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BUILDING TECHNOLOGIES PROGRAM

Side-by-Side Testing of Water Heating Systems: Results from the 2010 – 2011 Evaluation

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Building America Partnership for Improved Residential Construction (BA-PIRC)

March 2013

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Side-by-Side Testing of Water Heating Systems: Results from the 2010 – 2011 Evaluation

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Office of Energy Efficiency and Renewable Energy

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Definitions

AC	Air conditioning
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BA	Building America
BPA	Bonneville Power Authority
Btu	British thermal unit
cfm	Cubic feet per minute
COP	Coefficient of performance
DC	Direct current
DIY	Do-it-yourself
EF	Energy factor
FP	Flat Plate (refers to solar thermal collector)
FPL	Florida Power and Lights
FSEC	Florida Solar Energy Center
Gal	Gallon(s)
Gpd	Gallons per day
HPWH	Heat pump water heater
HWS	Hot water systems
ICS	Integrated Collector System
I_{MP}	Maximum power point current
I_{SC}	Short circuit current
I-V	Current-voltage
kWh	Kilowatts-per-hour
NREL	National Renewable Energy Laboratory
P_{MP}	Maximum Power Point
PV	Photovoltaic
RH	Relative humidity

SEF	Solar energy factor
SID	Static impeller driver
STC	Standard test conditions
V_{MP}	Maximum power point voltage
V_{OC}	Open current voltage
VAC	Volts - Alternating Current
W	Watt

Executive Summary

The Florida Solar Energy Center (FSEC) has completed a second testing rotation (Phase II) and evaluation of seven water heating systems operating side-by-side. These systems are housed at the Hot Water Systems (HWS) laboratory, a 160 ft^2 unconditioned building that resembles and can exceed garage-like temperature conditions in central Florida in part due to the six storage tanks. Figure ES-1 presents a summary of the overall averaged daily efficiency performance (COP) obtained from seven hot water heating systems for the period ending in August 31, 2011.

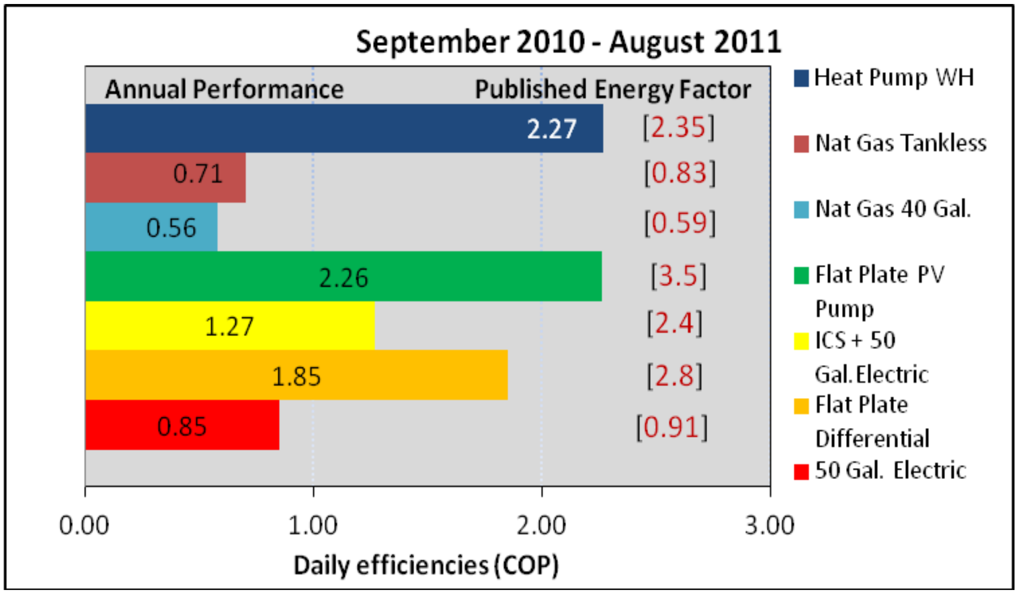

Figure ES-1. Comparative average COP of tested systems over 12-month period [Nominal EF in bracket].

Three of the systems served as the baseline for each energy source category (electric, renewable-electric and natural gas):

- Standard 50-gal electric water heater (electric baseline reference (EF = 0.91)
- Flat-plate solar thermal system (40 ft^2)—direct open loop and 80-gal solar storage tank w/auxiliary electric (4500 W), 120 VAC recirculation pump (60 W) with active differential control. Solar energy factor (SEF = 2.8).
- Standard (upright vent) 40-gal natural gas water heater (EF =0.59).

High efficiency configurations:

- Integrated collector system (ICS - 32 ft^2) in series with a standard electric 50-gal tank and single upper element (bottom element disabled)
- Flat-plate solar thermal system (40 ft^2) – direct open loop and 80-gal solar storage tank w/auxiliary electric (4500 W), oversized 40-W photovoltaic (PV) and direct current (DC) pump (20 W), passive (PV powered) differential-control (SEF = 3.5)
- Electric heat pump water heater (HPWH); EF = 2.4)
- Tankless natural gas (EF =0.83).

The solar thermal flat-plate PV-pumped system demonstrated an averaged overall daily coefficient of performance (COP) efficiency of 2.26. This system appears on chart ES-1, as the only renewable-electric system operating at the level of efficiency demonstrated by the HPWH (COP of 2.27). As a note of importance to the reader, it is worth mentioning that solar thermal collectors operated under extreme plumbing lengths to and from the storage, while the HPWH had favorable sensible temperatures conditions within the unconditioned HWS laboratory.

The most significant system upgrade in the electric water heating category for the Phase II evaluation came from the new state-of-the-art electric HPWH. In the solar thermal category, new strategies were implemented on systems previously evaluated in Phase I (2009-2010). Under the new strategies, the PV-pumped system received an upgrade in pumping capacity via a 20 W static impeller drive (SID) pump with oversized PV modules (40 W total). In January 2011, a PV-powered differential controller was added. On the 50-gal electric tank serving in series plumbing configuration to the ICS thermal system, the bottom heating element was disconnected, leaving the upper element as the only means for auxiliary water heating. Of all systems operating during the 1-year period ending on August 2011, the 50-gal HPWH earned the lowest daily average energy consumption of 2.75 kWh/day (Figure ES-2). This represents a 68% electric reduction compared to the standard 50-gal electric baseline heater when both draw schedules combined are analyzed. Solar systems, those with a flat-plate collector and open (direct) loop recirculation, managed to limit the auxiliary electric energy to 3.0 and 3.4 kWh/day. These two solar flat-plate 80-gal storage systems reduced electric energy by 58% on average, while the improved ICS/50-gal system reduced electric consumption by 36%.

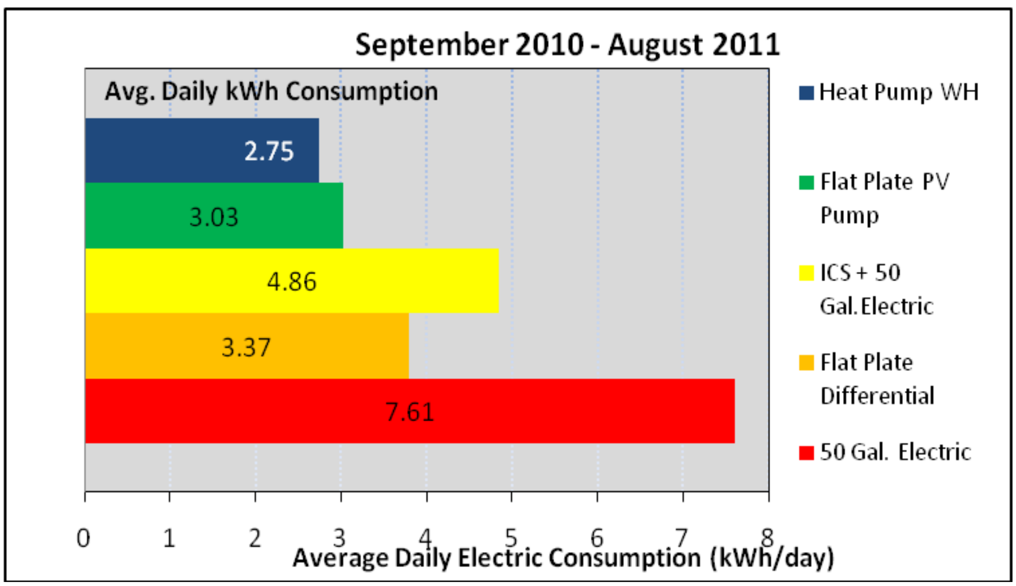

Figure ES-2. Daily average electricity used from combined draw profiles for the period of September, 2010 to August 2011.

All systems were set to deliver 120°F hot water at1.5 gal per minute (gpm) and were submitted to alternating hot water draw schedules changing about every two weeks per month. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1 calls for draws of 64.3 gal per day (gpd)year-round while the National Renewable Energy Laboratory (NREL)/Building America (BA) schedule varies in magnitude each month. The latter represents a typical family hot water draw pattern, shown in red (grouped hourly) in Figure ES-3 as compared to the ASHRAE schedule.

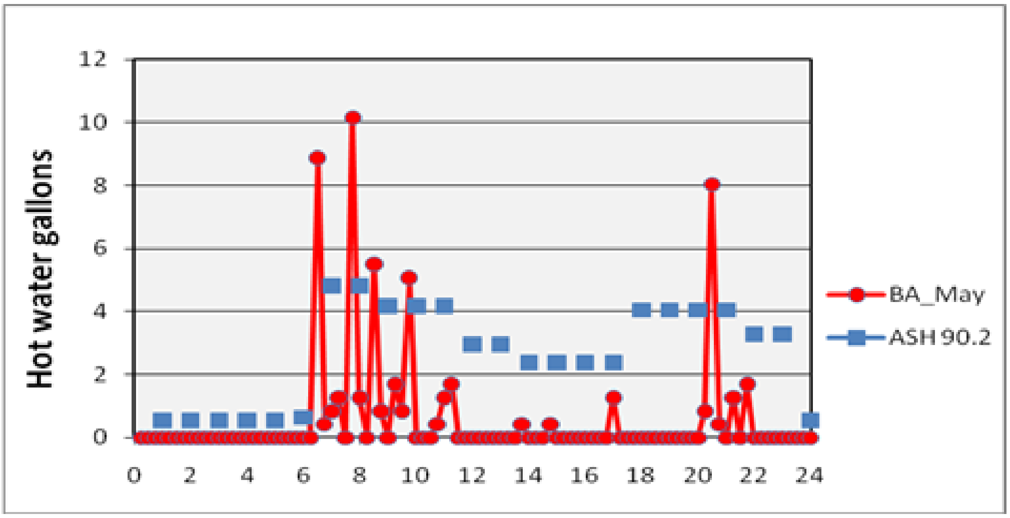

Figure ES-3. ASHRAE 90.2 and NREL/BA (May 2011) hot water draw profiles compared.

Natural gas systems continued to operate for a second year. Operation was interrupted for short periods for other minor related research such as pilot lamp standby measurements (11,194 Btu/day) on the standard 40-gal heater and a flush maintenance procedure on the tankless heater. The average daily natural gas consumption during 2010-2011 is shown in Figure ES-4, which agrees with results reported during the 2009-2010 (Phase I) rotation. When comparing the standard 40-gal natural gas tank (EF=0.59) vs. tankless water heater (EF=0.83), the average daily natural gas consumption indicates that a tankless water heater can offer a 24% natural gas energy reduction in central Florida.

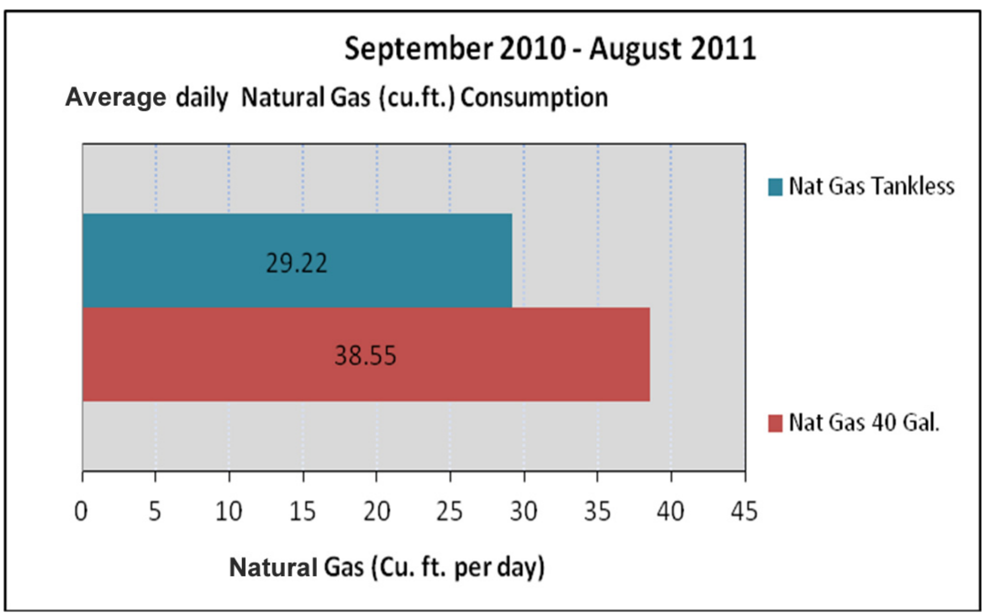

Figure ES-4. Average daily natural gas consumption (cu. ft) for gas systems over 12-month period.

Table ES-1 provides a daily average summary of the combined and draw-dependent input energy values recorded on each system at the HWS Laboratory between August 2010 and September 2011. In general, an energy decrease appears under the NREL/BA draw schedule as compared to ASHRAE 90.2. Except for the ICS/50-gal system, a similar correlation was found during Phase I (2009-2010). The new ICS/50 gal results are attributed to the electrical heating hardware change from dual to single-heat element configuration.

Table ES-1. Summary of Draw Dependent Energy Consumption by System.

System	Daily Average Consumption All data days (N=365*)	Daily Average Consumption ASHRAE 90.2 Draws (N=170)	Daily Average Consumption NREL/BA Draws (N=171)
Standard electric 50-gal tank	7.61 kWh/day	8.00 kWh/day	7.26 kWh/day
Solar flat-plate differential w/80-gal tank	3.37 kWh/day	3.6 kWh/day	3.31 kWh/day
ICS w/50-gal tank	4.86 kWh/day	5.23 kWh/day	4.60 kWh/day
Solar flat-plate PV-pumped w/80-gal	3.03 kWh/day	3.17 kWh/day	2.95kWh/day
HPWH	2.75 kWh/day	3.09 kWh/day	2.41 kWh/day
Natural gas 40-gal tank	38.55 cu. ft/day (Nat. Gas)	42.73 cu. ft/day (Nat. Gas)	36.08 cu. ft/day (Nat. Gas)
Tankless natural gas	29.21 cu. ft/day	27.38 cu. ft/day	27.37 cu. ft/day

*Includes programmed pattern changeover days

As mentioned earlier, a target hot water delivery temperature of 120°F was intended for all systems. Setting of control thermostats was performed within a few trials as best as user interaction was allowed. In contrast, setting of the single upper thermostat to 120°F on the ICS/50-gal system was not easily accomplished and required many tries to satisfy one good setting for all seasonal variations. This strategy may not provide enough hot water during low solar radiation days with large loads. Furthermore, in the case of solar systems, mixing valves were used to regulate excess heat to deliver the 120°F temperature target. Overall data indicates deviations throughout the seasons with temperature variations larger than anticipated. To understand system behavior and enhance the analysis, daily weighted average hot water temperatures delivered by each system are shown in Table ES-2. The column on the left shows weighted average temperature delivery for all draw schedules combined. Average daily low (min.) and high (max.) temperatures are only shown for the NREL/BA draw schedule.

Table ES-2 Summary of Weighted Average Hot Water Delivery by System.

	All Draws (F)	NREL/BA (F)	Min. Delivered (F)	Max. delivered (F)
E50	119.4	118.4	116.2	120.3
FP 80 diff	118.2	116.4	109.7	120.6
ICS-50	121.7	119.3	103.8	130.1
FP 80 PV	122.4	122.1	114.3	136.0
Natural gas 40	123.7	122.2	116.3	132.1
Tankless	116.6	117.0	111.4	118.4
HPWH	118.1	116.9	112.2	119.9

Throughout the year, the standard electric 50-gal water heater demonstrated the least deviation from the intended target delivery temperature (120°F) regardless of the draw schedule used. During the periods when the NREL/BA schedule was implemented, averaged data indicates lower average delivery temperatures. This is likely due to the larger draw event magnitude and dynamic seasonality of hot water demand during winter imposed by this schedule. The overall weighted average temperature exhibited by the tankless natural gas hot water temperature of 116.6°F is due to the initial low water temperature delivery at the beginning of each draw until the tankless burner reaches the intended target temperature. The tankless heater is the only system tested without significant hot water tank storage. However, under the NREL/BA draw schedule, the weighted average temperatures appear to be on par with the HPWH and flat-plate solar differential.

Further analysis comparing the standard 50-gal water heater to the HPWH shows the seasonal variation of hot water temperature delivered by each individual draw schedule. Figure ES-5 displays the average weighted daily temperatures delivered by the HPWH (blue) compared to the standard E-50 WH (red). The weighted average inlet water temperature (mains) is also shown for reference. The plot shows a full year of alternating (~ every 2 weeks) draw profile-dependent temperatures. Larger hot water temperature dips experienced during the NREL/BA load schedule can be compared to the ASHRAE schedule. These larger temperature deviations are more pronounced under the NREL/BA draws where frequency and magnitude have an effect on delivered hot water temperatures as compared to the ASHRAE schedule. Temperatures at the HPWH outlet deviated below 115°F, while the standard E-50 electric water heater shows a tight consistency, also due to its faster form of recovery. Temperature fluctuations caused by such demand, compounded with residential hot water distribution plumbing, could present a comfort issue because hot water would have to travel further, resulting in a lower point of use delivery temperature.

