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Measured Performance of a High-Efficiency Solar-Assisted Heat Pump Water Heater

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Abstract

This paper describes a novel solar photovoltaic-assisted heat pump water heater (PV-HPWH). The system uses two 310 W_p PV modules, micro-inverters and innovative controls to produce and store daily hot water. The system likely costs half that of solar thermal systems, with greater reliability, no freeze protection and potentially superior performance in cloudy locations. Moreover, no net metering is needed for the PV, which with two modules makes for a simple installation.

The HPWH controls have been modified through experimentation such that higher tank temperatures are achieved during the day when solar availability is high while avoiding triggering the compressor during early morning hot water draws. When tank temperatures are satisfied, the remaining PV electricity is stored in the tank using staged electric resistance elements. Typical performance sees hot water storage greater than 65ºC at sunset. A mixing valve provides hot water at the target temperature (52ºC). By altering tank temperature, an equivalent of ~2 kWh of electrical energy is stored for use during evening hours. Typically, there is no grid electricity demand during the utility summer peak demand window.

The system has been tested for twelve months in a laboratory at the Florida Solar Energy Center. Realistic hot water draws were imposed with detailed data recorded on system performance. Long term COP, averaging 5.4, has been as high as 8.0 during sunny summer days. Average daily grid electricity consumption has been 1.2 kWh/day– less than many refrigerators. Prospects for further development and refinement are discussed.

Introduction

Reducing energy use for heating water remains a major challenge around the world. Field data shows that heat pump heat pump water heaters (HPWH) can significantly reduce electricity needs in warm climates. For instance, in eight Central Florida homes in 2013, comparison of one year pre and post-retrofit hot water energy after changing from electric resistance to HPWH showed 68% (5.3 kWh/day) sub-metered savings [1]. Effective COPs for 2012-generation HPWHs are approximately 1.5 – 2.5, depending on climate, location within a building, and machine characteristics [2]. Recent work has shown that HPWH interaction with space conditioning loads are potentially significant with interior locations—for instance, reducing cooling loads by more than 5% in warm climates [3].

For electric water heating to be an attractive substitute against efficient natural gas heating for reducing greenhouse gas emissions, seasonal system electrical COP must be greater than 3.0 at average emission rates for U.S. generation resources.[1] While solar thermal water heating systems have high COPs (often above 3.5), these systems are typically expensive and can have high maintenance needs [10]. At the November 2013 ACEEE Hot Water Forum in Atlanta, a thought-provoking presentation compared solar thermal water heating systems with heat pump water heaters (HPWH) powered by photovoltaic (PV) modules. [4] The simple premise was that with the introduction of high-efficiency HPWHs in the U.S. market coupled with rapidly falling PV prices, it was now more cost-effective to install a PV-driven HPWH rather than a conventional solar thermal system. Using an example of a 1.0 to 1.3 kW PV system powering a HPWH with an Energy Factor (EF) of 2.5, it was calculated that a PV-driven HPWH currently had a $5,000 to $8,500 installed cost before incentives, while the installation of a conventional solar water heating system cost $7,000 to $10,000 before incentives. In addition, the PV-driven HPWH saved more energy, was easier to install with no plumbing, used less space, required less maintenance, and could not leak, overheat, or freeze.

[1] This calculation assumes an emission rate of 681 g/kWh for average U.S. electrical generation against an emission rate of 227 g/kWh for natural gas at an energy factor of 0.80 for an efficient new natural gas hot water systems (condensing or tankless). https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Background

Water heating in residential and small commercial buildings continues to pose a challenge as the overall efficiency of buildings improves with minimum energy efficiency code requirements for air conditioning, lighting and building envelope occurred over the last decade. Although some improvement in the minimum energy efficiency for storage water heaters in the United States was implemented in 2015, energy efficiency improvements to other building components appear to provide significant potential energy savings compared to those applied to standard water heating appliances.

Over the last 10 years, PV has gained momentum in the U.S. with improvement in conversion efficiencies as well as decreased cost. The use of PV to heat potable water has been discussed by many researchers. Previously in 1998-99, direct resistance water heating using PV was first explored and tested at the Florida Solar Energy Center (FSEC) in a novel design by Dougherty and Fanney [6]. The system featured a 1060 W_p PV array with proprietary control algorithm to switch between a three-resistance capable heating element to maximize power transfer. In recent years, other PV system designs for dedicated water heating have evolved into the market.

