdoor to indoor temperature difference allowed evaluation of how the learning thermostat influenced savings. At an average daily summer outdoor temperature of 80°F, the average outdoor to indoor temperature difference for the regression was 5.34°F (Pre) and 4.66°F (Post).

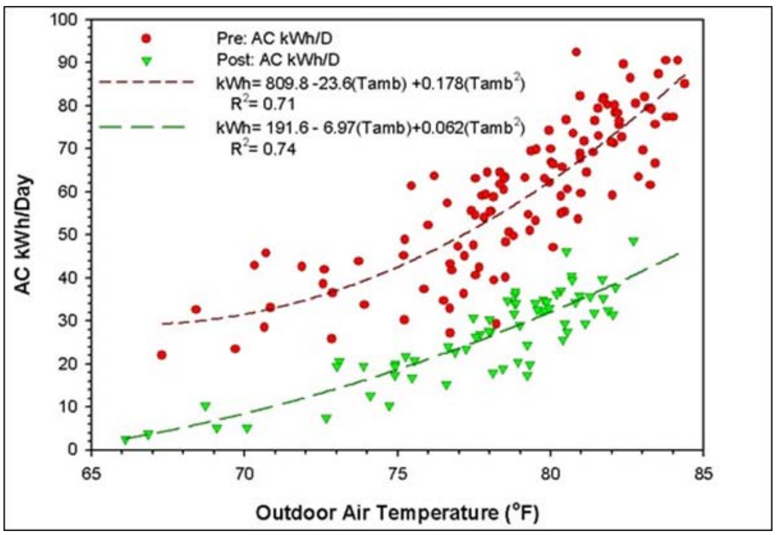


Figure 7. Site 19 average air conditioning vs. outdoor temperature May – October, 2013.

Evaluating pre- and post-retrofit energy consumption at the post-Nest temperature difference, the predicted pre consumption falls to 58.4 kWh per day. Thus, when controlling for changes to indoor to outdoor temperature the AC retrofit and duct repair reduced consumption by 26.3 kWh per day (58.4 -32.1 kWh) or 45%. The remainder of the cooling energy savings (2.1 kWh/day) comes from the learning thermostat with an implied cooling energy savings of ~4%. For sake of comparison, a separate evaluation of Nest thermostats alone in the PDR project showed cooling savings averaging about 10% in a sample of 22 homes, but with high variability.

### Heat Pump Water Heater

On September 19, 2013, the water heater in the garage at Site 19 was changed from a 50 gallon electric resistance GE model GE50M06AAG to an A.O. Smith 80 gallon heat pump water heater (HPWH). Evaluated over 30 days pre and post-retrofit, the change to the HPWH reduced water heating loads by 67% or 5.8 kWh per day (weather normalized). This highlights a major success within the collective energy retrofits in the PDR project which averaged 65% savings in pre-retrofit water heating electricity use. Figure 8 shows the water heating energy consumption data plotted a year before the HPWH was installed at Site#19 and then a year after. The impact of both the shallow retrofit in mid-April 2013 (two showerheads changed to lower flow models and tank wrapped with exterior insulation) can be seen as well as the large change from the installation of the HPWH in September of 2013. Consumption prior to intervention is cut by approximately 80% (14 kWh/day to 3 kWh/day) through the combination of new showerheads, tank wrap and the heat pump water heater.