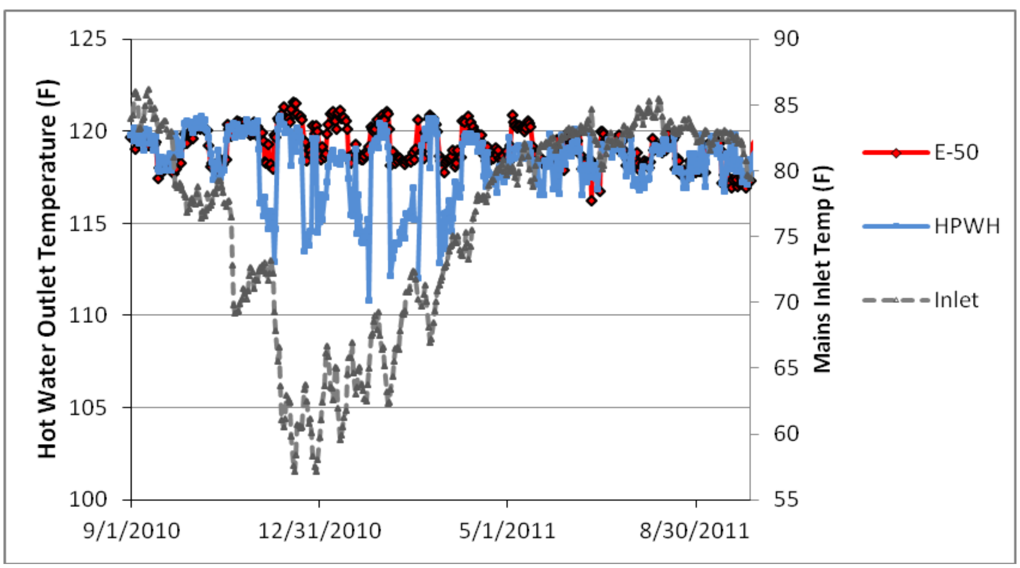

Figure ES-5. Weighted average hot water delivery temperature of HPWH and electric 50-gal tank compared.

The HPWH is rated as a 700 W appliance by manufacturer, General Electric (GE); however, it demonstrated that it can operate as an average load of 530 W under Florida mild ambient temperatures. Although cooling capacity was not measured, cold airflow temperatures reaching 67.3°F were evident at the unit's rear-facing discharge vent when ambient surrounding temperature was 87.1°F (19.8°F ΔT cooling). The HPWH also provided latent heat removal (condensate) at an average of 3.2 pints per day. Its auxiliary-resistive heating element saw limited operation activity during the 12-month period. In fact, data indicated that resistance heating operation only occurred during twelve days for a total of 39 hours during the 1-year data period. Electric resistance heating was evident during those days averaging daily temperatures of 52°F, where minimum temperatures of 42°F were reached as measured inside the HWS laboratory. These numbers suggest that when operating under its default setting (120°F), the HPWH activated the resistance element approximately 2.34% of the time during the 1667.5 hours that compressor-mode operation was detected.

In October 2011, the airflow of the HPWH was measured at 130 cubic feet per minute (cfm) following a nonscheduled hot water purge of at least 30 gal. Further investigation on this subject, which ended in communication with Bonneville Power Authority (BPA), revealed that this particular HPWH model has a variable-speed fan (170 to 100 cfm) inversely proportional to the hot water tank temperature. However, the airflow test performed at FSEC indicates that under normal loads, the higher airflow rates would rarely be seen under daily operation conditions in Florida, except for during initial cold startup of the unit.

There has been much speculation over whether the HPWH can surpass the level of efficiency performance of the solar flat-plate systems. The plot shown below (Figure ES-6) compares the efficiency performance of the solar flat-plate (FP) thermal systems against the HPWH under the family-realistic NREL/BA draw schedule. The standard electric 50-gal (E-50G) system is also shown as baseline reference. Compared to the performance of solar thermal flat-plate systems, efficiencies obtained from the HPWH indicate a higher level of performance during winter, which represents the most critical season.

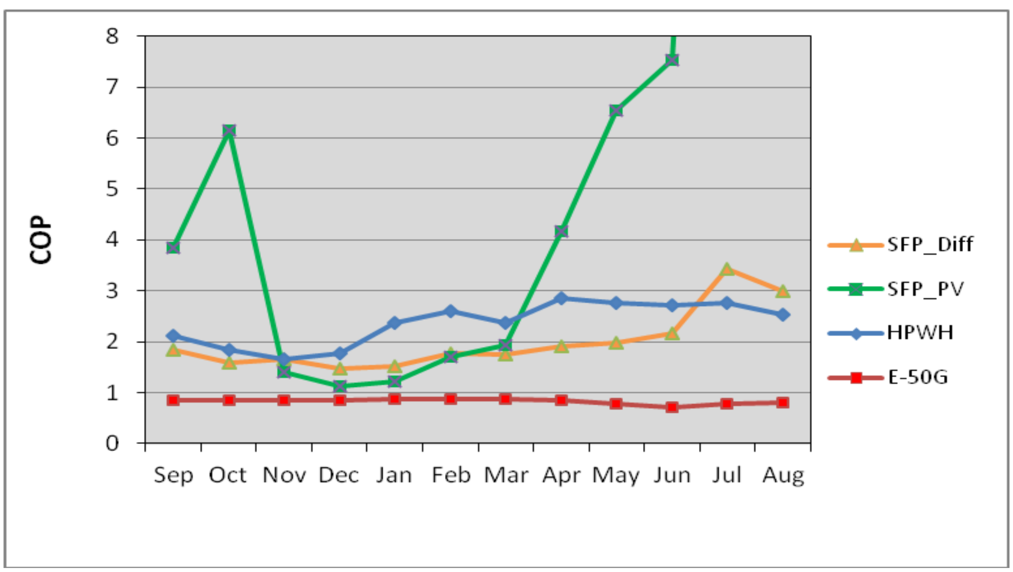

Figure ES-6. Solar flat-plate systems vs. HPWH under NREL/BA draw profile.

Design changes implemented on two solar thermal water heating systems previously evaluated in Phase I appear to provide a marginal gain in energy efficiency. A larger pumping capacity on the DC PV solar thermal system appears to be working, but improvements are needed to deactivate a diode protection when it is most needed—during low solar radiation and cloud passages. The unsolved challenge in design revolves around providing maximum power to the pump during overcast days while protecting the pump from excess voltage (20 V max.) from the PV modules during high solar radiation conditions. This control strategy would be ideally solved with the use of reliable passive cost-effective components.

Electric energy savings examined by the draw profile are shown in Table ES-3. When comparing results obtained from solar flat plate systems against the standard electric baseline, the percentage of savings under the NREL/BA draw schedule is slightly less but about equal to the ASHRAE 90.2. These results were also evident during 2009-2010 Phase I testing. The ICS/50 gal solar system recorded a slight 2% increase favoring the NREL/BA draw profile. Assuming the user accepts the variability of hot water (higher dead band) the one-element tank strategy adds additional energy savings. The largest noticeable percentage gain in energy savings by draw profile were recorded for the HPWH, where the percentage is 5.4% better under the NREL/BA hot water draws compared to the ASHRAE 90.2.

Table ES-3. Energy Savings Results from Electric Systems During Phase II (2010-2011) Testing Rotation by Draw Profile.

	ASHRAE 90.2	NREL/BA
SFP differential w/80-gal. tank	55.0%	54.4%
ICS w /50-gal. tank (single-element)	34.6%	36.6%
SFP PV (40W) pumped w/80-gal tank	60.4%	59.4%
HPWH	61.4%	66.8%

<u>Time-of-Day Electric Energy Savings</u>

Seasonal peak load for electric-based water heating systems was analyzed when systems operated under the family-realistic NREL/BA draw profile. All systems were compared to the standard 50-gal baseline water heater. The highest averaged electric-peak demand hours (i.e., 8:00 AM and 9:00 PM) for the standard baseline heater were chosen to calculate the reduction peak values for all electric-based systems. Table ES-4 shows a summary of reductions from the selected data (NREL/BA draws) ending on August 2011, winter (2010-2011), and summer (2011) seasons. The highest peak reductions achieved are highlighted in bold.

Table ES-4. Electric Peak Reductions Compared to Electric Standard 50-Gal Water Heater under the Family-Realistic NREL/BA Draw Schedule.

	NREL/BA schedule (Sep. 2010- Aug 2011)		Winter Season (Dec. 2010 – Feb 2011)		Summer Season (June – Aug. 2011)	
	Morning 8:00 AM	Night 9:00 PM	Morning 8:00 AM	Night 9:00 PM	Morning 8:00 AM	Night 9:00 PM
Diff. Solar	61.5%	73.6%	48.3%	65.8%	89.8%	90.4%
ICS/50-gal	47.1%	25.9%	23.0%	20.0%	80.1%	50.7%
Diff. PV	68.0%	**88.0%**	42.1%	**83.2%**	**97.1%**	**100%**
HPWH	**75.1%**	76.3%	**76.3%**	82.0%	81.8%	75.6%

Time-of-day Site and Source Energy Compared

Further data analysis of time-of-day related to site and source-energy loads was completed for the 1-year data period. All hourly load values were converted to a common energy metric (kBtu/hr) including natural gas systems. The site-to-source conversion factors (Me = 3.365, Mg = 1.092) for electricity and natural gas were used to generate the hourly average source energy from the actual site loads incurred. Figure ES-7 illustrates the average hourly source-energy demand for seven systems under the NREL/BA hot water draw profile averaged for the 1-year period ending in August 2011.

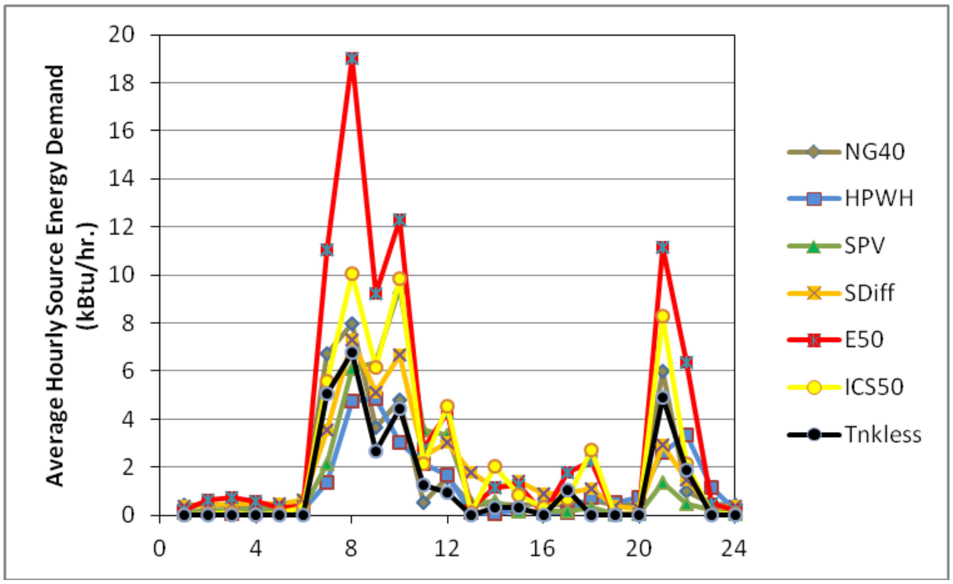

Figure ES-7. Time-of-day source-energy consumption demand for seven HWS under the NREL/BA family-realistic draw profile.

The plot shows the hourly demand demonstrated by a tankless natural gas (Tnkless) and the HPWH as the least energy demand overall form a source. In fact, the HPWH, a 520-W appliance (1.8 kBtu/hr) with hot water storage, appears favorable during morning and night peak hours when compared to the natural gas tankless water heater. Other site and source-energy analysis for winter and summer seasons by draw profile are found elsewhere in the body of this report.

Hybrid and High Efficiency Hot Water Systems Testing in 2012

During the time this report was being revised, FSEC has initiated testing the next rotation of high efficiency hybrid hot water heating systems. These systems will integrate solar thermal with heat pump and natural gas tankless heaters. The purpose is to investigate the highest efficiency for water heating systems that can be achieved under Florida weather conditions by integrating equipment currently available in the marketplace. A target average daily energy use for these hybrid systems should be in the range of less than 2.0 kWh/day for electric and 20 cubic feet per day for natural gas systems or less.

1 Introduction

Following the completion of the Phase I side-by-side hot water systems testing (Colon & Parker, 2010), changes to the HWS laboratory at FSEC were implemented to begin a new 1-year testing rotation. Reconfiguration on three HWS took place during June and August 2010. New strategies on two of the solar systems were implemented to investigate overall efficiency performance improvement. The most significant system change involved the evaluation of a new state-of-the-art HPWH that replaced the electric tankless water heater evaluated in 2009-2010. The widely available HPWH (shown in Figure 1) provides a promising alternative for efficiency improvements in the area of residential water heating technology. With the recent variety of HPWH's offered by major manufacturers and the recent drop in prices, this technology promises to dominate or replace the conventional resistance electric water heating system in the near future.

Figure 1. New hybrid HPWH under evaluation.

1.1 Objective

The objective of the hot water heating systems evaluation task can be summarized under these general statements:

- Compare energy-efficiency performance of side-by-side systems by alternating draw schedules (i.e. ASHRAE 90.1 and NREL/BA) every two weeks within a month.
- Help verify simulation models and code compliance ratings on water heating systems
- Communicate to BA teams, industry, and consumers the efficiency of HWS operating under central Florida (southeastern) weather region.
- Provide guidance and recommendations for energy-efficient retrofits on residential buildings.
- Analyze the overall status of water heating equipment in the United States and encourage development of system designs that would improve efficiency.

Data analysis performed during the first testing rotation (Phase I, 2009-1020), allowed us to compare the efficiency performance of systems on a side-by-side basis. Results of this research laid out the baseline-data foundation to which new systems would be compared. Under Phase I, the differentially-controlled solar water heating system earned the highest overall performance and demonstrated the lowest average daily auxiliary electric consumption of 2.84 kWh/day. For Phase II (2010-2011), all water heating systems continued to be submitted to hot water draws as specified in the ASHRAE 90.1 (64.3 gpd) or the monthly dynamic NREL/BA draw profile (ASHRAE, 1993; Hendron & Burch, 2008).

2 Hot Water Systems Facility Description: Test Configuration and Recent Upgrades

The HWS laboratory underwent some key system changes during late summer 2010. A side-by-side system layout with seven systems in total was submitted for evaluation (Figures 2 and 3). Three systems remain the baseline for each category (electric, renewable and natural gas):

- Standard 50-gal electric water heater (electric baseline reference, EF=0.91)
- Flat-plate solar thermal system (40 ft^2), AC pump differentially-controlled and 80-gal solar storage tank (SEF=2.8)
- Standard (upright vent) 40-gal natural gas water (EF=0.59)

New systems configuration:

- ICS (32 ft^2) in series with standard electric 50-gal tank with single-element operation only—bottom element disabled
- Flat-plate solar thermal system (40 ft^2) with larger 40-W PV and DC pump (20-W rating) for improved hot water circulation (SEF = 3.5)
- Hybrid electric HPWH (EF = 2.4)

Figure 2. Panoramic view of hot water heating systems at the HWS laboratory (June 2010 – December 2011).

The tankless gas water heater unit (shown second from right) was left unchanged from the previous year to investigate further on efficiency degradation as part of its life-cycle. After operating for 18 months, the tankless system underwent a flush treatment procedure, as recommended by some manufacturers.

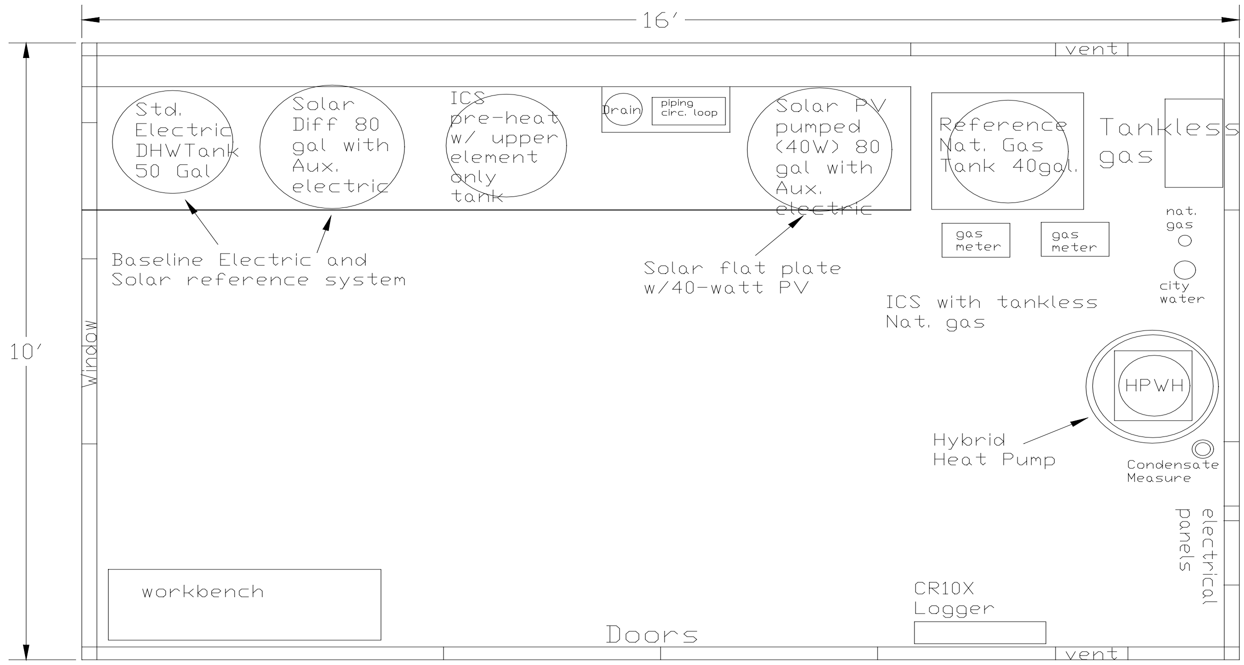

Figure 3. HWS systems layout (2010–2011). Systems line up against the south-facing wall.

Upgrades to the laboratory instrumentation included the following:

- HWS indoor relative humidity (RH) measurement
- Condensate measurement to measure latent heat removal by the HPWH
- Ground temperature measurement 18 in. below the ground and six in. away from the solar circulation loop
- Aspirated (active fan) ambient temperature radiation shield.

3 Laboratory Findings

3.1 Seasonality of Water Heating Loads: Inlet Water Temperature Variation 2009-2010

Since February 2009, the HWS laboratory has been measuring mains inlet water temperature during draw events. Those measurements are reported as weighted averages on a periodic basis. Figure 4 compares the monthly weighted average of the inlet water taken from the reference electric water heating system in 2009 plotted against those from 2010. During fall 2010, the mains inlet water showed a drop in temperature during the October–November period because of the early arrival of cold weather conditions in Central Florida.