While PV has been combined with heat pumps for solar-assisted space heating and air conditioning, there are not many instances where PV is used with a heat pump for water heating. In one of the few examples, Aguilar et al. [6] conducted an experimental year-long study of a PV-assisted split-system heat pump for water heating in Spain. The system consisted of two PV modules of 235 Watts each, a 189 liter storage tank, and a heat pump with a long-term coefficient of performance (COP) of 3.15. Under a typical residential hot water load, the annual solar contribution was greater than 60%.

Compared to standard electric resistance, residential heat pump water heaters provide considerable energy savings due to their high efficiency. Currently in the United States, HPWH's ranging from 189 to 303 liters are rated with an energy factor (EF) as high as 3.4 as indicated under the advanced product list published by the Northwest Energy Efficiency Alliance (NEEA). [7] The design and integration of PV and heat pump water heaters provide a synergistic combination to improve overall efficiency at a reasonable cost.

As part of the effort towards zero energy buildings and high efficiency water heating systems, the Florida Solar Energy Center (FSEC) -- working under contract with the National Renewable Energy Laboratory (NREL) -- has been developing a PV-assisted heat pump water heater (PV-HPWH) prototype (Figure 1). The system combines two 310 W_p solar photovoltaic (PV) modules and grid-tied microinverters with a commercially available 189-liter HPWH. Using the HPWH's integrated tank to store solar energy, the PV is used without any grid interconnection, thus avoiding potential net metering issues that have recently emerged in many U.S. states.

Figure 1: PV modules (310 Watts each) and 189–Liter HPWH shown with added insulation

The PV-assisted HPWH prototype began evaluation in February 2016 at the FSEC hot water systems laboratory in Cocoa, Florida. The testing utilized an automated hot water load schedule totaling 223 liters per day, typical of an average 3-4 person family. An average COP of 3.5 was obtained for the first month of February. (By subtracting the PV-generated electricity produced from the total electricity used by the system, the net grid electricity is used in the calculation of the PV-HPWH system COP.) Further analysis excluding the PV contribution indicated a HPWH-alone performance COP of 2.1 in February which is virtually identical to manufacturer claims for the unit [8]

The PV-HPWH prototype evolved with a series of automated control improvements through the spring and summer. Beginning on March 2016, the system was upgraded to autonomously change the thermostat setting from 52^{o}C (baseline) to 60^{o}C depending on the power produced by the PV and micro-inverters. The thermostat setting change was triggered by a minimum PV power threshold of 260 W averaged over one minute. Following that change, during the month of April, the factory-supplied 4500 Watt bottom heating element was removed and replaced with one of a lower wattage (750 W). The bottom heating element was then re-wired and independently activated via a controller board and software developed at FSEC.

System Description

A diagram of the PV-driven HPWH as tested at FSEC can be seen in Figure 2. The HPWH used in the study is rated at 600 Watts: however, depending on tank temperatures, data indicated that power draw changes between 490 and 700 Watts. A higher than rated power draw was routinely demonstrated as the compressor operated and heated water approaching the highest thermostat setting of 60^{o}C. Furthermore, fix-mount PV modules facing south at a 24^{o} tilt produce the highest power during mid-day hours (11:00 am – 2:00 pm). On average, the power produced by the PV modules was 369 Watts during the mid-day period. The balance or net energy to operate the HPWH compressor is sourced from the grid.