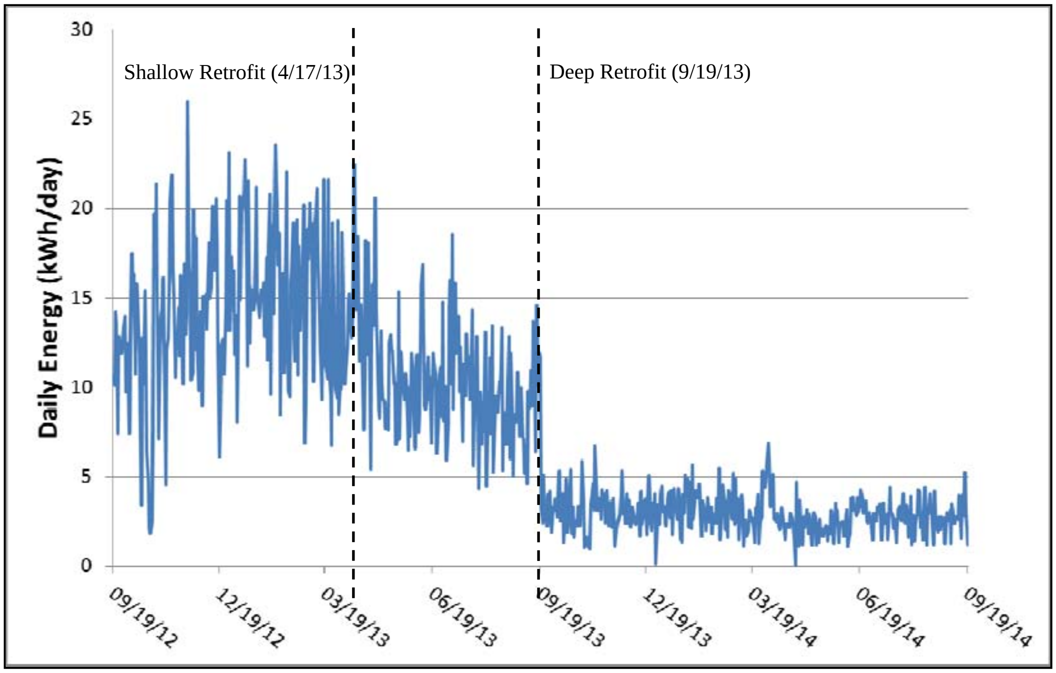


Figure 8: Daily water heating energy a year before & after installation of HPWH: September 2012 to September 2014.

## Clothes Dryer

The electric resistance clothes dryers in eight homes were replaced with a new higher efficiency Samsung DV457 model including that in Site 19. Seven of these homes received a matched Samsung washer/dryer pair. The standard matched clothes washer was a Samsung Model WF457 with a Modified Energy Factor (MEF) of 3.42. The original interior-located appliance set at Site 19 included a Kenmore Elite 110.65942401 clothes washer with a top-loading Whirlpool WTW6200SW2 washer. Data analysis of the eight home sample revealed that achieved energy savings of the clothes dryer was highly variable, but averaged 0.60 kWh/day or 18%. Savings were lower than expected as homeowners, unhappy with long drying times in ECO mode, opted for the less efficient but quicker standard mode. Site 19, with the largest PDR clothes dryer use (8 kWh/day), showed a savings of 26% (2.0 kWh/day) in the sixty-day period after the installation of the new unit (11/18/13).

## Change to Heat Pump Clothes Dryer

The PDR project conducted further clothes dryer research in 2015 by replacing electric resistance units in eight homes (including site 19 on 6/3/15) with a new Whirlpool Heat Pump Clothes Dryer (HPCD). The dryer model (WED99HED) is designed to be approximately 40% more efficient than standard units. The dryers were matched with a Whirlpool 4.5 $ft^3$ washer (WFW95HED: Energy Guide label of 109 kWh/yr) and a Modified Energy Factor (MEF) of 3.2.

The HPCD is a 7.3 $ft^3$ condensing unvented clothes dryer, similar to European models. It has both a heat pump section as well as a supplemental electric heating element. There are three operation modes: ECO mainly using the heat pump, but with long dry times; BALANCED with both and SPEED with full heat pump and resistance elements for fastest drying.

The new clothes dryers and washers were installed in early summer 2015. As described, Site 19 had started the PDR project with a standard washer and dryer, but then had participated in early retrofits which included the more efficient Samsung DV457 dryer (installed 11/18/13) which reduced consumption by 26%. With continued heavy dryer usage at Site 19, we were interested in what impact the HPCD dryer could have on their clothes drying energy usage. Measured baseline data were from January 1, 2014 to the install date of 6/3/2015. The post period data were from install date through mid-July 2015, a much shorter period comprising about 45 days. Table 1 summarizes the measured data for Site 19 as well as PDR study averages.