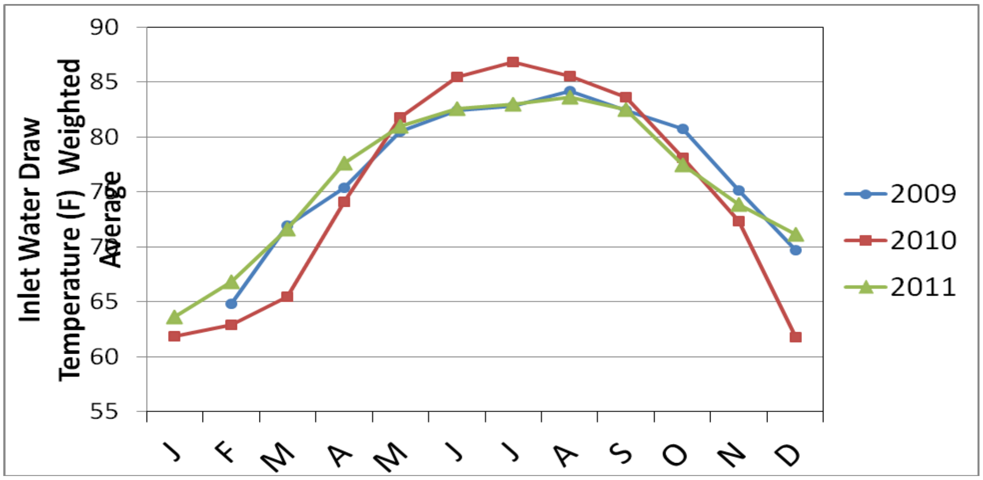

Figure 4. Mains inlet weighted average temperatures, Cocoa, Florida.

3.2 Ground Temperatures

Ground temperature measurement was added at the HWS laboratory during June 2010. The thermocouple probe was buried at a depth of 19 in. and six in. away from the insulated circulation loop. Figure 5 shows an hourly plot of ambient and ground temperatures at the HWS facility in Cocoa, Florida, during December 2010. The data represent triple cold front conditions passing through central Florida between November 30 and December 21, 2010. Ambient temperatures reached 33°F and 28°F degrees, both appearing at 7:00AM in the morning. No immediate relationship between ambient and ground temperature can be concluded from the three-week period.

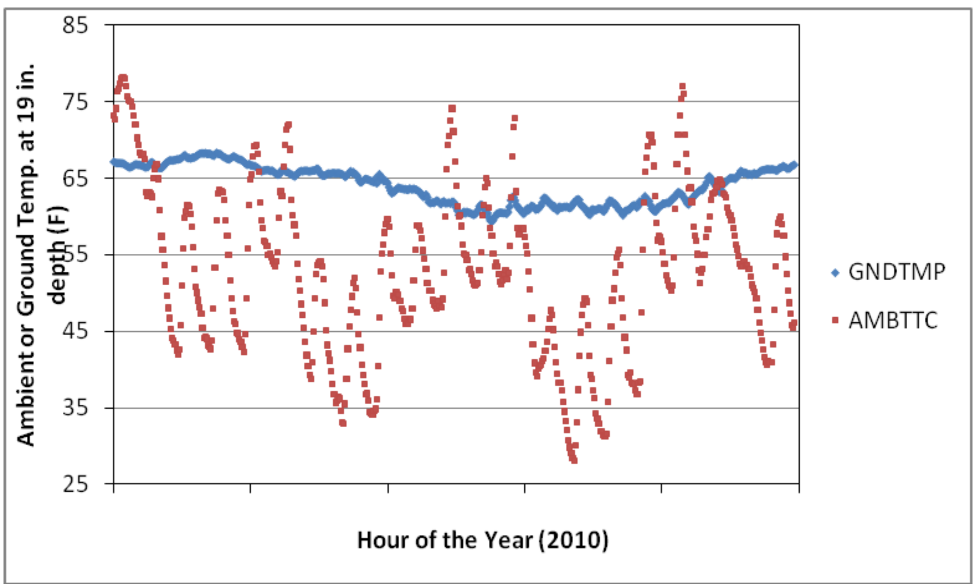

Figure 5. Ambient and ground temperature relationship between November 30 and December 21, 2010.

Furthermore, the ground temperatures are plotted against the daily weighted average inlet water temperature recorded from the electric baseline 50-gal water heater (Figure 6). The trend of inlet water temperatures appears to follow those temperatures measured from the ground.

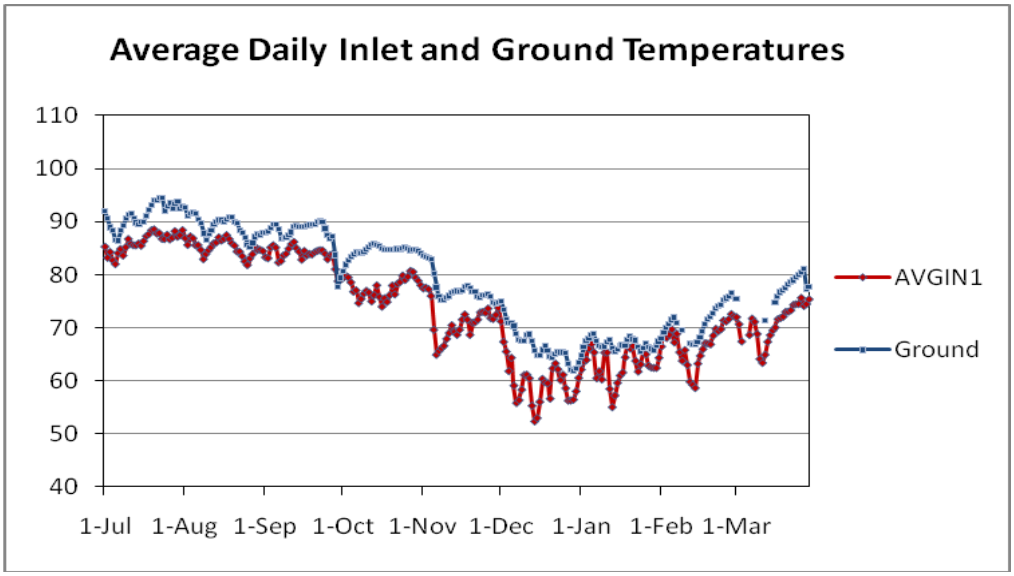

Figure 6. Inlet and ground temperatures at HWS laboratory.

3.3 Natural Gas Consumption on Pilot Burner: Standard 40-Gal Water Heater

During September 2010, draw schedule activities were stopped on the natural gas water heater to investigate the pilot burner and standby natural gas consumption. Table 1 shows the natural gas consumption during three days of hot water draws and three days when hot water draws were stopped on September 10, 2010.

Table 1. Data from Natural Gas Tank Prior to and During Standby (Pilot Burner).

Date	Natural Gas Consumption (Cu ft.)	Average Weighted Draw Temperature	HWS Laboratory Average Interior Temperature (F)	Notes
9/8/2010	33.0	118.7	82.8	40-gal. gas tank under ASHRAE draw schedule
9/9/2010	38.2	120.5	83.9	Same as above
9/10/2010	21.6	120.8	84.6	40-gal. gas tank draw schedule stopped at Noon
9/11/2010	11.1	n/a	86.2	First full day of 40-gal. tank on pilot standby
9/12/2010	11.3	n/a	90.4	Second day of 40-gal. tank on pilot standby
9/13/2010	11.3	n/a	88.3	Third day on standby, no burner activity for 3 days

While on standby, the 40-gal natural gas water heater consumed an average of 11.2 cu.ft/day of natural gas. This consumption represents the amount of gas used by the pilot lamp. No indication of burner activity was recorded since the energy provided by the pilot lamp appears to provide sufficient energy to maintain the thermostat setting (~120°F) within its dead band. Eleven (11.2 cu. ft of natural gas at 1,020 Btu/cu. ft represents approximately 11,424 Btus of daily standby energy consumption by the pilot lamp. This daily standby consumption is in agreement with manufacturer pilot burner rate consumption reported by others (PNNL, 1998).

3.4 Tankless Water Heater Maintenance

The natural gas tankless water heater, which demonstrated lower efficiency than its rated EF (EF=0.83), received a flush cleaning procedure in November 2010. Three flushing solutions were recommended by the manufacturer: a 10% sulfamic acid dilution in hot water, citric acid, and vinegar solution. When using vinegar, the flush treatment requires a longer period of treatment than the sulfamic (or citric alternative) acid solution. The commonly available vinegar solution was chosen to flush the tankless system. An electric pump (1/2 hp) with plastic impeller was used to circulate a 1-gal vinegar solution through the unit for a period of two hours. The tankless heater was set to heat at minimum temperature for a few minutes at the beginning of the procedure and after one hour into the procedure. The rest of the flush procedure was run with the tankless heater turned to “OFF”. After two hours of vinegar circulation through the unit, accumulation of scaling debris was visible at the bottom of the vinegar reservoir, as shown in Figure 7.

Figure 7. Tankless flush procedure showing scaling debris after two hours of vinegar flush circulation.

3.5 Improving Water Heater Tank Energy Factor: Jacket Insulation Evaluation

During September and October 2010, a portion of the research time was dedicated to evaluating currently available water heater tank blankets and energy savings they provide on both electric and natural gas tanks. Figure 8 shows two common blanket products available at major do-it-yourself (DIY) hardware stores. The one-sided, white-faced vinyl blanket relies on 3 in. of fiberglass insulation to obtain an R-11 thermal resistance. The 1 in. R-4 product is a double, foil-sided fiberglass insulation. The inner foil is perforated to allow moisture transfer through the fiberglass. Both products are offered in a 48 in. height roll that proved to be somewhat inadequate for standard tall size (50-52 in.) water heater tanks. When users install the blanket using the 48 in. coverage, they are left with two choices:

- Slide the blanket upwards to cover the top
- Align with the blanket insulation along the top of the tank perimeter.

Figure 8. Water heater blanket insulation products available at do-it-yourself hardware stores.

The first option results in a compressed and irregular coverage of the top of the tank, and the area along the tank bottom would be compromised and left uncovered. The second option would cover a larger area at the bottom but would leave the top uncovered, which is considered most important to retain the tank heat. An evaluation of pre- and post-data analysis concluded that the commercial blanket (R-11) product can provide a 3% increase in efficiency for the standard electric 50-gal water heater. The investigation of water heater blankets led to the development of an innovative insulated cap (FSEC patent applied for) for natural gas water heaters. The concept was also adapted to electric water heater tanks (shown in Figures 9 and 10).

The new product could lead to the adoption of retrofit improvements on water heaters across the United States. Ultimately, further testing was conducted using the FSEC design insulation cap with double layers of bubble wrap with radiant foil insulation (R-6), since fiberglass may present a health hazard condition when used indoors.

Note: Insulation blanket and cap insulation research investigation was conducted prior to receiving BA funding under Task Order 1 but reported here as it is related to the funded research.

Figure 9. Development of natural gas retrofit insulation cap.

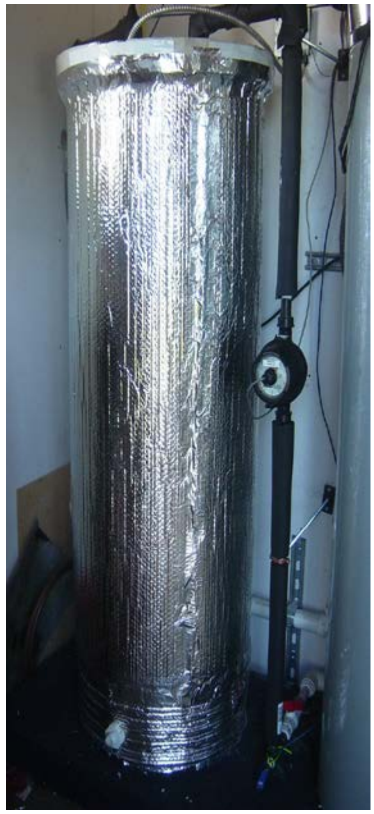

Figure 10. Insulation cap installed with bubble-wrap blanket on standard electric water heater.

Energy Gauge simulations were performed to evaluate blanket insulation to increase energy efficiency in older stock water heaters (pre-1994, EF=0.88) and the current stock (EF=0.91). Results were communicated to Florida Power and Light (FPL) and are available in Appendix A.

3.6 Hot Water Delivery Temperatures

As indicated previously, all hot water systems undergoing testing at the HWS laboratory attempt to deliver hot water temperatures at approximately 120°F during schedule draws. This is accomplished by setting all thermostats to the target level. The use of mixing valves is required in the case of solar systems because of the uncontrolled extra energy that solar collectors can supply; however, exact settings can prove difficult to achieve, and in some cases a slight seasonal adjustment to the mixing valve (or thermostat) was needed during the evaluations. In the case of the 50-gal tank supplemented by the ICS with one thermostat/element configuration, the consistency of 120°F hot water delivery was more difficult to attain. Table 2 provides a summary of average (weighted) hot water temperature delivery as provided by the seven systems during the evaluation period (Sept. 2010–Aug. 2011).

As expected, the overall average temperature delivered by the natural gas tankless system was the lowest, since it requires some time for the burners' heat exchanger to reach stability. The thermostat setting of 122°F was selected for this unit from the electronic display controls.

Table 2. Delivery of Hot Water Temperatures as Measured and Reported as Average Weighted.

HWS	Average Weighted Delivery Temperature During 12-month Evaluation Period (Sep 2010 - Aug 2011)
Standard 50-gal electric water heater	119.4°F
Flat-plate (40 ft^2) 80-gal differentially-control solar System (AC Pump)	118.2°F
50-gallon one-element configuration supplemented by ICS 32 ft^2	121.7°F
Flat-plate (40 ft^2) 80-gal differentially-control solar system (PV Pump)	122.4°F
Natural gas 40-gal water heater	123.7°F
Natural gas tankless water heater	116.6°F
HPWH (50-gal)	118.1°F

Further inspection of the averaged, weighted delivery temperature data obtained from the baseline electric 50-gal water heater was compared against the HPWH. Figure 11 shows the average daily temperature delivered by each system. Note that NREL/BA draw schedule activity did not start until the end of September, where it draws a daily total of 44.8 gal per day with peak volume draws between 6:30 and 7:45 AM. As winter approaches, larger dips in daily average hot water delivery were observed. The impact of this draw profile combined with the lower inlet water temperatures of the winter season reveal that the delivery of hot water temperature by the HPWH is not nearly as constant as the standard 50-gal heater. This overall daily temperature reduction obtained from the NREL/BA load profile is due to peak draw quantities that can be nearly double those on the ASHRAE 90.1 draw profile. It is clear on Figure 11 that following through the spring season, reduced hot water delivery temperature goes into effect. In high demand, electric resistance would be needed to meet household loads (Hudon, Sparn, Christiansen & Maguire, 2012).

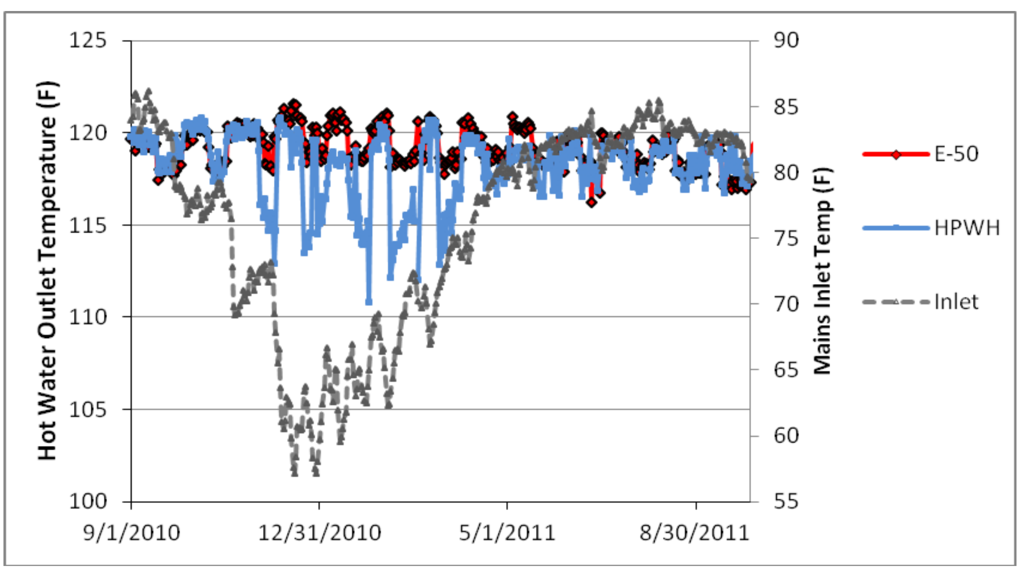

Figure 11. Delivery temperatures of standard electric vs. HPWH (September 2010 – August 2011).

4 Analysis and Results

During the period of September 2010 thru August 2011, all seven HWS were submitted to hot water draws using alternating hot water draw schedules (ASHRAE 90.1 and NREL/BA profiles). Figure 12 illustrates the average overall efficiency of systems obtained for the year period ending in August 2011. As indicated in Figure 12, the HPWH averaged the highest overall efficiency, closely followed by the PV-pumped solar flat-plate system.

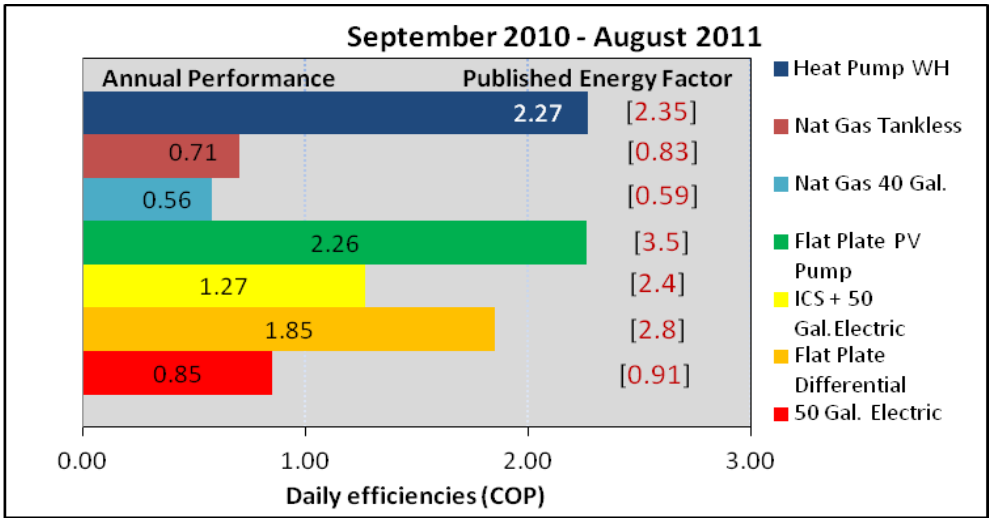

Figure 12. Average daily efficiency performance for seven HWS for the period of July 2010 – April 2011.

4.1 Daily Electric Consumption

A comparison of daily electric consumption for those electric-dependent water heating systems is illustrated in Figure 13. The baseline electric standard water heater (50-gal) consumed 7.61 kWh/day during the 12-month period. During the same time, the HPWH demonstrated a 63.8% daily electric reduction by consuming an average of 2.75 kWh/day.