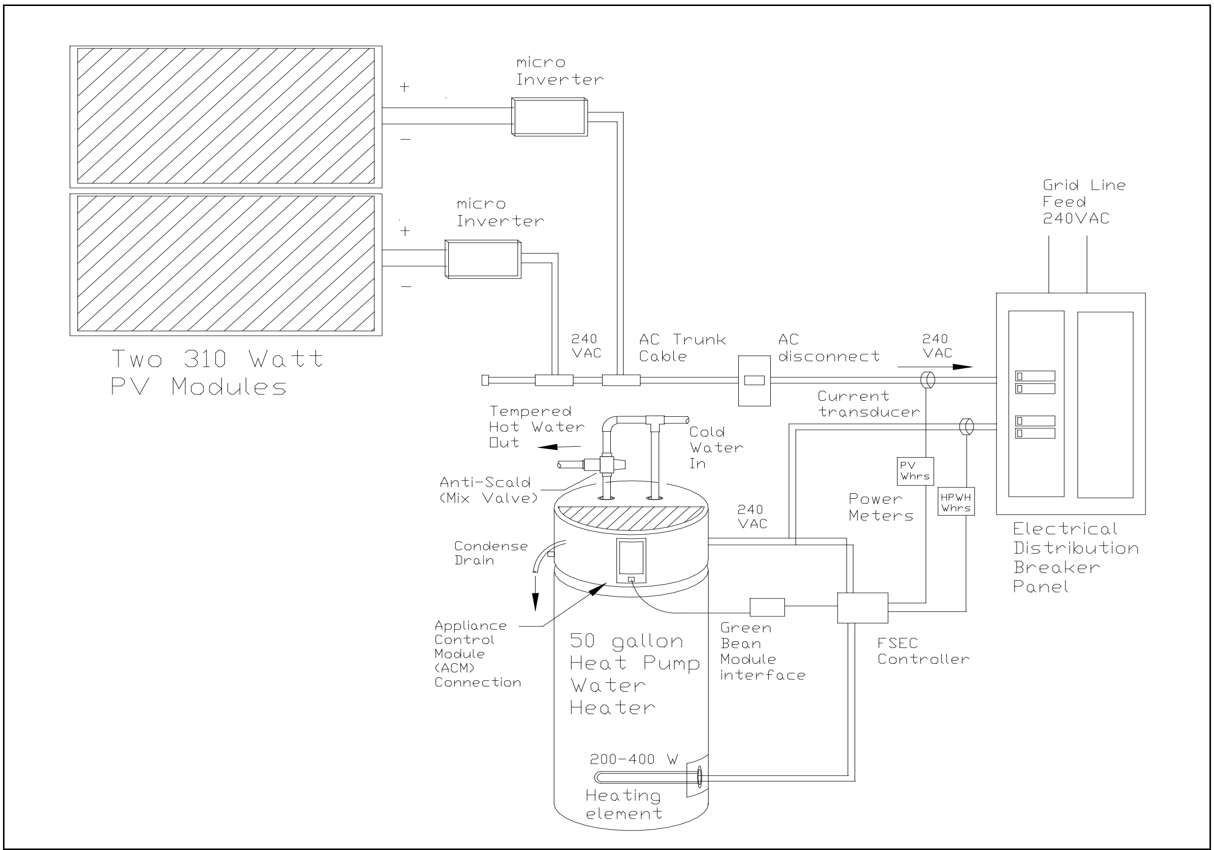

Figure 2: Schematic diagram of prototype PV-assisted HPWH.

To match the energy produced the PV modules to the electric resistance heating element load, power control circuitry using capacitive reactance was implemented, resulting in a two-stage resistance heating element (192 and 396 Watts). Further development of the FSEC-developed controller led to techniques to maximize the compressor operation efficiency and store most PV energy as hot water. Once a full tank of 60°C temperature water was reached and the compressor was shut-off by the HPWH thermostat, additional heat energy is transferred into storage via the two-stage electric resistance element. Hot water delivery temperatures were tempered by a mixing valve set at 52 °C, enabling the HPWH tank to act as thermal storage for the PV-generated energy.

Increasing temperatures in a 189-liter tank from the 52 °C baseline upwards to 60°C is the thermal storage equivalent of 1.7 kWh. By adding extra energy past 60 °C into the tank, the system was able to store an additional 0.5 kWh per day. Therefore, additional thermal storage in the tank from raising the thermostat setting is equivalent to approximately 2.2 kWh (neglecting standby losses.) Data indicated that thermal storage levels above 60°C appear during 75% of the days analyzed. Peak hot water temperatures reached past 65°C in May and August as measured at the hot water outlet port during the 3:49 pm hot water draw and average 62°C in late afternoons.

On a daily basis, tank heating in response to early morning hot water draws (83 liters) before 7:45 am was begun typically around 7:30 am, but the heating process was interrupted at 8:30 am by a thermostat setback to 46°C. Hot water recovery using the HPWH compressor is then completed at a later time in the morning -- 10:30 am when solar resources are typically higher -- by resuming a 52°C thermostat setting. This process is illustrated in Figure 3 showing data recorded on August 23, 2016. The compressor turns on at 7:38 am for only 10 minutes, due to previous day storage and the 49ºC thermostat setting, and then is followed by 192 Watts of electric resistance heating. The compressor resumes heating again at 9:07 am due to its thermostat setback of 46ºC: and completes recovery by 11:30 am. The operation of the two-stage electric resistance heating operation is visible in the afternoon indicating extra energy being stored at a rate of 396 and 192 Watts, respectively.