Table 1. Summary heat pump clothes dryer energy for Site 19 and the entire PDR study

| | Install Date | Pre kWh/d 2014/2015 | Pre kWh/yr | Post kWh/d 2015 | Post kWh/yr | Savings kWh/yr | Savings (%) | People |
|---|---|---|---|---|---|---|---|---|
| Site 19[a] | 6/3/2015 | 7.00 | 2555 | 5.38 | 1964 | 591 | 23% | 4 |
| Avg all sites | Mid-2015 | 2.56 | 932 | 1.57 | 573 | 359 | 39% | 2.3 |
| Median all sites | Mid-2015 | 1.94 | 707 | 1.11 | 403 | 312 | 44% | 2 |

[a] Original, standard dryer at Site 19 used 8.30 kWh/day prior to 11/18/13

Median energy savings of the eight home sample were estimated at 312 kWh/year or about 44% of baseline consumption with average savings of 359 kWh/year (39%). The savings for Site 19 would be 35% if based on the original baseline unit, rather than more efficient Samsung DV457 unit in operation in 2014. The monthly energy use for clothes drying at Site 19 shows a large drop in daily dryer energy use to the Samsung unit and then a smaller drop after the HPCD is installed, as seen in Figure 9, but with increasing long term dryer consumption as less efficient dryer modes were selected over time.  A change in occupancy at the end of 2014 strongly impact daily average consumption. Average daily use falls from ~8.5 kWh/day to about 5.5 kWh/day with the more efficient resistance unit and then about 4.5 kWh/day initially with the HPCD. However, in subsequent months the household chose more energy intensive dryer cycles.

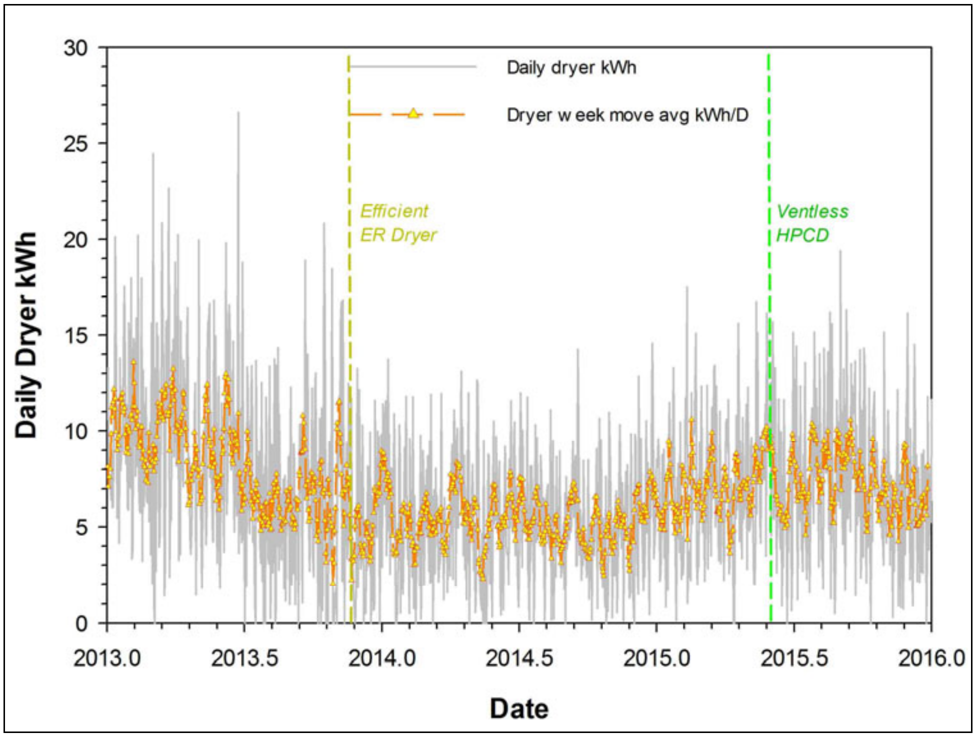


Figure 9. Change in Daily Dryer Electricity Use 2013-2015. Daily averages and weekly moving average.

The homeowners at Site 19 were not pleased with the unvented Whirlpool HPCD as it made the utility room very warm. In future work, we hope to substitute a vented HPCD (manufactured by LG) to see how well this might work in this home—which remains the site with highest dryer energy use—although it has been cut by 25-30%. Still, the household is strongly attached to daily laundry with very dry cycles preferred, even though aware of the energy implications.