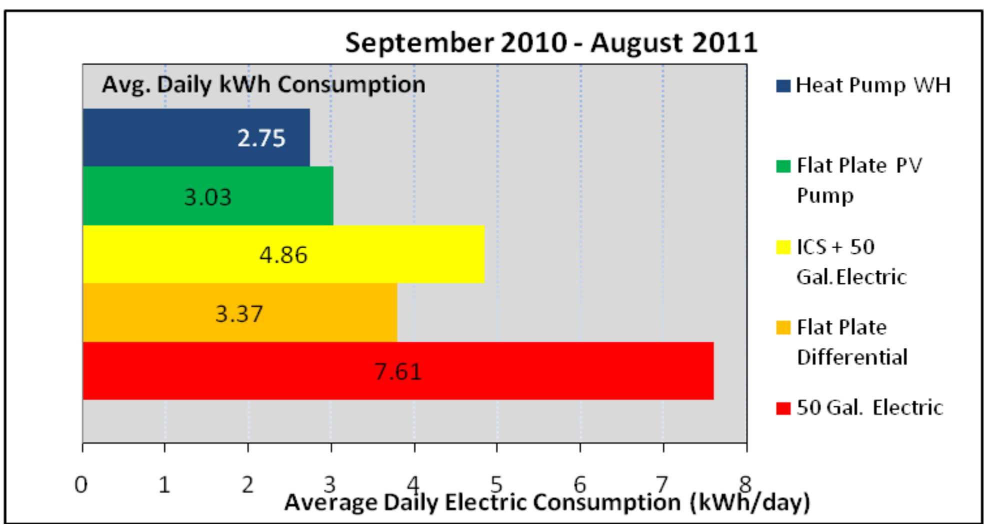

Figure 13. Average daily electric consumption of water heating systems for the period of September 2010 - August 2011.

Table 3 provides a daily average summary of the combined and draw-dependent input energy values recorded on each system at the HWS laboratory between August 2010 and September 2011. In general, an energy decrease appears under the NREL/BA draw schedule as compared to ASHRAE 90.2. Except for the ICS/50-gal system, a similar correlation was found during Phase I (2009-2010). The new ICS/50-gal results are attributed to the electrical heating hardware change from dual to single-heat element configuration.

Table 3. Average Daily Energy Consumption for HWS (September 2010 – August, 2010).

System	Daily Average Consumption All Data Days (N=365)	Daily Average Consumption ASHRAE 90.2 Draws (N=170)	Daily Average Consumption NREL/BA Draws (N=171)
Standard electric 50-gal tank	7.61 kWh/day	8.07 kWh/day	7.53 kWh/day
SFP differential w/80-gal tank	3.80 kWh/day	4.03 kWh/day	3.84 kWh/day
ICS w /50-gal tank	4.86 kWh/day	5.13 kWh/day	4.87 kWh/day
SFP PV-pumped w/80-gal	3.03 kWh/day	3.17 kWh/day	3.17 kWh/day
HPWH	2.75 kWh/day	3.09 kWh/day	2.50 kWh/day
Natural gas 40-gal tank	38.55 cu. ft/day	42.73 cu. ft/day	36.08 cu. ft/day
Tankless natural gas	29.22 cu. ft/day	27.38 cu. ft/day	27.37 cu. ft/day

4.2 Daily Average Natural Gas Consumption

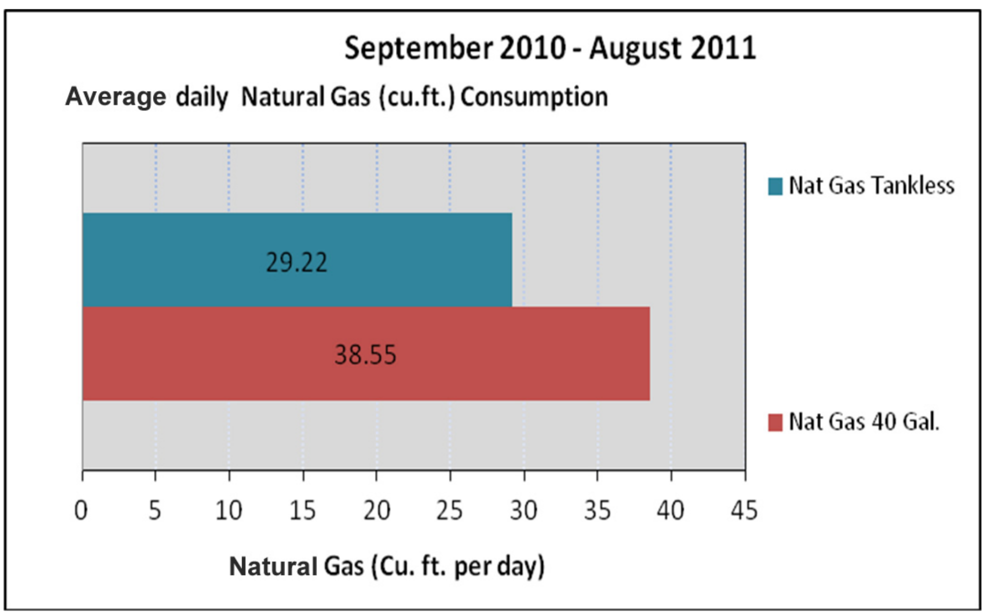

Figure 14. Average daily natural gas consumption of water heating systems for the period ending in August 2010.

*Note: An adjustment for additional gas consumption was made for those days where gas meter pulser demonstrated erratic measurement of standby pilot gas consumption.

4.3 Efficiency Results by Hot Water Draw Schedule

Further analysis was performed to examine the efficiency of systems based on the draw pattern imposed. Figure 15 shows the average monthly efficiency of electric-based systems for the NREL/BA draw schedule. The solar flat-plate PV-pumped systems efficiency for July 2011 reached a COP of 25 during the month (shown off the scale). The solar flat-plate PV-pumped system was able to deliver consistent hot water during the July period using only 0.2 kWh/day on average.

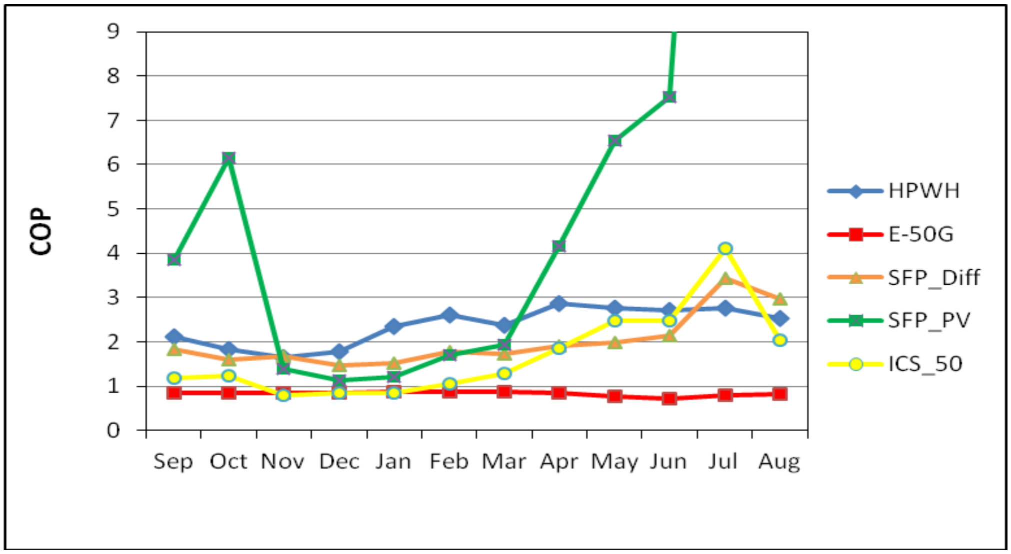

Figure 15. Monthly efficiencies of electric-based systems compared under the NREL/BA draw schedule.

Similarly, efficiencies demonstrated by each system under the ASHRAE 90.2 draw schedule can be observed in Figure 16 for the same period.

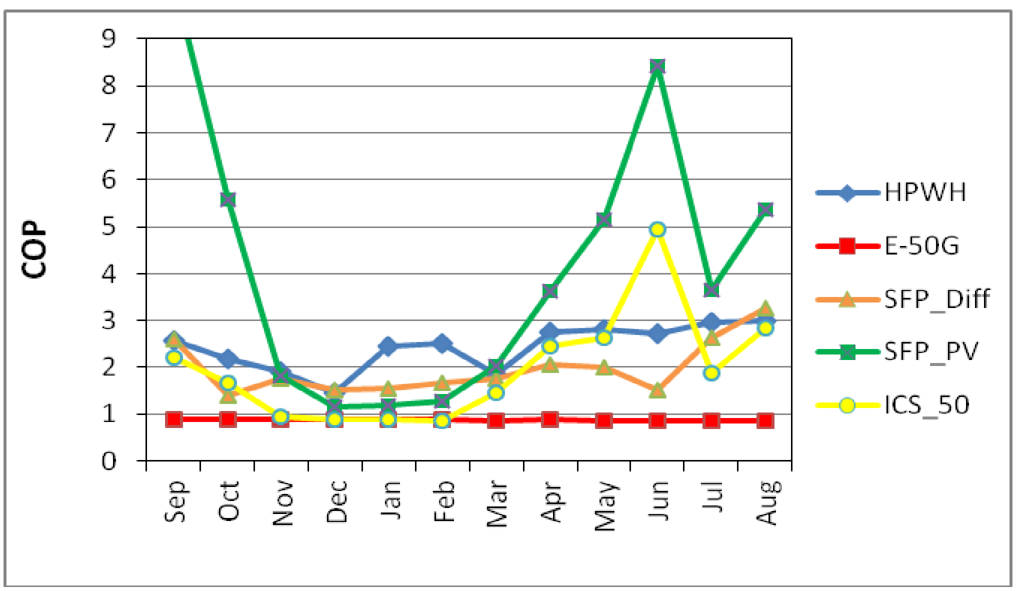

Figure 16. Monthly efficiencies of electric-based systems compared under the ASHRAE 90.2 draw schedule.

Averaged Monthly Daily Electric Consumption by Draw Schedule

Electric consumption was also affected by the hot water draw profile. Figures 17 and18 show monthly averaged kWh/day of electric used for the respective draw schedule.

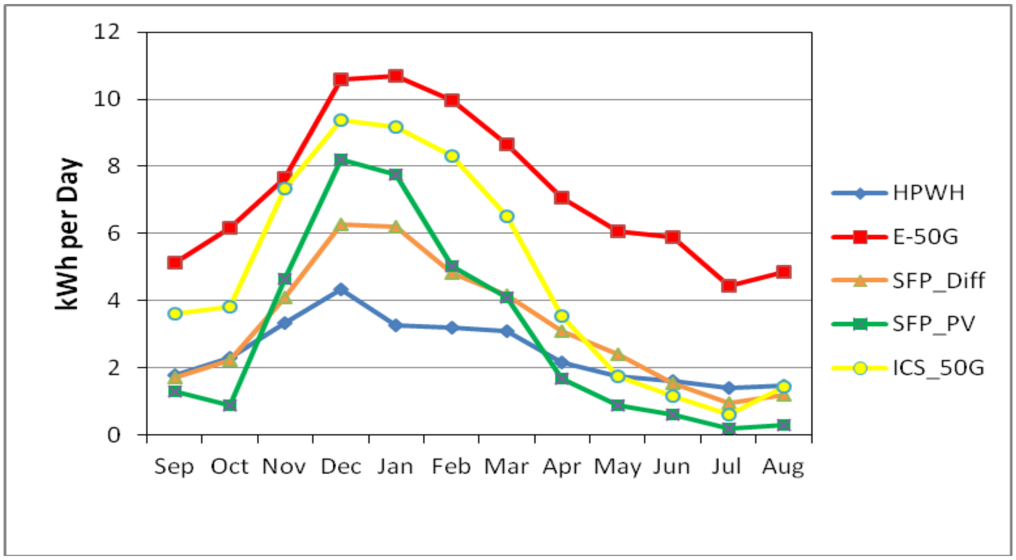

Figure 17. Average daily electric consumption of electric-based systems compared under the NREL/BA draw schedule.

Overall, the monthly trend of kilowatt hours used looks similar on both plots regardless of draw schedule utilized. A higher peak during the month of February can be observed for the ICS/50 gal system, and the efficiency of the flat-plate differential solar system during the ASHRAE draw schedule appears flat duirng winter months.

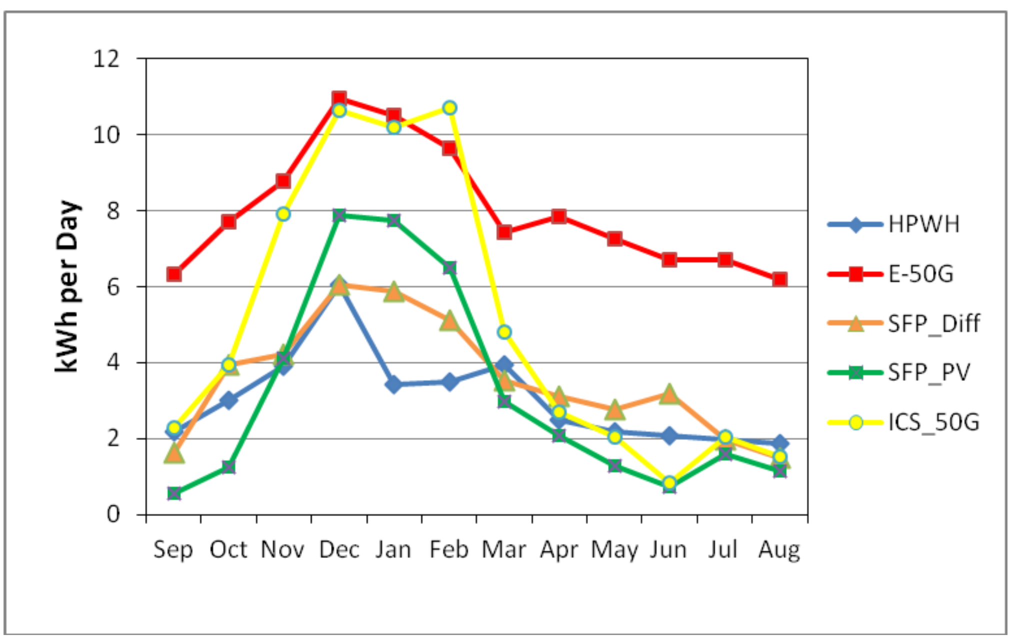

Figure 18. Average daily electric consumption of electric-based systems compared under the ASHRAE 90.2 draw schedule.

4.4 Heat Pump Water Heater Results

In June 2010, a commercially-available HPWH was installed and set into operation at the HWS laboratory. The unconditioned space of the HWS laboratory simulates garage or exceeds conditions in a Florida building. Typical garage-like conditions provide plenty of air source heat available to the HPWH. Following startup, current on the HPWH was measured at 2.9 amps (240 VAC) after 20 minutes into operation. During the first two hours of operation following the initial startup, the unit measured an average electric power load of 530 W. Figure 19 plots the COP efficiency of the air source heat pump compared to the standard 50-gal baseline electric water heater under the NREL/BA load profile between September 2010 and August 2011.

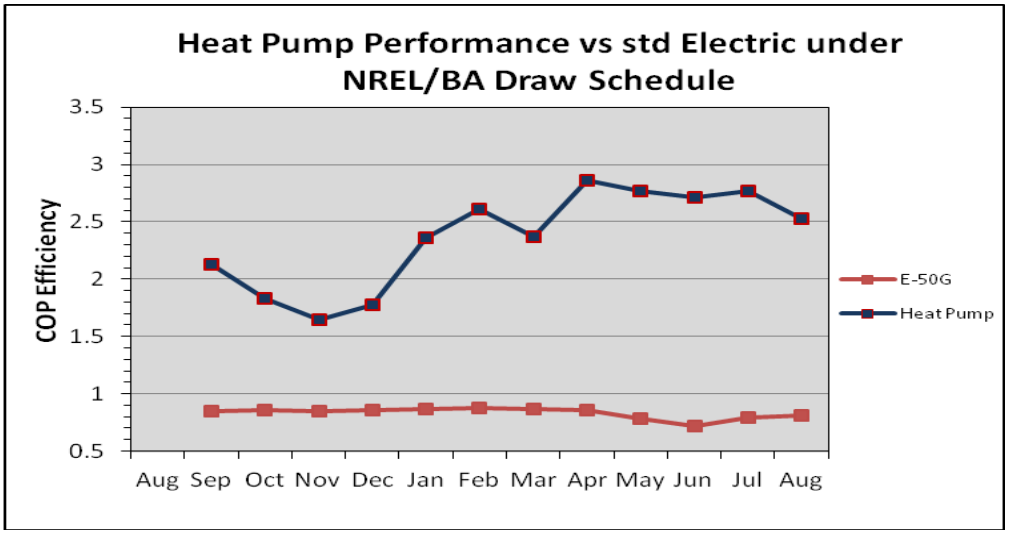

Figure 19. Efficiency of a HPWH compared to a standard electric water heater under NREL/BA draw schedule (September 2010 – August 2011).

Figure 20 shows the HPWH efficiencies are not drastically affected by the hot water draw schedule. The lowest efficiency (COP = 1.5) was observed during December 2010.

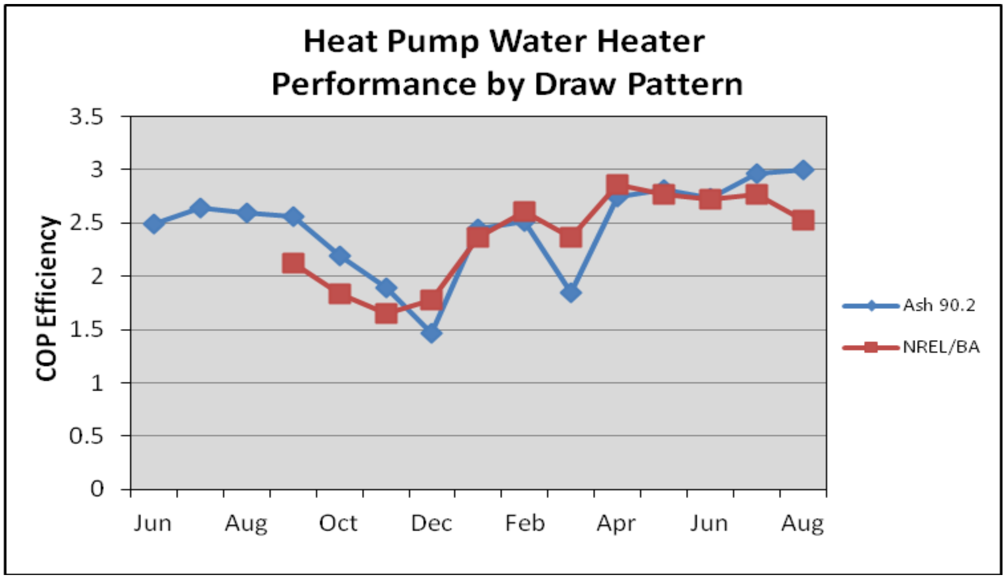

Figure 20. Efficiency of HPWH under NREL/BA draw schedule.