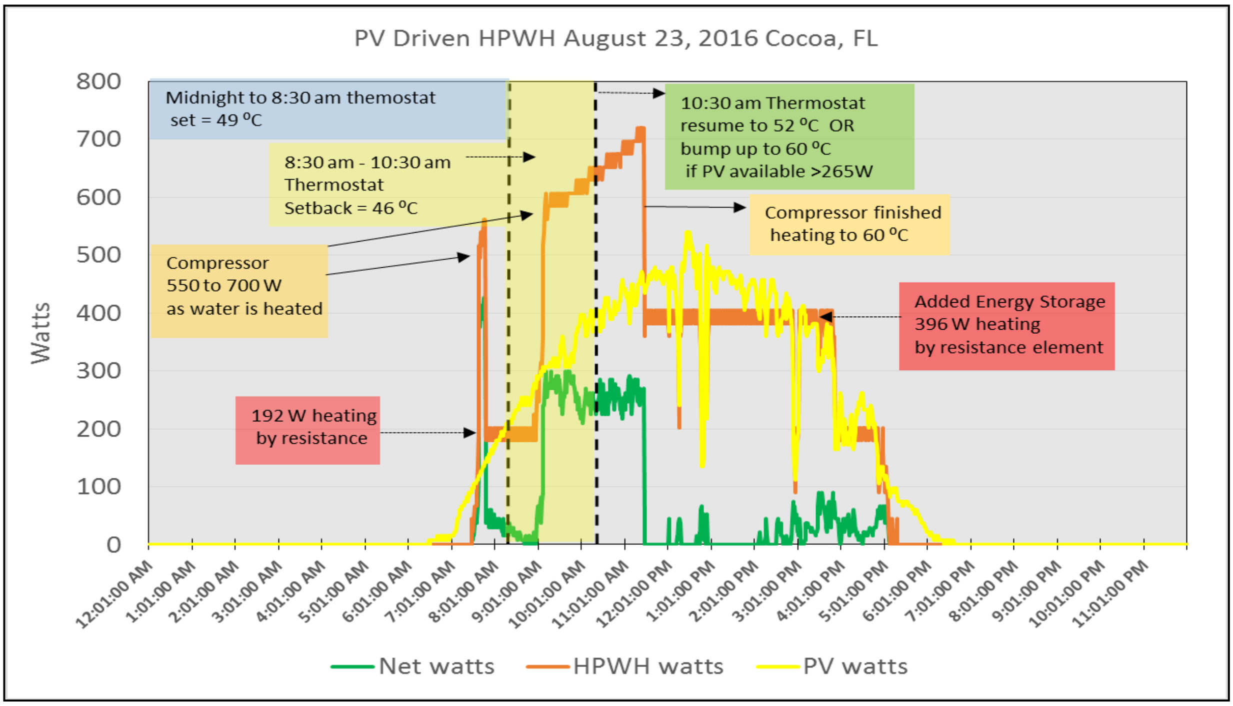

Figure 3: Example PV production and HPWH power usage in the prototype PV- HPWH

Results

Figure 4 displays recent results from testing the prototype PV-assisted HPWH in Central Florida. The bar graph shows the daily coefficient of performance (COP) of the overall system for the month of September 2016 as defined by the relationship:

$$\mathrm{COP} = \frac{\text{Hot water energy out}}{\text{Grid electrical energy in}}$$

Figure 4 also shows the daily solar radiation on the two PV modules (dotted line) in Watt-hours per square meter per day on the right axis. It is apparent from the figure that COPs above 4.0 are typically possible on days with daily plane of array solar radiation above 4 kWh per square meter. Variation in the COP on any particular day is not only affected by the solar irradiance, but also by its distribution against loads on that particular day. Efficiency is also influenced by the solar irradiance on the preceding day as this influences the stored thermal energy over evening hours. Overnight tank thermal storage is particularly important for the efficiency with which early morning hot water draws are served.