## Summary of Retrofits

Considering all the retrofit measures, we were able to estimate that total electricity use at the previously high-consuming home at Site 19 was cut by nearly half-- 47%. Figure 10 is a plot of Site 19's total daily energy use from September 2012 through June 2014.

Figure 11 shows the energy use of Site 19 broken down by end uses before intervention and after the completion of all retrofits. The left bar, showing an average daily energy use of 72 kWh, represents the home during the first year of monitoring (9/1/12 to 8/31/13) before energy measures were implemented except for the shallow retrofit on 4/17/13 and a few days of deep retrofit measures installed on 8/26/13. Energy use at site 19 was originally dominated by heating, cooling and water heating which made up 68% of measured consumption.

The middle bar in Figure 11 shows the post-retrofit average daily energy use, which dropped to 46 kWh for a savings of 38%. Reduction to heating, cooling and water heating usage accounts for the majority of the savings (26.8kWh/day between those end uses). The more difficult loads to address like clothes drying, home entertainment, lighting, fans and other plug loads now make up a far greater share of total remaining energy use. The large amount of dryer energy remaining at site 19 is apparent. The right bar represents the entire sample of PDR homes, which were 30% smaller than Site 19 on average (1,777 ft$^2$).

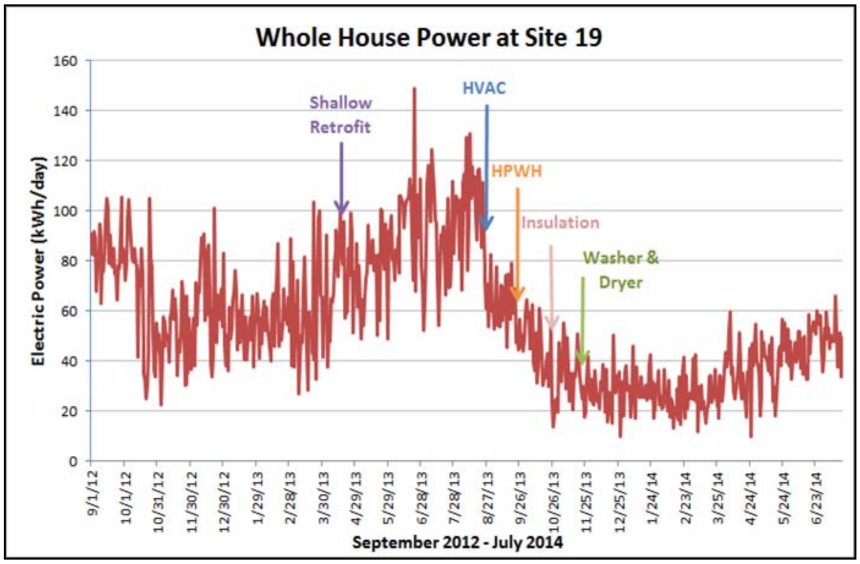

Figure 10. Change in daily electricity use Site 19; 2012-2014 as retrofits installed.

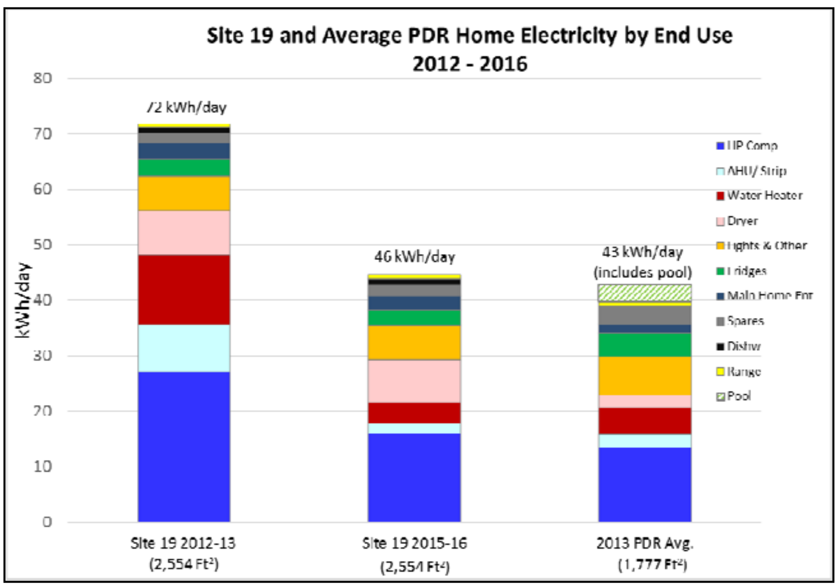


Figure 11. Measured annual electric end-use pre-retrofit (left), after retrofits (middle) and average pre-retrofit home in entire PDR study (right).