Further analysis of monthly demand by draw schedule can be observed in Figure 21.

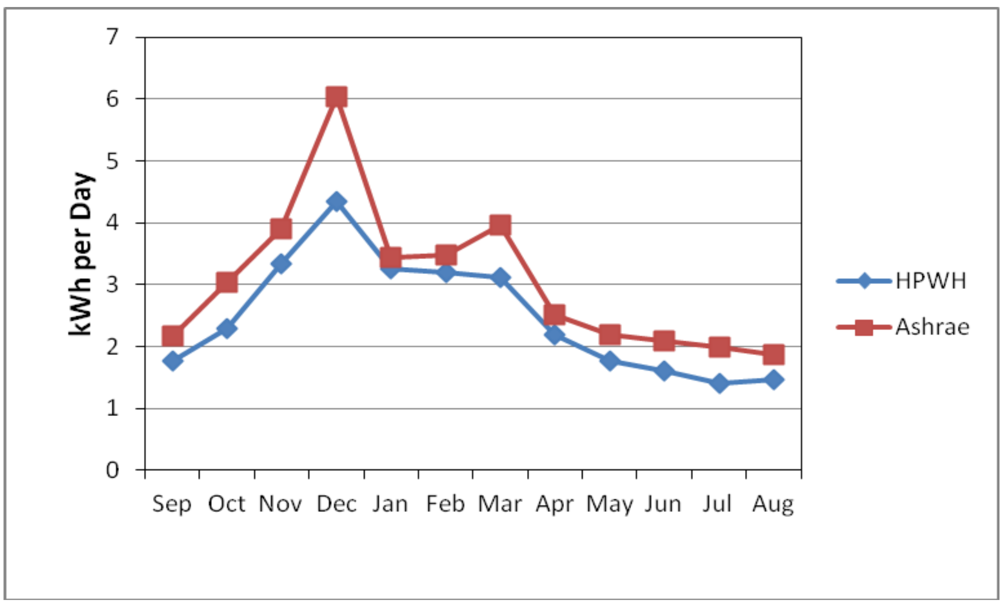

Figure 21. Monthly averaged electric demand for HPWH by draw schedule.

4.5 Heat Pump Latent Removal: Condensate

The HPWH also demonstrated that it can discharge cold air at 67°F under ambient operating conditions close to 90°F. In July 2010, a condensate measurement device (calibrated rain bucket) was installed to measure latent heat removal by the HPWH. During the 12-month testing period, the HPWH demonstrated an average latent (condensate) heat removal of 3.2 pints of water per day. Average daily condensate removal by month can be seen in Figure 22.

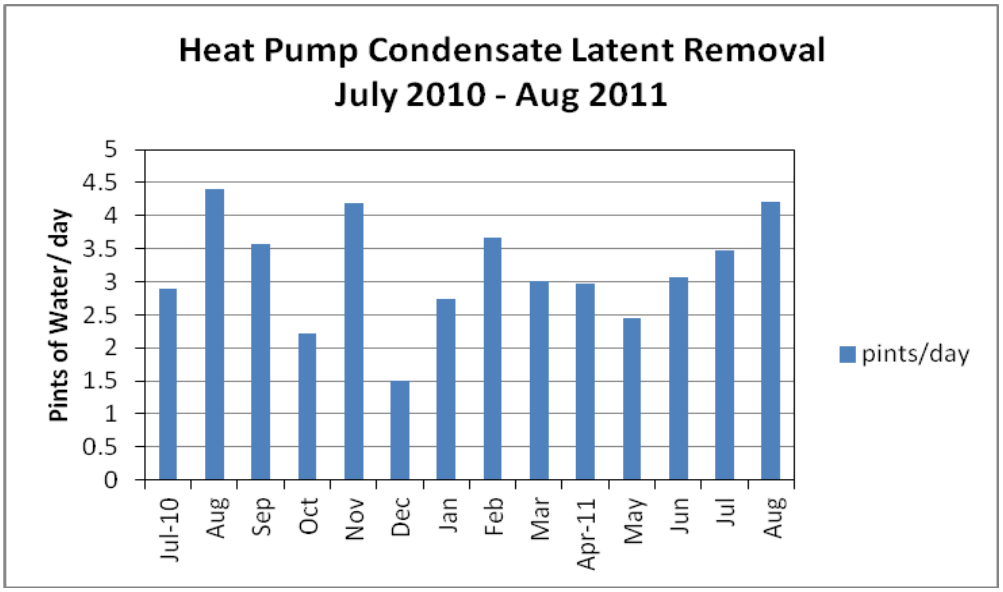

Figure 22. Average daily condensate removal demonstrated by the HPWH (July 2010 - August 2011).

4.6 Heat Pump Water Heater: COP vs. Ambient Temperatures

The average daily electrical (COP) efficiency of the HPWH was plotted against the interior space temperature where the unit operated. The HPWH efficiency can drop below unity (COP= 1.0) when average daily temperatures drop below 52°F (shown in Figure 23). Although low temperature extremes are few in the central Florida area, this would present a lower than expected performance for other weather regions above the southern belt of the United States.

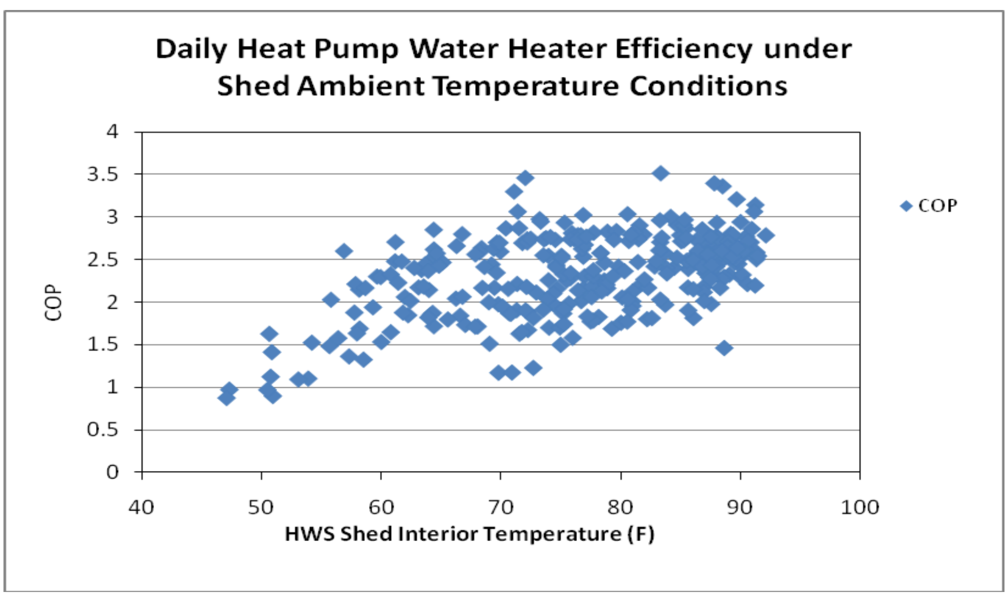

Figure 23. HPWH electrical COP vs. average daily space room temperature.

4.7 Heat Pump Water Heater: Auxiliary Electric Consumption vs. Temperatures

The HPWH was set to its default hybrid setting since its first day of operation. The unit defaults to a thermostat setting of 120°F in "hybrid" mode, where most of the heating is performed from the refrigeration cycle. However, based on demand and ambient temperature, the unit energizes the electric resistance element for heating controlled by a proprietary algorithm. Its auxiliary-resistive heating element saw limited operation activity during the 12-month period. In fact, data indicated that resistance heating operation only occurred during twelve days for a total of 39 hours during the 1-year data period. Electric resistance heating was evident during those days averaging daily temperatures of 52°F, where minimum temperatures of 42°F were reached as measured inside the HWS laboratory. These numbers suggest that when operating under its default setting (120°F), the HPWH activated the resistance element approximately 2.34% of the time during the 1667.5 hours that compressor-mode operation was detected. Figure 24 shows the hourly electric consumption of the unit plotted against the average hourly ambient temperature where it operated—HWS indoor ambient temperature. Although the unit is rated as a 700 W appliance by the manufacturer, it operated at an average of 530 W in compressor mode.

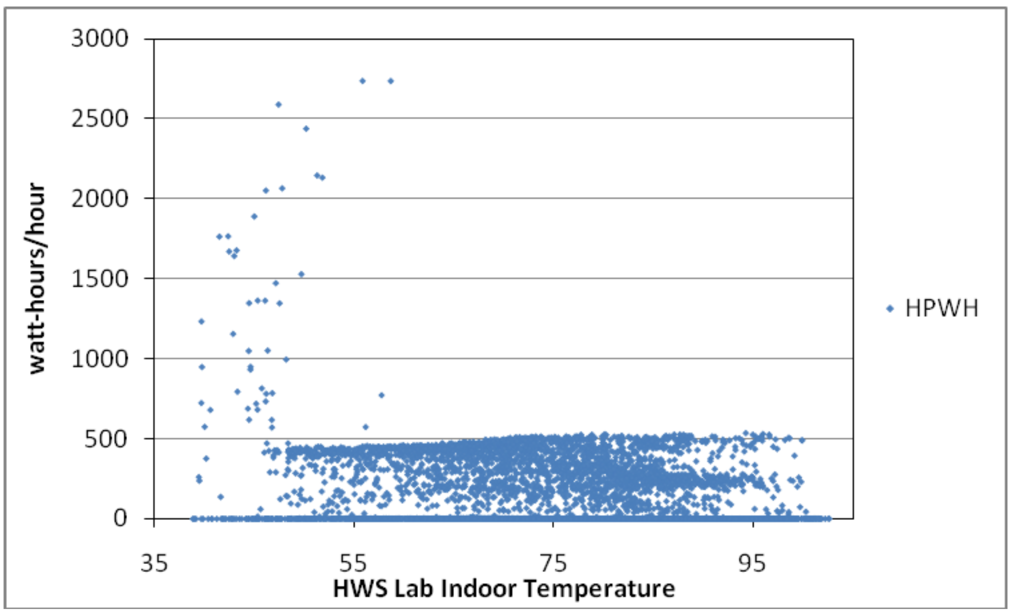

Figure 24. HPWH electric data (July 2010 – Apr 2011) showing electric resistance heating activity when ambient temperatures reach below 58°.

4.8 Heat Pump Water Heater: Experimental Laboratory Testing Fan Airflow Measurement

During October 2011, a measurement of the airflow passing through the HPWH evaporator cooling coils was performed. The HPWH top plastic compressor/evaporator shroud was removed and a temporary cardboard cover was constructed to allow connection of a duct blaster duct (see Figure 25). The unit was purged of hot water until the fan and compressor were energized. It was noticed that prior to the compressor being energized, the fans operated for approximately 70 seconds before the compressor begun operation. This indicates that some of the condensate leftover from the previous cycle may evaporate and be introduced into the space if the HPWH is installed indoors under conditioned space. The calibrated duct blaster measurements indicated an average airflow of 130 cfm.

Figure 25. Measurement of HPWH airflow using a calibrated ductblaster attached to sealed cardbox cover.

Further realization on this topic was found in a table included under a BPA report on HPWHs (BPA, 2011). The report indicates a variable airflow range of 100 to 177 cfm on this particular unit. Furthermore, the author of the report was contacted to verify the airflow-to-tank hot water relationship, leading to the discovery that the airflow is inversely proportional to the temperature of hot water stored. The findings play an important role in the interaction of a HPWH operating in a conditioned space, as the HPWH contributes to heat removal of the space in a residence. In summary, it is expected that this particular HPWH model will provide the maximum airflow (175 cfm) most likely during cold startup or colder climates and gradually reducing airflow in steps, as indicated by the plot and information provided by the BPA. However, it is important to realize that in real-world operation under a family load, it can be inferred that, following a partial purge of hot water from the HPWH, cooling would be delivered with an airflow rate somewhere in the middle of the airflow range. It would then be concluded that following a purge of hot water, enough to energize the compressor, a flow of approximately 130 cfm (as observed in the FSEC test) can be expected.

4.9 Heat Pump Water Heater Performance in a Confined Space

As mentioned in this report, a typical garage in central Florida would be considered an ideal operating space for a HPWH. However, a percentage of these units would end up installed inside conditioned living space such as a confined closet. The manufacturer of HPWH, GE, recommends a minimum space of 700 cu. ft to allow for enough air source heat during operation. In the case of Atlantic Housing, a BA-PIRC partner and multifamily housing builder who has installed more than 600 of these units, HPWHs are being installed in a quasi-conditioned space confined closet. The closets are being outfitted with two wall vents to provide air exchange with the dwelling's interior. A typical Atlantic housing installation of HPWHs in confined closets includes two vents (16 in. × 20 in. and 14 in. × 20 in.) on adjacent walls positioned at 72 in. from the ground. At least 660 of these units have been reportedly installed and the ventilation details explained may be the case for a majority of these installations. In order to investigate the efficiency reduction of the "less than ideal" configuration, a small confined space enclosure was built at the HWS laboratory to investigate the HPWH performance. During the period of October 29 and November 6, 2011, the HPWH was confined into a 92.5 cu. ft of space, similar to the

Atlantic Housing setup. Also, the same venting area was provided through grilles but on opposite walls (as opposed to adjacent), as shown in Figure 26.

Figure 26. HPWH enclosed in vented confined space.

Although the walls were constructed of rigid sheets of R3.4 insulation, the purpose of the test was to investigate whether the heating elements of the HPWH would energize because of the rapid cooling of the limited space volume. The testing was performed using the NREL/BA draw schedule, which drew a morning peak of 7.4 gal during October and totaled approximately 50 gal of daily hot water on average. The ambient airspace temperature of the HWS laboratory was kept from reaching extreme temperatures during the day by using a small window air conditioner. Table 4 summarizes the findings of the HPWH performance under conditioned ambient temperatures (77.5°F) and under conditioned area (70.7°F) plus confined into a 92.5 cu. ft closet space. The increased percent of electric agrees with that reported by others (Fitzpatrick & Murray, 2011)

Table 4. Summary of Test Results for HPWH Under Conditioned and Confined Space.

	Days	Avg kWh/day	Avg COP	Avg Inlet (F)	Avg Outlet (F)
HPWH in conditioned lab	6	2.050	2.64	74.78	118.47
HPWH in conditioned + confined space (92.5 cu. ft)	7	2.342	2.30	74.21	117.49
Percent increase of electric use	14.27%	0.292			
Percent COP reduction	12.78%				
Average outlet temperature reduction	0.98°F				

To simulate conditioned space in the HWS lab, a window air conditioner was left running during the test period with a lower thermostat setting to allow the compressor to cycle periodically. Figure 27 shows the relative humidity measured in the confined space (HWSLRH), the HWS laboratory temperature (labeled as SHEDTE), the confined "closet" temperature (labeled " SPARE2"), and the outdoor temperature shown for October 30, 2011. The RH sensor probe was set inside the confined space at a height of 44 in. from the floor opposite to the HPWH cool discharge air flow. The confined closet reaches a low temperature of 54°F and RH% spike at the end of the HPWH compressor cycle to approximately 74%.

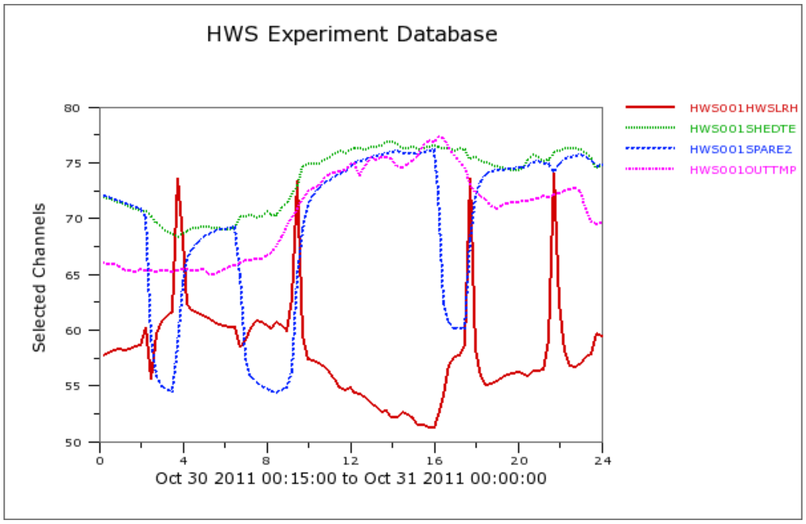

Figure 27. Experimental conditions at the HWS laboratory and HPWH operating in a confined space.

4.10 Solar Thermal System vs. Heat Pump Performance

There has been much speculation regarding whether the HPWH system can perform at the same efficiency level of performance as the flat-plate solar systems. The following plots present the efficiency levels of the solar and heat pump system under the two draw schedules used in the test evaluation—ASHRAE 90.2 (Figure 28) and NREL/BA (Figure 29).

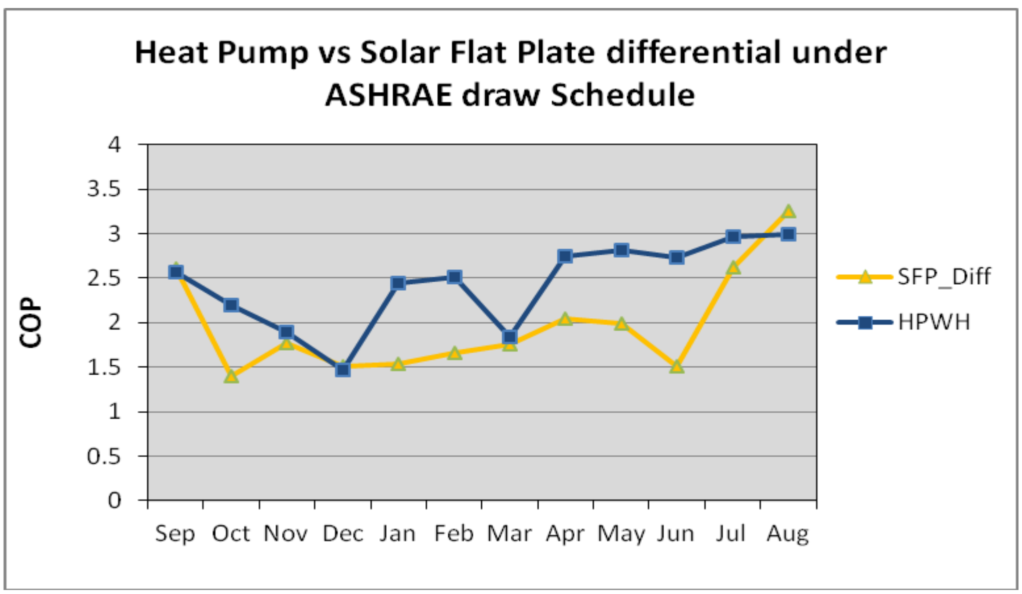

Figure 28. Monthly efficiencies for solar thermal and HPWH systems compared under ASHRAE 90.2 draw schedule.