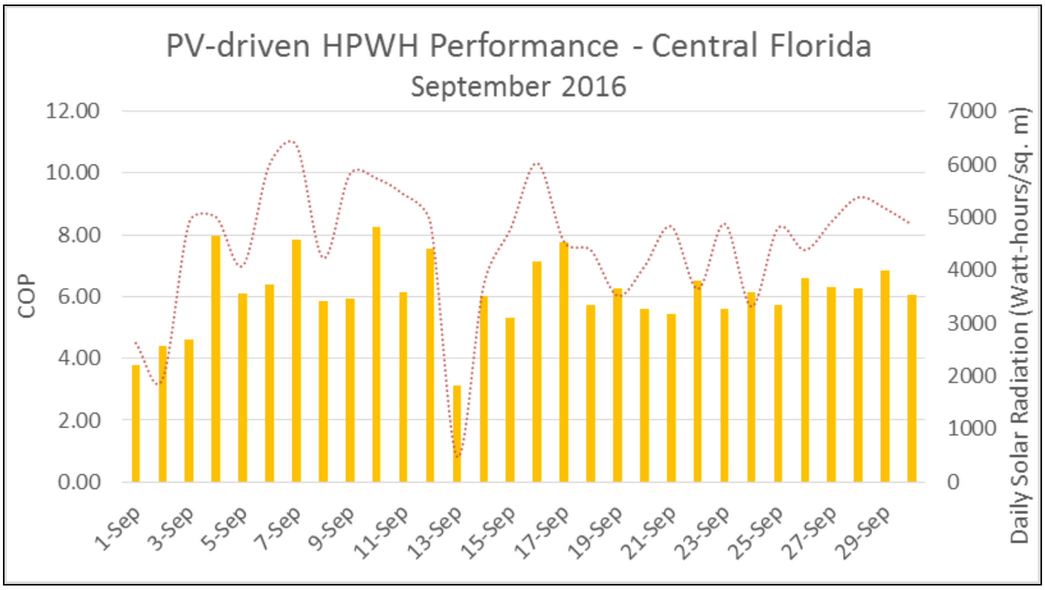

Figure 4: Prototype PV-assisted HPWH Performance in September 2016 in Central Florida

Measured long-term performance recorded through January 2017 can be seen in Figure 5. The plot shows the average monthly COP (left y-axis) and kWh per day of electricity consumption (right y-axis). Performance of the PV-driven HPWH has been exceptional, demonstrating average monthly COP's as high as 6.6 and 7.0 for the months of May and July. COP's leveled off at around 6.0 for the months of August thru October and declining in November. Further improvement could be realized by utilizing a portion of the 18% of total energy produced by the PV/micro-inverters that is unused and is fed back into the grid during early mornings and late afternoon hours. Future development work is planned to maximize PV-supplied energy to be used by the system.

Performance data for the months of December and January 2017 reveals COPs of 5.1 and 4.8 respectively which are consistently higher than during February 2016 when controls optimization and the two-stage heating element was not in place.