## Installation of 10 kW PV System

Given the large reductions seen to overall energy at Site 19, the homeowner wished to capitalize and install a 10 kW PV system to bring the home close to net zero when evaluated over an annual period. The PV system consists of 36 - 280 watt modules feeding a pair of 5kW inverters with a rated efficiency of 97.0%. Each inverter has two strings with nine modules. The homeowner installed the system on the only suitable roof area– a west-facing expanse.  Analysis of the PV system using BEopt suggested the west-facing PV orientation would provide a better match to daily measured energy for the post-retrofit home (Figure 12). Note that the red trace (pre-retrofit energy in 2013) and the blue trace for 2014 for the following year after the retrofits shows the dramatic reduction associated with the energy improvements.

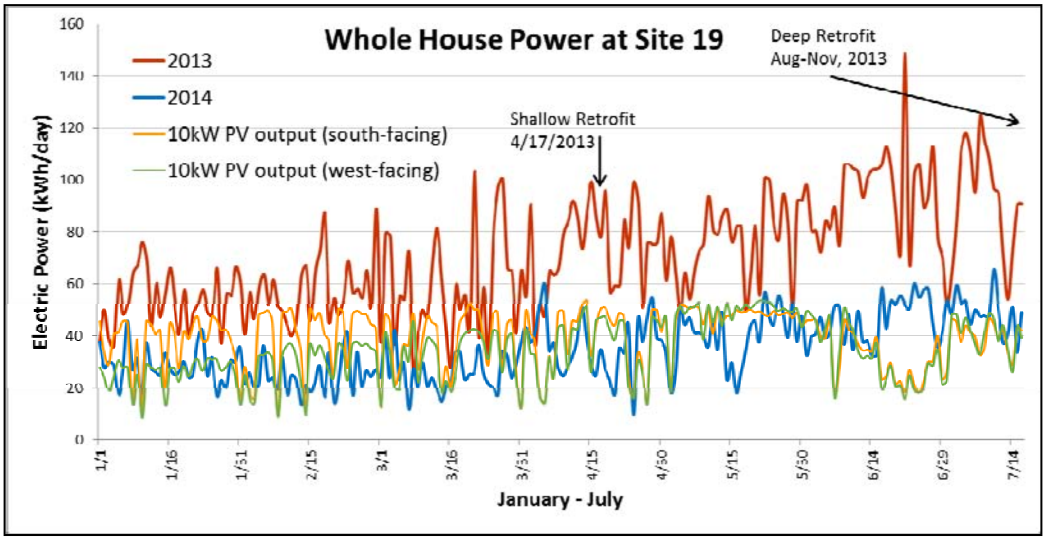


Figure 12. Comparison of daily PV output: 10kW PV facing South versus West in Central FL.

A photo of the PV array installed on the 5/12 pitched roof is presented in Figure 13. Figure 14 shows PV performance of the 10 kW PV system since April 30, 2015 over a year long period. Home total energy use is averaging 44 kWh/day against daily PV power production of 31 kWh leaving a net energy usage of 13 kWh/day for an 82% savings over the pre-retrofit average of 72 kWh/day.

Figure 13. 10 kW West-facing PV system installed at Site 19.