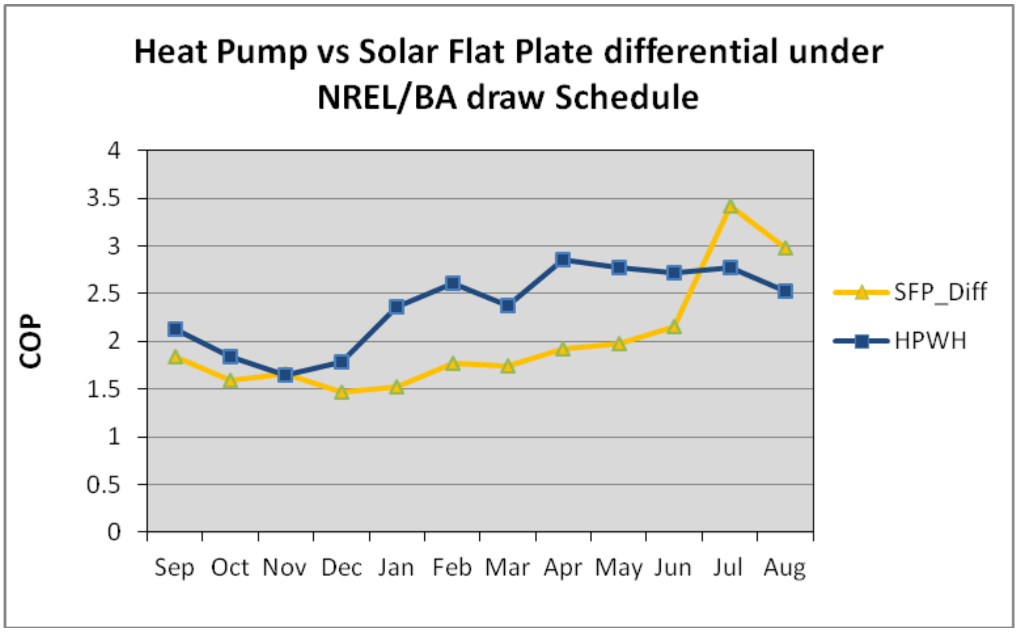

Figure 29. Monthly efficiencies for solar thermal and HPWH systems compared under NREL/BA draw schedule.

The effects of draw schedule on efficiency performance are evident and due to the amount and frequency of hot water used. The HPWH achieved COP efficiencies between 2.4 and 2.5 during the winter months of January and February 2011, matching those of the solar thermal system under the ASHRAE 90.1 draw schedules. Similarly, the efficiencies obtained from the HPWH match those from the solar system COP of 1.6 and 1.7, respectively, for the fall-winter months of November and December 2010—both systems performing at a reduced efficiency levels under the NREL/BA hot water draw schedule.

4.11 Solar Flat-Plate Systems: AC Pump Differential-Control vs. 40-W PV-Pump System

During the first year of testing (2009-2010), it was demonstrated that the differential-controlled system outpaced the PV pumped solar system during the winter months. A design change was made with the attempt to improve the PV solar system performance by increasing its pumping capacity. Figure 20 shows that this goal was accomplished, although not enough to surpass the differential-controlled system. However, further refinements could be made to close the gap in efficiency between the two systems. Detailed data comparing the critical performance period (November-February) of a 10-W pumping system and the improved 40-W solar thermal system can be found in Appendix B. An explanation of the electric control strategy follows.

On June 2, 2010, the solar flat-plate with PV pump received an upgrade by increasing its pump capabilities. A 20 W SID pump was installed along with a 20 W PV module. The purpose of the pumping upgrade was to achieve better pump flow rate during cloud passages and winter months. Telephone conversations with the pump manufacturer suggested that further pumping capacity could be increased by doubling the module power to this pump. However, precautions needed to take place to prevent excessive voltage to the pump since its maximum recommended rating is at 20 V. At the manufacturers' suggestion, a second 20 W PV module was added on August 12, 2010, along with a string of diodes connected in series to allow current flow and limiting the voltage (see Figure 31). The second module (12V nominal) was connected in parallel for a total of 40 W available to the pump. Three diodes per PV module (shown in Figure 30) were utilized, whose voltage drop measured at 2.2V per string, effectively protecting the pump below 20V during full sunlight conditions.

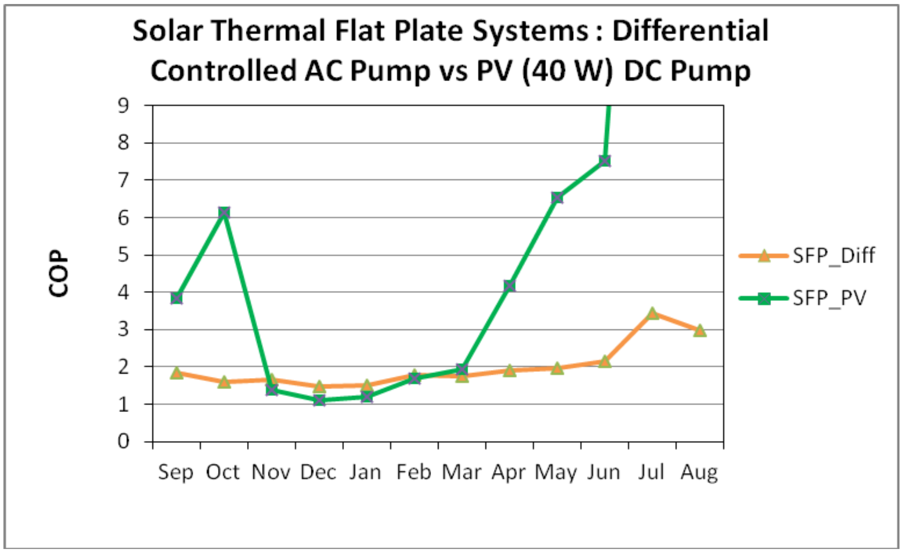

Figure 30. Solar flat-plate systems compared under NREL/BA draw schedules (September 2010 – August 2011).

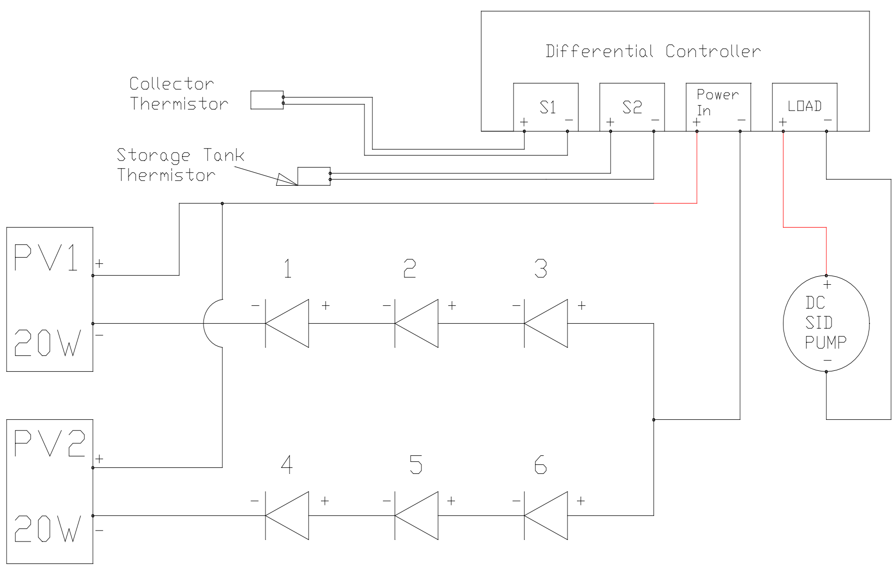

Figure 31. Electrical diagram of dual 20W PV modules with differential controller and diode strings to protect pump from exceeding 20V max.

After demonstrating a lower than expected performance during half of the winter season, the PV solar thermal system was outfitted with a DC differential controller in January 2011in hopes of improving performance. The DC differential controller underwent a bench test procedure to determine the differential control on/off characteristics. A 1.7°F ΔT "ON" temperature differential to trigger pump activation was found when the tank sensor resistance was set to an equivalent of 71°F (11.7kΩ). An "OFF" temperature differential of 0.77°F ΔT was also determined on the bench test procedure. Closer hysteresis dead band was found on the DC differential-controller device as the temperature of the tank sensor was raised to 100°F and 120°F by adjusting to lower resistance, as shown in test results (Table 5).

Table 5. Results from Differential DC Controller Bench Test.

Tank-Simulated Temp Sensor 70.6°F (S2)	Collector Temp Sensor (S1)	Delta T (Δ)
On	72.357	1.74
OFF	71.390	0.77°F
Tank-Simulated Temp Sensor 100 °F(S2)	**Collector Temp Sensor (S1)**	**Delta T (Δ)**
On	100	0°F
OFF	99.3	-0.70
Tank-Simulated Temp Sensor 120 °F (S2)	**Collector Temp Sensor (S1)**	**Delta T (Δ)**
On	-0.07°F	0°F
OFF	-0.70°F	-0.70

A current-voltage (I-V) curve test was performed on both PV modules before being exposed to solar radiation. The first 20 W module underwent a flash simulator test at FSEC prior to and after three days of exposure. No degradation was detected after initial exposure. The second 20 W single-crystalline module also underwent I-V testing under the flash simulator. The 20 W module revealed a lower performance and slightly skewed I-V curve prior to outdoor sunlight exposure. The results obtained from testing can be compared in Table 6 and Figures 32 and 33.

Table 6. Measurements Obtained from 20 W Modules Simulator I-V Test.

Parameter	SPM 020 Module #1	SPM 020 Module #2
I_{sc*} (A) at STC**	1.42	1.37
I_{mp***} (A) at STC	1.31	1.19
V_{oc****} (V) at STC	21.58	21.25
$V_{mp*****}$ (V) at STC	17.43	17.33
$P_{mp******}$ (W) at STC	22.83	20.64

*Short circuit current
**Standard test conditions
***Maximum power point current
****Open circuit voltage
*****Maximum power point voltage
****** Maximum power point

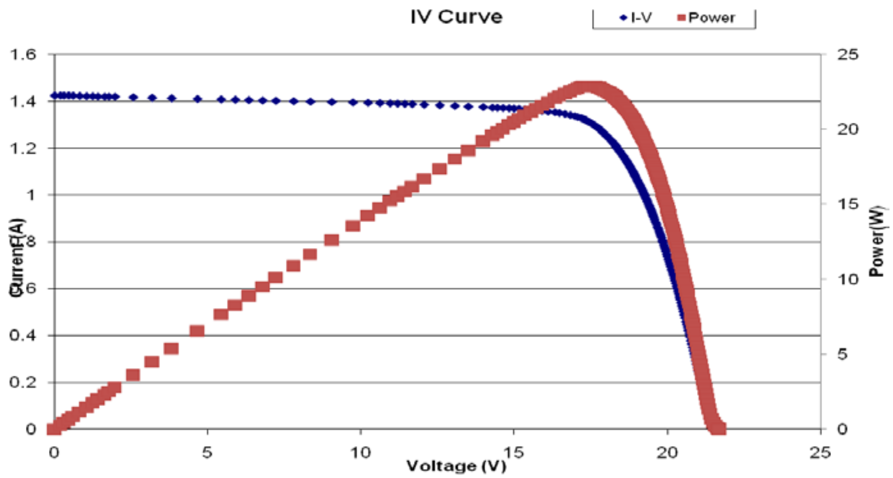

Figure 32. Results from I-V flash simulator performed at FSEC on 20-W PV module #1.

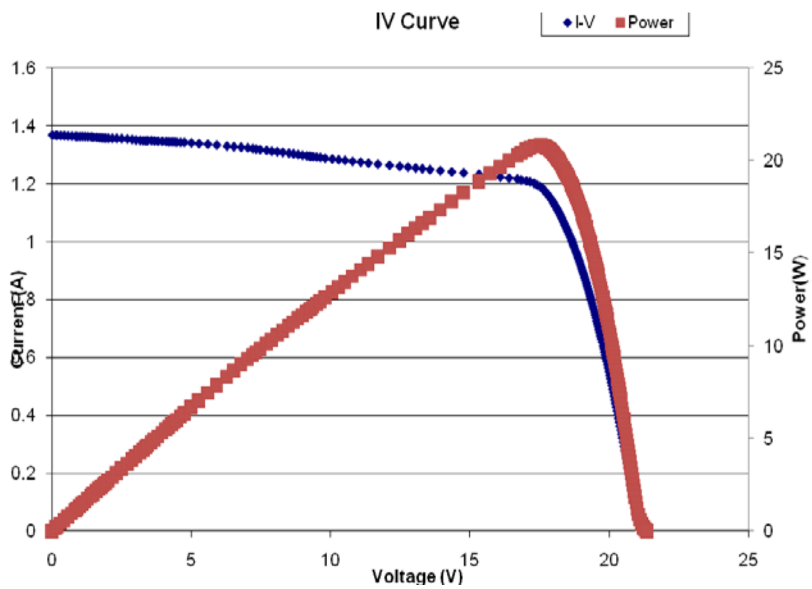

Figure 33. Results from I-V flash simulator test performed at FSEC on 20-W module #2.

4.12 ICS with 50-Gal Tank: Single-Element vs. Dual-Element Performance

The efficiency performance of the ICS/50-gal system with single heating element arrangement was compared against the 2011 dual-element water heater tank configuration. Note that the adjustment of the thermostat setting to 120°F on the 50-gal tank upper thermostat proved to be difficult. After a thermostat setting was achieved, the following days resulted in subsequent increments in hot water temperature delivery. A setting close to the target of 120°F was achieved during February 2011. However, during April 2011, delivery of hot water had deviated down to 117°F. The increase in efficiency appears during February 2011, as shown in Figure 34. Detailed data on the comparison between dual and single tank element configurations on the ICS system performance are available in Appendix C. Results are shown in Tables 7 and 8, also

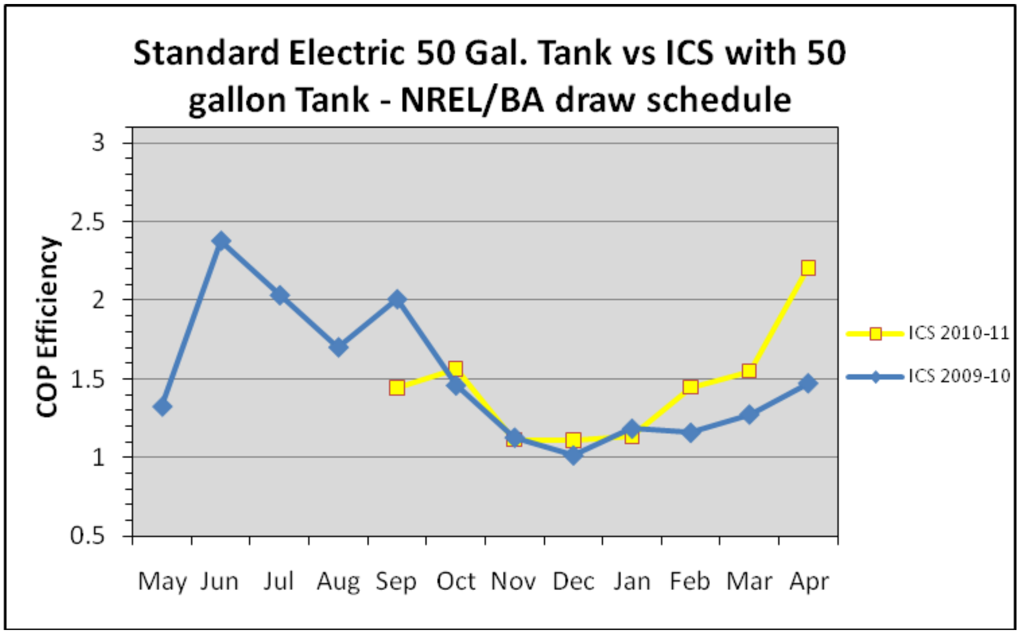

Figure 34. ICS/50 system dual-element configuration (2009–2010) vs. single-element configuration (2010–2011).

Table 7. Energy Savings Results from Phase I (2009-2010) Testing Rotation by Draw Profile.

	ASHRAE 90.2	NREL/BA
Solar flat-plate differential w/80-gal tank	62.7%	61.2%
ICS w/50-gal tank (dual elements)	39.2%	26.3%
Solar flat-plate PV (10W) pumped w/80-gal tank	60.7%	59.4%
Tankless electric	6.9%	5.1%

Table 8. Energy Savings Results from Phase II (2010-2011) Testing Rotation by Draw Profile.

	ASHRAE 90.2	NREL/BA
Solar flat-plate differential w/80-gal tank	55.0%	54.4%
ICS w/50-gal tank (single-element)	34.6%	36.6%
Solar flat-plate PV(40W) pumped w/80-gal tank	60.4%	59.4%
HPWH	61.4%	69.8%

4.13 Natural Gas Tankless Water Heater: 18+ Month Efficiency Performance History

A history of the average monthly efficiencies recorded from the natural gas tankless water heater operating under the NREL/BA draw schedule since 2009 is shown in Figure 35. The tankless heater underwent a flush maintenance procedure during November 2010 (Risinger, 2009). Although the plot shows a bump of increased efficiency during January 2011, it cannot be attributed to the heat exchanger cleaning procedure. In fact, a small and almost imperceptible efficiency increase was recorded after the flush cleaning procedure that was negated after three days of heating operation. Data suggest higher Btu output delivery in December 2009 because of lower inlet temperatures compared to 2010. The trend of heat exchange efficiency in 2010 appears to match those obtained from 2009. For example, on both 2010 and 2011, the unit demonstrated efficiencies below 70% during April. Efficiencies above 80% on this unit were only recorded during a few days of the first two months in operation when testing began in March 2009. Daily efficiencies exceeding or approaching 80% efficiencies have not been recorded in the last 18 months. Residential studies performed in the northern U.S. climate also reveal efficiencies below their ratings ((Pigg, Cauley, & Mendick, 2010).