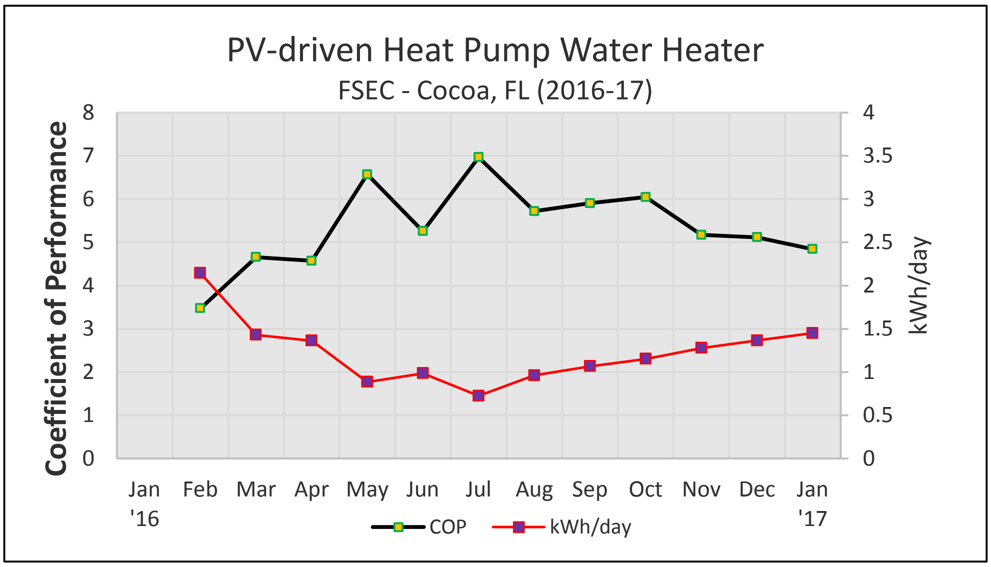

Figure 5: PV-HPWH monthly average COP and kWh per day (February 2016 – January 2017)

A time-of-day analysis was also performed to determine the hourly peak demand reduction potential of the PV-HPWH against standard electric resistance water heating. Figure 6 presents the hourly demand as compared to a 189-Liter standard electric water heater (red line) that was operated simultaneously in the laboratory.

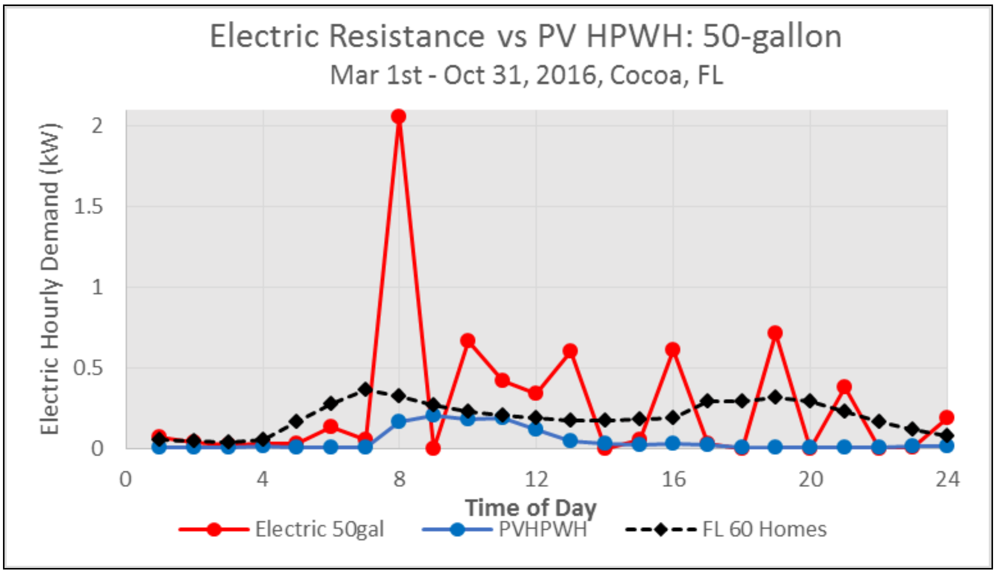

Figure 6: Time of day load profile of PV-HPWH compared to a single 189-Liter electric water heater and the load profile of 60 Florida homes with electric resistance water heaters

The plot also shows the diversified demand profile (black dashed line) of 60 residential electric water heaters operating in Florida homes, recently monitored in 2013 as part of the U.S. DOE Building America Phased Deep Retrofit (PDR) study. [9] Because of the extra thermal energy storage (~2.2 kWh), the PV-HPWH would not increase the late afternoon ramp-up demand on utility generation caused by conventional PV's decreasing electricity production.

The PV-HPWH has demonstrated impressive performance by integrating photovoltaics with compressor-based refrigerant water heating, smart controls, and added energy storage. Table 1 provides a summary of its 12-month performance since February 2016. Analysis performed on the data after May 2016, when the auxiliary heating by electric resistance was implemented for additional heat storage, indicated that the solar contribution from the PV and micro-inverters averaged 65.6% of the total electricity used by the system. The average long term COP of 5.4 was exceptional.