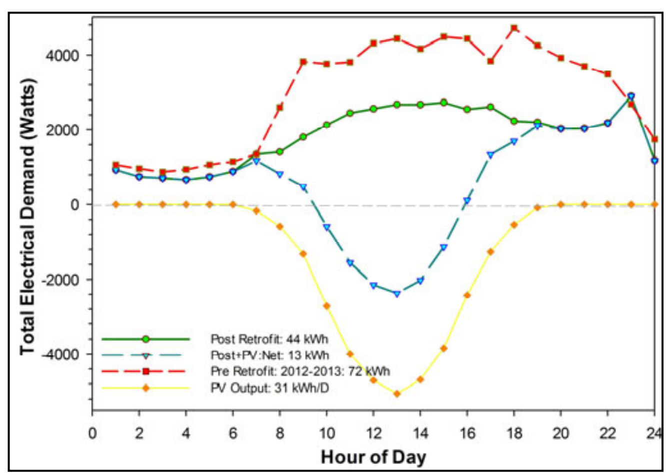


Figure 14. Evaluated over a year, the PV output made up 82% of the total energy requirement for Site 19.

Figure 15 below shows the utility peak summer day performance of Site 19 prior to deep retrofits being applied (August 13, 2013), after the installation of the extensive retrofits (July 28, 2014) and then a year later after the homeowner installed a 10 kW PV system. The peak days are those experienced by the supplying utility (FPL). Consumption after the shallow retrofits but before the deep retrofit was 104.8 kWh in summer 2013 with a utility coincident peak demand of 5.47 kW between the hours of 3 - 5 PM in the afternoon. On July 28, 2014 after the deep retrofits, total daily use fell to 57.1 kWh with a peak period demand of 4.06 kW. On August 20, 2015, after the installation of the PV the previous spring, consumption was actually higher for the overall household than the previous year (73.2 kWh) with a demand of 5.65 kW. This came from nearly continuous dryer use taking place on the peak day in 2015 (as opposed to 2014) with an average HPCD demand of 0.95 kW. The PV output for the same day accounted for (31.4 kWh), total energy use was 41.8 kWh with a peak period demand of 3.63 kW. This peak demand was lower than any previous year with the peaks coming at different times of the day than those experienced by the utility. The results clearly demonstrate how PV with building efficiency can help to reduce summer utility coincident peak demand.

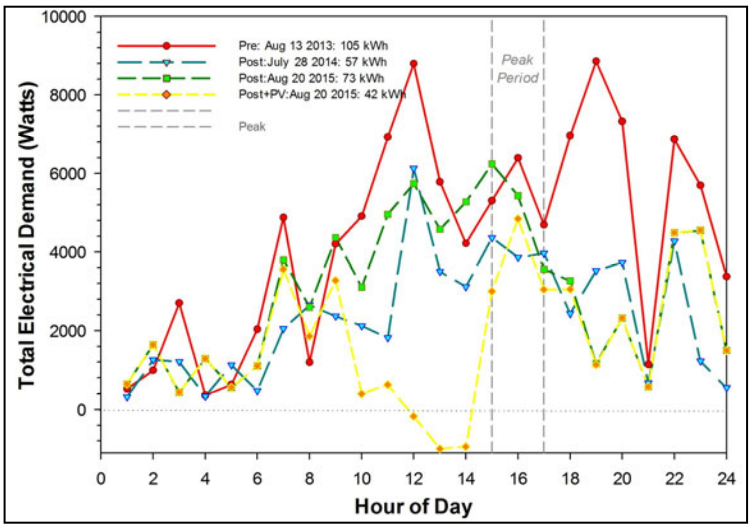


Figure 15. Peak summer total electrical demand for pre-retrofit (2013), post-retrofit (2014) and post-retrofit with PV (2015) at Site 19.

Our results show that successful near zero energy solutions and reductions to utility peak electrical demand can be obtained from homes even judged to be “guzzlers” and in a difficult hot and humid region.

## Conclusions

Our paper highlights the progress of Site 19 in the Phased Deep Retrofit project, which went from one of the highest energy consumers before intervention (24,483 kWh/year) to a measured consumption of 12,862 kWh (a 47% reduction). This was accomplished through a series of retrofits that were individually sub-metered and evaluated: efficient lighting, increased roof insulation, heat pump water heater, duct sealing, high-efficiency heat pump with smart thermostat and heat pump clothes dryer. Each option was evaluated separately for savings.

Measured consumption during the warm months from April – August 2013 vs. 2014 dropped from 87 to 46 kWh/day. Encouraged by results, the homeowner installed a 10 kW PV system in April 2015. Since then, the home has had an average net electricity use of 13 kWh/day after accounting for PV system output (31 kWh/day)— an 82% reduction towards zero energy.

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