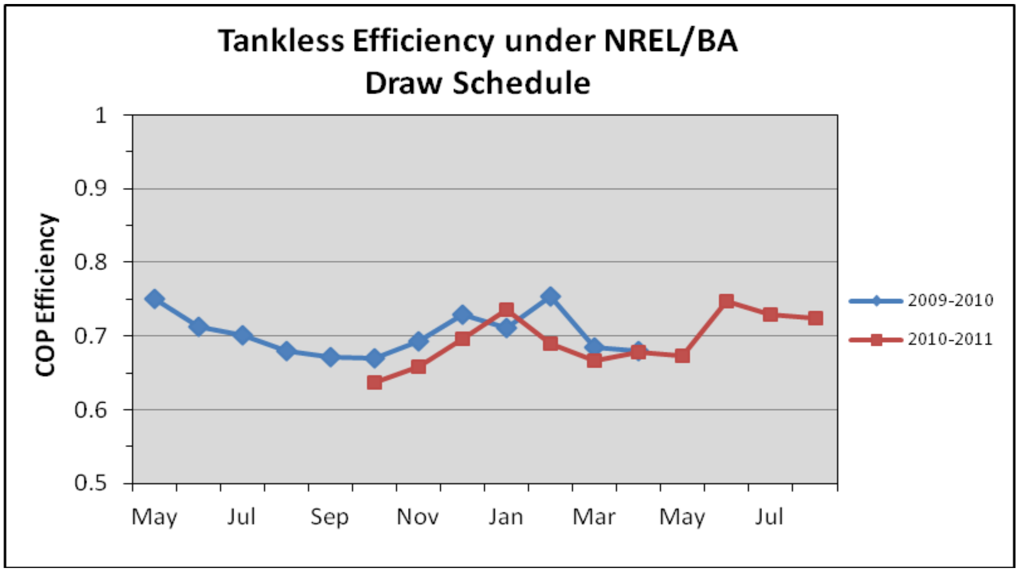

Figure 35. Efficiency of natural gas tankless water heater during last 2 years.

4.14 High Efficiency Water Heating: Electric and Natural Gas Options

Figure 36 was generated from Internet commerce survey of sites including pricing of high efficiency water heating systems currently available in the U.S. market (as of 2010). Data points on the plot compare the retail price ($) and efficiency of the best natural gas tankless systems versus the mix of electric heat pumps currently available. Only natural gas systems with EFs above 0.90 are shown. The least expensive heat pump systems available in the market today are of retrofit form. Except for two models (retrofit type), the majority of other HPWH systems shown are integrated-type with storage tank. The comparison is for informational purpose only from a consumer ($) point of view, given that these systems operate on different source-energy fuels. However, this data is of interest and was sent to our residential BA team, which constantly evaluates all possibilities for cost optimization of energy efficiency upgrades on new and retrofit programs.

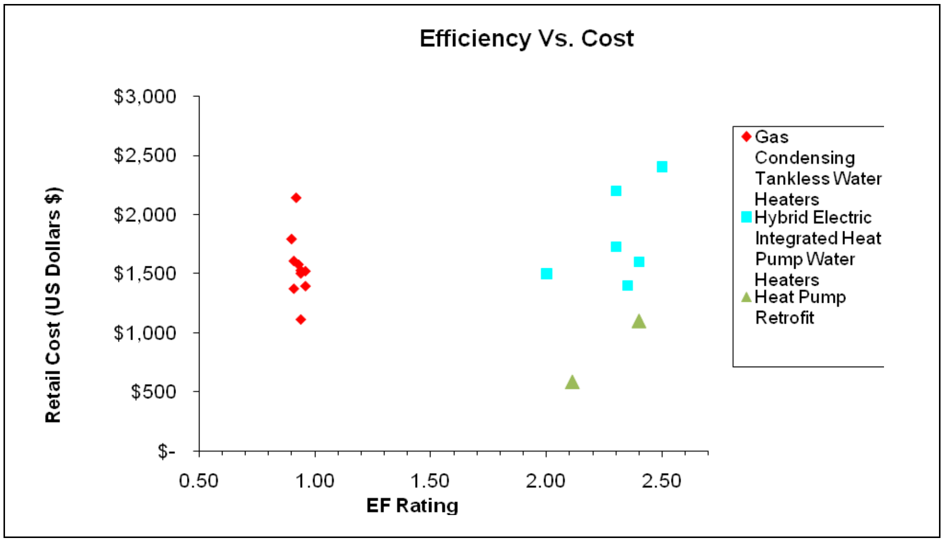

Figure 36. Highest efficiency and cost of natural gas tankless and HPWHs.

4.15 Time-of-Day Analysis

A time-of-day demand analysis was performed to understand hot water heating peak and load characteristics and to compare each system type. Energy input data (i.e., kWh or cu. ft. natural gas) originally collected in 15-minute intervals was averaged for the hour and extrapolated (x4) to determine the average hourly demand. Figure 37 was generated for electric-based systems indicating the averaged annual hourly demand for the 1-year period of September 2010 through August 2011. The plot shows the hourly demand for the ASHRAE 90.2 and the NREL/BA draw schedules combined.

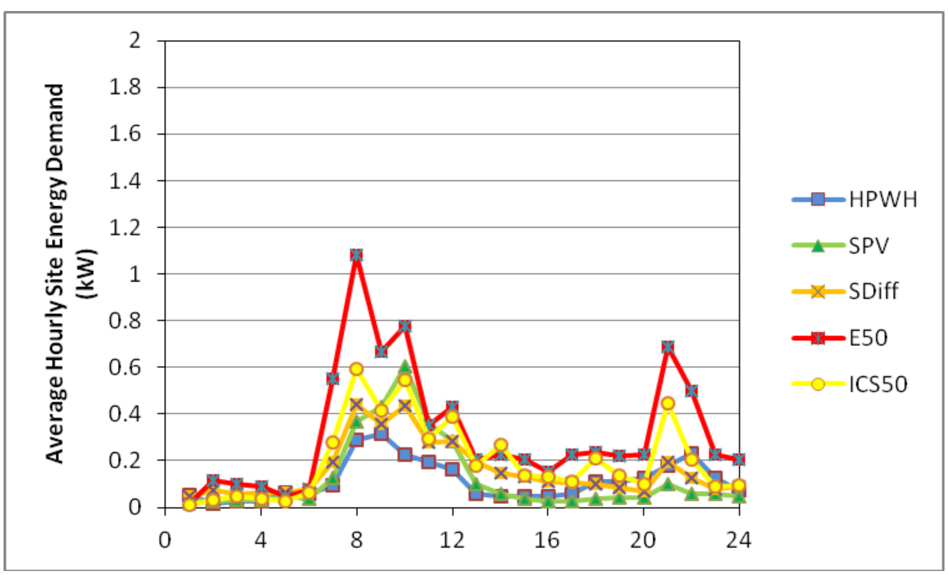

Figure 37. Averaged hourly demand for five hot water heating systems representing a combination of all draw schedules for 1-year period (September 2010 – August 2011).

The plot indicates the dominant peaks caused by the NREL/BA draw profile. It also demonstrates the peak reductions by solar thermal systems compared to the standard 50-gal electric water heater. In addition, it illustrates the conservative peak loads of the HPWH. The HPWH operating in a Florida environment is a ~555W appliance (700W Spec. rated). Similarly, the average hourly demand plot was generated for the days the ASHRAE 90.2 (Figure 38) profile was imposed.

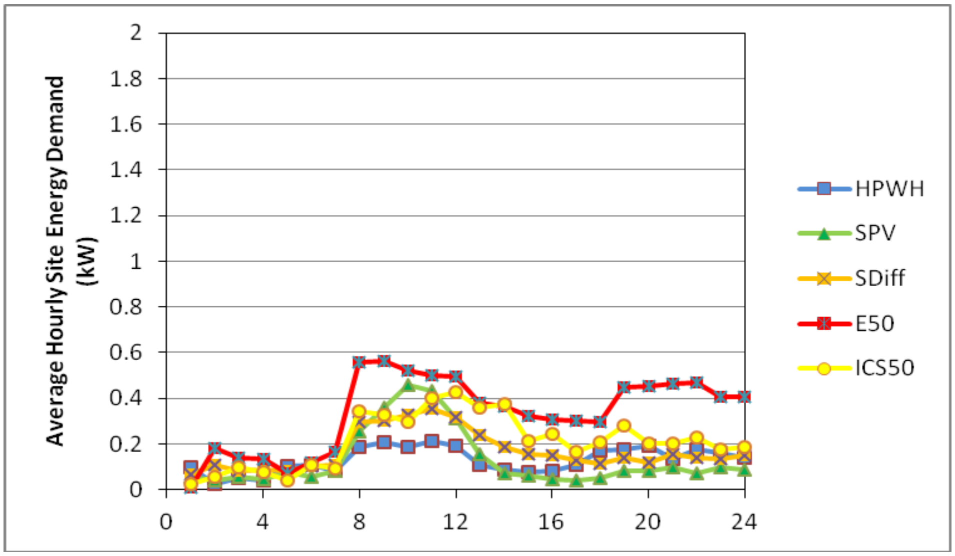

Figure 38. Average daily demand load for electric systems for 1-year period generated from the ASHRAE 90.2 draw profile.

Subsequently, the average hourly demand plot was generated for the days when the NREL/BA (Figure 39) draw profile was imposed.

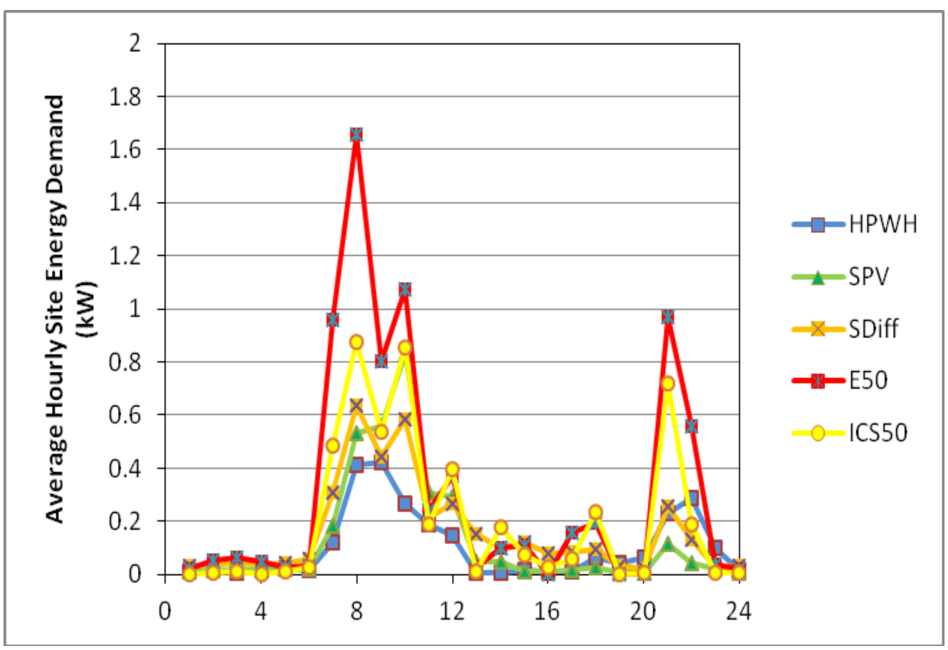

Figure 39. Average daily demand load for electric systems for 1-year period generated from the NREL/BA draw profile.

Of particular interest to electric utilities in Florida is the average hourly demand for all electric category systems, including solar thermal systems, during the winter season (Dec. 2010- Feb. 2011). Figure 40 compares demand loads during winter, which represents the highest electric seasonal demand in Florida.

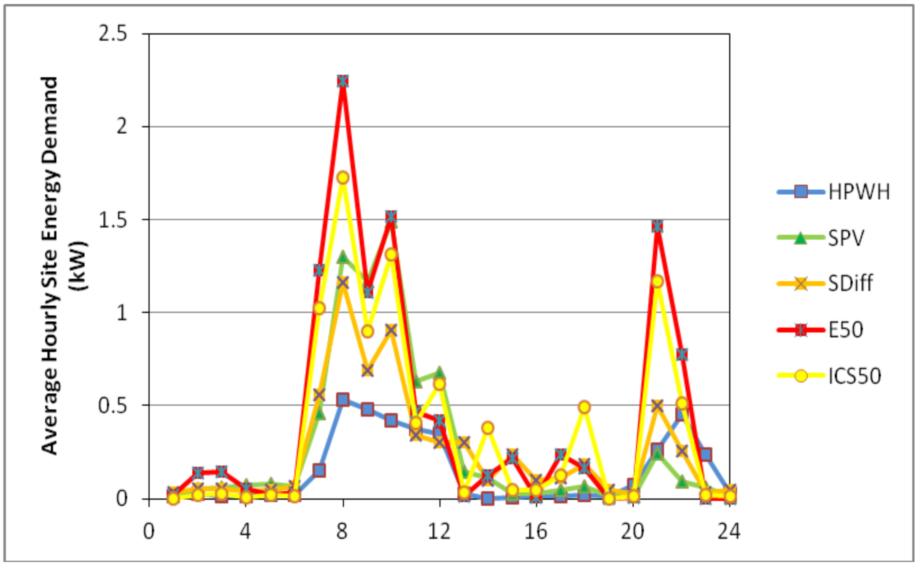

Figure 40. Average daily demand load for electric systems for 1-year period generated from the NREL/BA draw profile during winter season.

4.16 Site and Source Demand Analysis

The BA program currently encourages a comparison between site and source energy used by a building or appliance as part of the energy analysis investigation. The following data analysis was performed to investigate site energy demand, and compares all systems under the same fuel metric (kBtu/hr). Figure 41 displays the time-of-day site energy demand for all seven water heating systems generated for the year period including both draw schedules combined.

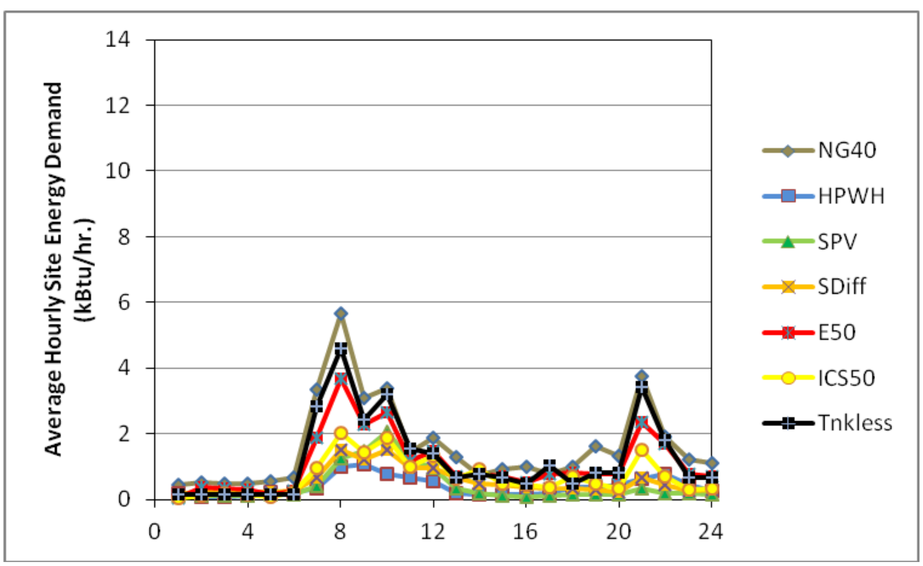

Figure 41. Averaged hourly site demand for seven hot water heating systems under combined draw schedules for 1-year period (September 2010 – August 2011).

Using the U.S. Department of Energy (DOE) site-to-source energy conversion multiplier of 3.365 for electric and 1.092 for natural gas, Figure 42 was generated to compare all water heating systems to source energy demand. As expected, the standard electric water heating system (E50) shows the highest source peak and overall demand.

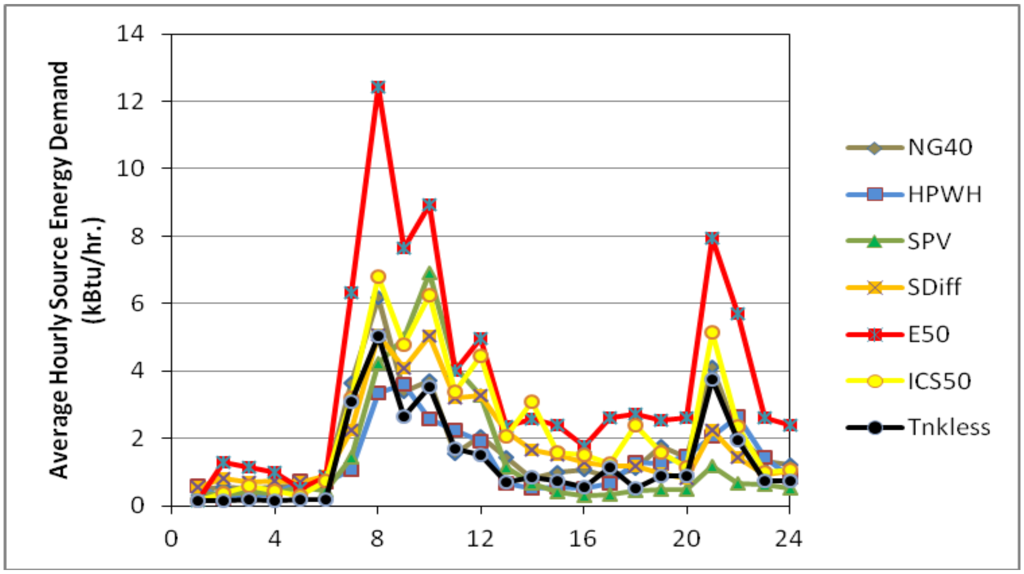

Figure 42. Averaged hourly source demand for seven hot water heating systems under combined draw schedules for 1-year period (September 2010 – August 2011).

Subsequently by using FSEC's database filter capabilities, each of the draw patterns was analyzed. Figure 43 reveals the time-of-day site energy used by each system obtained from the NREL/BA draw pattern.