Table 1: Summary of PV-HPWH performance (February 2016 -- January 2017)

Average Monthly Daily Electric consumption		Average Monthly COP (min /max)	Average PV Energy Generated	Added storage above 52°C	Average Hot water Max Temp Stored	Average Daily Hot Water Delivered (w/ 52°C mix valve setting)		
kWh/day	Min-Max kWh/day		kWh/day	kWh/day		L	kJ	kWh
1.2	0.7 – 2.1	5.4 (4.5 / 7.0)	2.3	2.1	62°C	215	21,868	6.1

Performance data collected from the PV-HPWH to date also indicates it is the highest efficiency electric water heating system ever tested under FSEC's hot water system evaluation program, conducted under the Building America Partnership for Improved Residential Construction thru 2016. [10] Figure 7 places the PV-HPWH at the top of the chart with an average grid electricity use of 1.2 kWh/day. Note that the conventional 189 L electric resistance tank used about 7.6 kWh per day with a typical COP of approximately 0.8. Accordingly the prototype PV-HPWH saved 84% of the energy typically needed for conventional electric resistance water heaters.

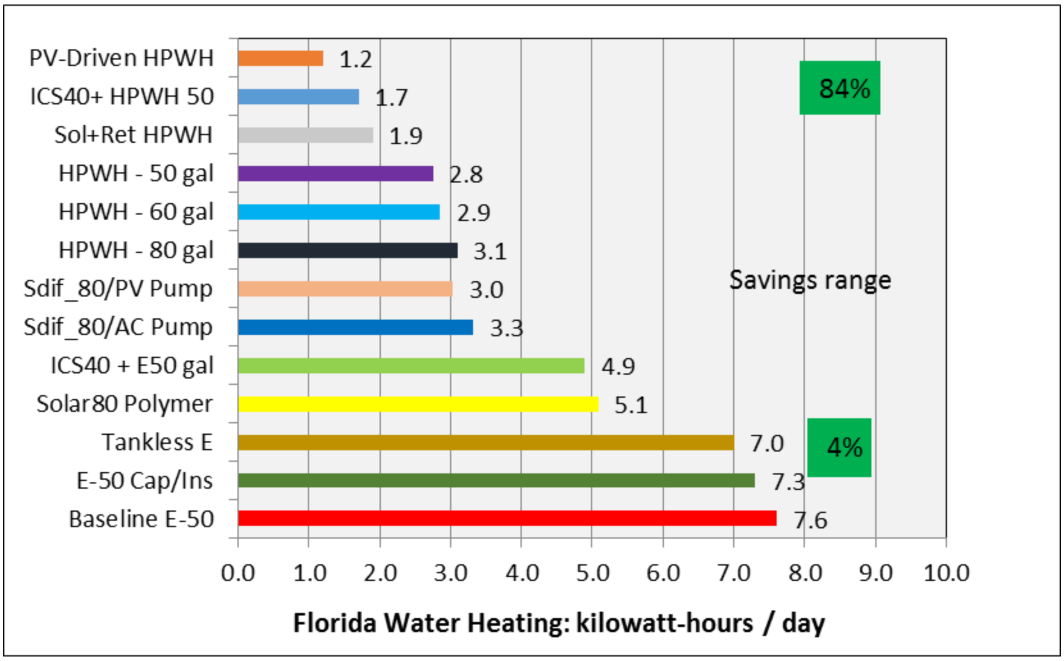

Figure 7: Representation of various electric water heating systems daily electric use compared to a baseline (standard 189 L electric) and the potential for energy savings (4%-84%)[2]

[2] Key: ICS40: Integrated collector storage solar system (40 gal); Sol+Ret: Solar heating of HPWH tank; HPWH: heat pump water heater of various sizes (40,60,80 gal); Sdif: Solar differential with PV or AC pumping; E-50: Electric resistance 50 gal tank; Solar80 Polymer: unglazed solar collector w/80 gal storage; Tankless E: tankless electric resistance; E-50 Cap/Ins: E50 tank w/ insulated cap and tank cover; Baseline E-50: Electric resistance baseline system. (EF=0.9).

Conclusions

The prototype PV-HPWH showcases innovative strategies for distributed PV systems that limit grid interaction and provide increased thermal energy storage. The system utilizes a custom appliance control module (ACM) interface to vary thermostat settings (46ºC to 60ºC) depending on time of day and solar radiation levels. It also prioritizes thermostat setbacks on a time of day basis. By setting the thermostat down to 46^{o}C during early morning draws, it can disrupt compressor heating recovery normally set to 52^{o}C and shift the remainder of recovery to times where higher solar resources are available (i.e., after 10:30 am). Long-term COPs through January 2017 have averaged 5.4 requiring grid power of only 1.2 kWh per day for a typical residential hot water load. The total daily grid electricity use is less than that for many household refrigerators.