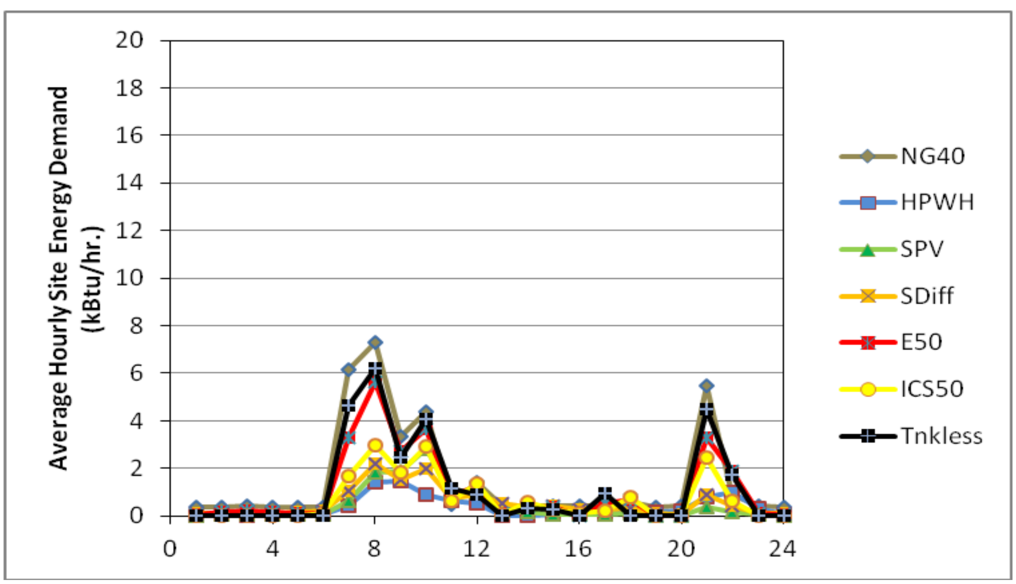

Figure 43. Averaged hourly site demand for seven hot water heating systems under NREL/BA draw schedules for 1-year period (September 2010 – August 2011).

In a similar fashion, using the site and source-energy multiplier conversion, the time-of-day source demand for all systems was determined from the NREL/BA draw schedule (Figure 44).

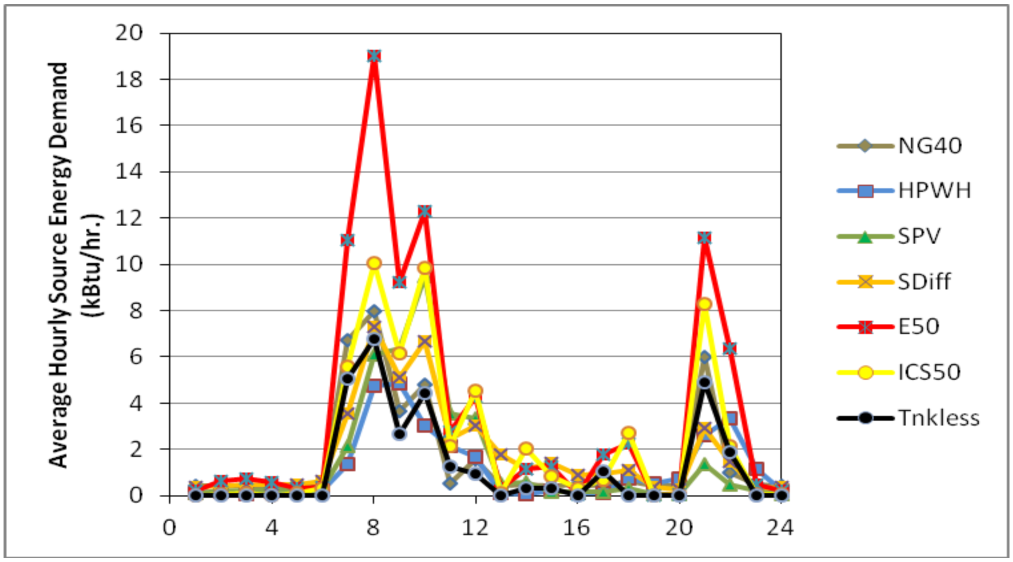

Figure 44. Averaged hourly source demand for seven hot water heating systems under NREL/BA draw schedules for 1-year period (September 2010 – August 2011).

In summary, it can be observed that the HPWH operating on its hybrid default mode appears to impose the least amount of peak load and ultimately uses the least source energy during most hours of the day. Finally, the source-energy demand was plotted for all systems under the NREL/BA hot water draw schedule during the winter season (Dec 2010 – Feb 2011). Higher demands are found during the winter period (Figure 45), with the HPWH using the least amount of source energy on most hours of the day.

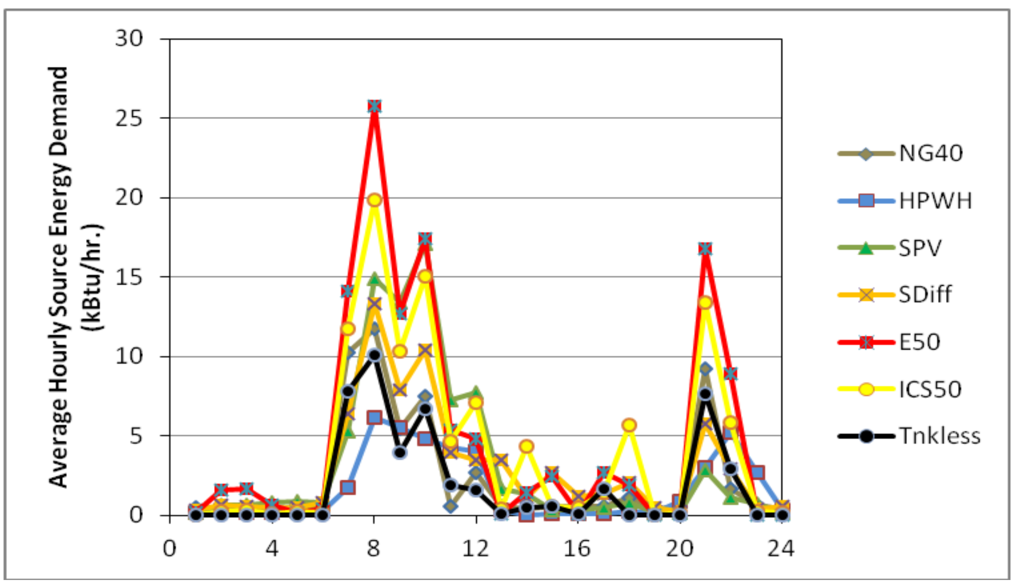

Figure 45. Averaged hourly source demand for seven hot water heating systems under NREL/BA draw schedules for winter season (December 2010 – February 2011).

5 Conclusions

The residential side-by-side HWS evaluation has demonstrated the energy load deviations and effects on water heater appliance efficiencies based on standard (ASHRAE 90.2) and family-realistic (NREL/BA) draw patterns. The seasonally-adjusted NREL/BA hot water draw pattern reveals that under Florida conditions, the impact on energy load for hot water heating appliances varies seasonally. Because of the variation of inlet (mains) city water temperatures, hot water heating appliances in Florida use less energy during summer and early fall seasons. The concept can be observed in Figure 46 where real averaged weighted inlet water temperatures (2010-2011) were used to calculate the energy necessary to heat water to 120°F. Calculations are also based on the volume of hot water demand specified by each draw schedule.

Overall, this exercise calculation yields 12.8% less energy using the seasonal dynamic volume of the NREL/BA draw profile when compared to the non-varying hot water volume called by the ASHRAE 90.2 (64.3 gpd). Because of standby energy losses of storage water heaters, the amount of energy incurred under the NREL/BA draw profile now becomes a larger portion in the efficiency equation, yielding lower seasonal efficiencies in most cases. Data analysis proves that hot water heating appliances operate at a lower efficiency than commonly thought during most of the year. This concept plays an important role in the accuracy and validation of current simulation and modeling techniques.

On a positive note, in the favorable warm and humid conditions in central Florida, the HPWH demonstrate the best overall efficiency and least magnitude of electric demand when hourly time-of-day data demand was analyzed. Surprisingly, power demand on this unit was conservatively low, demonstrating the least source-energy consumption. Performance findings seem to support the energy factor rating across a wide range of conditions under hot humid climates with a slow form of recovery (Sparn, Hudon & Christensen, 2011). Furthermore, testing performed on the HPWH in confined spaces (<100 cu. ft) and under quasi-conditioned spaces (75–75°F) resulted in a 14.3% electric increase (292W hr/day) and an estimated 12.7% reduction in performance (COP). Test results provide guidance on HPWH energy penalty for those units installed in conditioned space under confined places, a commonly observed practice by the residential building industry.

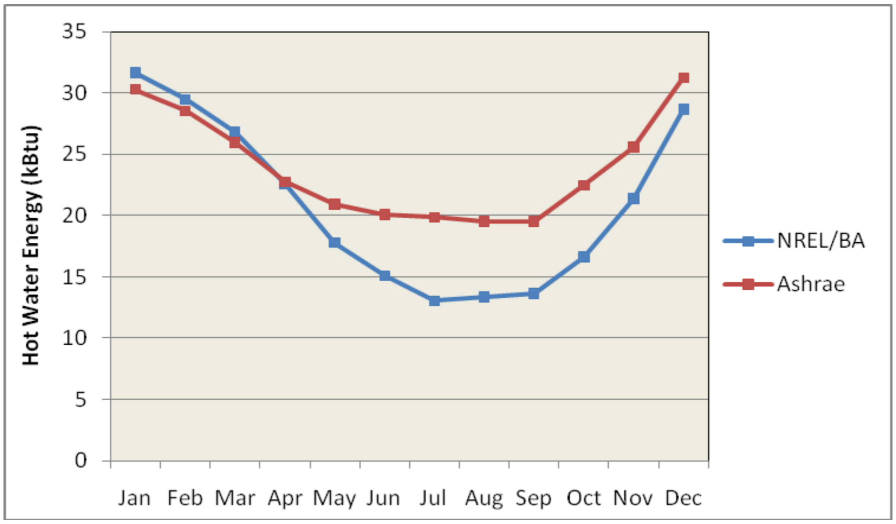

Figure 46. Comparison of calculated energy derived from averaged mains inlet water temperatures to intended set point (120°F) and volume of water called by NREL/BA and ASHRAE 90.2 hot water draw profiles.

5.1 Recommendations for Future Research

Testing and evaluations at FSEC's HWS Laboratory in Cocoa, Florida, will continue throughout 2012 to commence a full 1-year data performance analysis on ultra-high efficiency systems. Arrangements for the next testing evaluation cycle have already been implemented. Integration of various systems creating solar-assisted hybrid designs will be evaluated during the next phase (Phase III). The team expects that these new hybrid system configurations will lead to the highest form of water heating efficiency. The goal should be set to approach water heating at an average daily electric consumption of 2.0 kWh/day or less. Two high efficiency natural gas condensate tankless units will be put to the test including one in hybrid configuration with a solar thermal system.

5.1.1 Phase III Water Heating Systems Test Plan

The following systems are proposed for the Phase III test rotation and include equipment from BA-PIRC industry partners providing equipment cost share.

Baseline systems (unchanged):

- 50-gal standard electric water heater
- 40-gal standard upright vented natural gas water heater.

New high efficiency systems:

- Solar thermal flat-plate solar collector w/80-gal tank with differential-controlled DC pump with retrofit HPWH
- ICS in series with integrated HPWH
- Solar thermal PV-pumped in series with tankless condensing natural gas heater (EF=0.92)
- Condensing-type high efficiency natural gas tankless heater (EF=0.94 mounted outdoors)
- 50-gal standard electric with insulation blanket and FSEC-designed insulation cap.

References

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Appendix A

Simulated Savings for Electric Water Heaters using Tank Wrap and Pipe Insulation in Central and South Florida

A fairly large sample of FPL customers used an average of 2200 kWh per year for water heating. At the rate of $0.10/kWh this equates to $220/yr. of annual electricity used by these water heaters.

A variety of baseline water heater simulation cases were performed in EGUSA for two cities in Florida (Miami and Daytona) .These two regions encompass the majority of FPL service territory. Simulations were performed with water heater tanks of 40 and 50 gal, using 45 and 52 gpd respectively and thermostat settings of 120°F and 130°F. Simulations were also set to investigate older stock water heaters (e.g., EF=0.88) long with the newer generation water heaters (e.g., EF=0.91). The following average annual energy consumption results were generated:

Miami		Daytona	
Baseline Average Old Stock kWh/yr.	Baseline Average New Generation kWh/yr.	Baseline Average Old Stock kWh/yr.	Baseline Average New Generation kWh/yr.
2204.0	2062.8	2480.5	2328.4

Additional simulation runs were performed with water heater blankets and pipe insulation to quantify energy and dollar ($) savings. A summary of savings ($) results and the percentage they represent of the annual baseline energy use are given in the table below:

Miami Savings @$0.10/kWh WH Blanket only		Miami Savings@$0.10/kWh WH Blanket + Pipe Insulation		Daytona Savings@$0.10/kWh WH Blanket only		Daytona Savings@$0.10/kWh WH Blanket + Pipe Insulation	
Old Stock	New Gen.	Old Stock	New Gen.	Old Stock	New Gen.	Old Stock	New Gen.
134 kWh	60 kWh	165 kWh	91 kWh	148 kWh	64 kWh	182 kWh	98 kWh
$13.40	$ 6.00	$16.50	$9.10	$14.80	$6.40	$18.20	$9.80
6.07%	2.90%	7.49%	4.41%	5.97%	2.75%	7.34%	4.20%

Average savings of combined old stock and new generation water heaters:

Savings Summary - Miami		**Savings Summary - Daytona**	
Average WH Blanket Only	Average WH Blanket + Pipe Insulation	Average WH Blanket Only	Average WH Blanket + Pipe Insulation
97 kWh/yr.	128 kWh/yr.	106 kWh/yr.	140 kWh/yr.
$9.70	$12.80	$10.60	$14.00
4.49%	**5.94%**	4.36%	**5.77%**

Appendix B

80 Gal Solar thermal with PV pump Comparison (10 W vs. 40 W)

Phase I (2009 – 2010) vs. Phase II (2010 – 2011)

	Solar Insolation Integrated period (W/m^2/Month)	Aux kWh Nov. Total	Inlet temp (F)	Hot Out Delivery temp (F)
Nov. 2009	121,655	82.4	75.1	118.4
Nov. 2010	146,254	126.0*	72.3	119.8
Dec. 2009	99,725	181.6	69.6	120.6
Dec. 2010	159,198	237.9	62.3	120.2
Jan 2010	143,382	252.0	62.2	120.0
Jan 2011	145,895	239.1	63.7	120.2
Feb 2010	131,001	201.1	62.7	121.2
Feb 2011	152,637	160.1	67.2	120.2
Mar 2010	172,641	156.6	64.9	121.5
Mar 2011	185,233	110.9	71.8	122.4
Apr 2010	182,019	73.8	73.7	122.3
Apr 2011	209,418	62.5	77.4	124.5
May. 2010	188,425	8.7	81.8	114.1
May. 2011	207,991	34.5	81.1	117.4
Jun. 2010	172,293	0.004	85.5	114.4
Jun. 2011	167,158	30.7	83	118.1
Jul. 2009	167,979	12.2	82.8	121.5
Jul. 2011	170,037	23.1	83.1	117
Aug. 2009	170,361	1.3	84.1	123.1
Aug. 2011	153,109	21.1	83.8	116.6
Sep. 2009	142,406	17.1	82.4	120.6
Sep. 2011	175,192	11.0	82.5	115.9

*1.45 kWh/day more for November 2010

Appendix C

50 Gal Tank supplemented by ICS: Dual-Element Vs. Single-Element Tank Configuration

Phase I (2009 – 2010) Vs. Phase II (2010 – 2011)

	Solar Insolation Integrated (W/m2/month)	Aux kWh Total	Inlet Temp (F)	Hot Out Delivery Temp (F)
July2009	167,979	84.2	109.1	120.5
July 2010	176,302	51.9	114.3	117.3
August 2009	135,024	62.2	114.6	120.7
August 2010	158,053	59.3	112.8	117.0
September 2009	142,406	77.9	110.3	120.4
September 2010	161,094	84.2	112.2	122.1
October 2009	131,132	93.9	107.9	120.4
October 2010	202,060	122.4	111.3	125.6
Nov. 2009	121,655	164.4	94.5	120.6
Nov. 2010	146,254	227.2	96.8	130.8
Dec. 2009	99,725	246.8	82.8	121.1
Dec. 2010	159,198	308.1	83.5	130.3
Jan 2010	143,382	287.9	80.9	121.8
Jan 2011	145,895	297.5	84.3	129.5
Feb 2010	131,001	262.9	80.4	121.8
Feb 2011	152,637	265.3	90.3	124.3
Mar 2010	172,641	231.5	89.3	121.5
Mar 2011	185,233	177.6	98.3	120.5
Apr 2010	182,019	144.7	101.5	121.1
Apr 2011	209,418	102.3	108.2	117.1

Appendix D

In January 2012, configuration of the HWS laboratory was altered to accommodate the installation of hybrid water heating components as described in Section 4.17. The plumbing atop the differential solar system storage tank (80-gal.) had to be cut and re-arranged entirely to accept a retrofit heat pump water heater. During piping removal and inspection, at least three of the soldered connections exhibited a good amount of mineral growth deposit at pipe fittings and valves transition (see photo D-1). This phenomenon might explain the lower performance on the differential solar flat plate solar system during Phase II (2010-2011) when compared to the first phase year evaluation. When multiple calcifications (obstruction) are added together throughout the plumbing system, these present an added head loss to the pump resulting in a reduced flow rate. The plumbing on this system had been operating since its original installation in December 2009.

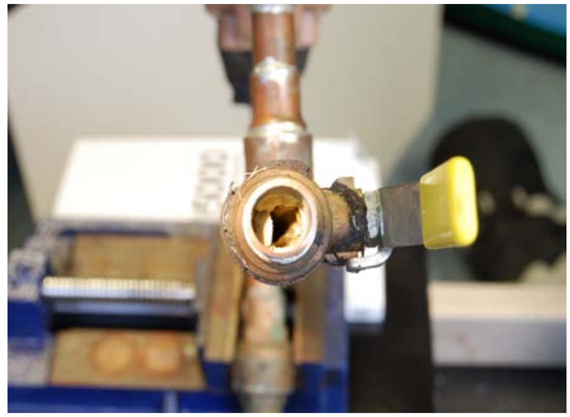

Figure D-1. Mineral deposit growth on solar recirculation plumbing where pipe was brazed into an isolation ball valve.

Another sign of wear applicable to storage tank longevity and life expectancy was discovered during the removal of the sacrificial anode rod (magnesium type). The anode rod had to be removed because of reports by a local plumbing contractor suggesting that installation of a new retrofit HPWH may accelerate the depletion of an existing anode rod. A picture of the removed anode rod (shown at right) shows depletion of the rod to be more pronounced near the top where hotter tank temperatures are present. Anode rods may eventually become thinner in this area, breaking away and falling to the bottom of the tank. When no sacrificial anode material is present at the top of the tank, galvanic corrosion at the top of the tank, where a transition of dissimilar metals such as copper and steel, accelerates, leading to premature failure (leaks) on a water heater.

Figure D-2. Partially depleted anode rod removal from differential solar storage tank after 3 years.

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