This level of efficiency improvement represents approximately an 84% reduction in electric power for heating hot water compared with a simultaneously monitored electric resistance system. The total PV-HPWH system equipment assembled had retail cost of $2053 for the prototype (including the HPWH) fares very well compared to traditional solar thermal systems. Other key advantages of the PV-HPWH technology:

- Simplified installation likely to further reduce installed costs
- No plumbing or pumps associated with the PV assisted system
- No need for freeze protection
- PV output at given irradiance higher under cold conditions when water heating loads higher
- Solid state components likely yield greater long term reliability
- PV to thermal storage strategy typically produces 2.2 kWh of evening load shift relative to standard electric resistance systems.

FSEC continues to collect data on the PV-HPWH in order to characterize performance of the latest control techniques for a full year. Various improvements along with smart controls have been created and demonstrated in this project which will likely continue to show performance improvement over the 2017 spring season (the final improvements were not fully implemented until summer).

The system will undergo further refinement in order to be demonstrated in a residential water heating field project. HPWH manufacturers show the latest generation of compressors operate at 50 watts less compared to the HPWH unit used in the PV-HPWH demonstration [11]. In northern climates, larger storage (303-Liter) HPWH's could also be utilized along with additional PV modules, which simulation analysis indicates likely have further performance advantages [2,8]. However, both of these promising potential improvements are yet to be tested.

References

[1] Parker, D., K. Sutherland, D. Chasar, J. Montemurno, and J. Kono, *Measured Results of Phased Shallow and Deep Retrofits in Existing Homes*, Proceedings of the ACEEE 2014 Summer Study on Energy Efficiency in Buildings, 1:261–276. Washington, DC. Ed.: American Council for an Energy-Efficient Economy.

[2] Maguire, J., Burch, J, Merrigan, T. and Ong, S., *Regional Variation in Residential Heat Pump Water Heater Performance in the U.S.*, National Renewable Energy Laboratory, NREL CP-5500-60295, Proceedings of the 2014 ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air Conditioning Engineers, New York, NY, January 18-22,2014.

[3] Colon, C., Martin, E., Parker, D. and Sutherland, K., *Measured Performance of Ducted and Space-Coupled Heat Pump Water Heaters in a Cooling Dominated Climate*, Proceedings of the ACEEE 2016 Summer Study on Energy Efficiency in Buildings, 1:1-16. Washington, DC. Ed.: American Council for an Energy-Efficient Economy.

[4] Slater, H., *Solar Hot Water: Which is better? PV + Heat Pump or Thermal*, 2013 ACEEE Hot Water Forum, Atlanta, Georgia, November 3-5, 2013.

[5] Dougherty, Brian P., Fanney, A. Hunter, *Experiences with Using Solar Photovoltaics to Heat Domestic Water*, Journal of Solar Energy Engineering, May 2003, Vol. 125, pp. 195-202.

[6] Aguilar, F.J., Aledo, S., and Quiles, P.V., *Experimental study of the solar photovoltaic contribution for the domestic hot water production with heat pumps in dwellings*, Applied Thermal Engineering, 25 May 2016, Vol. 101, pp. 379-389.

[7] http://neea.org/docs/default-source/advanced-water-heater-specification/qualified-products-list.pdf?sfvrsn=34

[8] Colon, C. and Parker, D., *PV-Driven Heat Pump Water Heater: Final Report*, FSEC-CR-2043-16, Florida Solar Energy Center, February 2017 (Revised).

[9] Parker et al., *Retrofits in Existing Homes in Florida Phase I: Shallow and Deep Retrofits*, FSEC-CR-2018-16, Final Report, Florida Solar Energy Center, February 2016

[10] Colon, C. and Parker, D., *Side-by-Side Testing of Water Heating Systems: Results from the 2010 – 2011 Evaluation*, Building America Partnership for Improved Residential Construction (BA-PIRC), FSEC-RR-386-12, Florida Solar Energy Center, March 2013.

[11] The more recent General Electric HPWH, the GEH50DFEJSRA, has a 3.25 EF with a compressor power of 550 watts under "Specs and Details" http://products.geappliances.com/appliance/gea-specs/GEH50DFEJSR