FLORIDA SOLAR ENERGY CENTER®

Creating Energy Independence

Potential of a Very High Efficiency Solar-Assisted Heat Pump Water Heater

FSEC-PF-472-18

August 17, 2018

Presented at

2018 ACEEE Summer Study on Energy Efficiency in Buildings

Authors

Danny Parker and Carlos Colon, Florida Solar Energy Center

Tim Merrigan and Jeff McGuire, National Renewable Energy Laboratory

1679 Clearlake Road

Cocoa, Florida 32922, USA

(321) 638-1000

www.fsec.ucf.edu

A Research Institute of the University of Central Florida

Disclaimer

Potential of a Very High Efficiency Solar-Assisted Heat Pump Water Heater

Danny Parker, Carlos Colon
Florida Solar Energy Center

Tim Merrigan, Jeff Maguire
National Renewable Energy Laboratory

Abstract

Reducing energy use for heating hot water remains a major challenge around the world. This paper describes a novel solar photovoltaic-assisted heat pump water heater (PV-HPWH which achieved an 83% reduction (COP 5.4) in water heating energy compared with electric resistance. This technology demonstrates very large potential residential energy savings around the United States.

Introduction

Field data shows that 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]. Research shows 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 [4]. At the November 2013 ACEEE Hot Water Forum in Atlanta, a highlighted presentation compared solar thermal water heating systems with heat pump water heaters (HPWH) powered by photovoltaic (PV) modules. [5] 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 would have a much lower installed cost compared to a conventional solar thermal water heating system even before incentives. In addition, the PV-driven HPWH was estimated to save more energy, be easier to install with no plumbing, used less space, required less maintenance, and could not leak, overheat, or freeze. Based on our experience in this demonstration project along with falling PV prices, we suggest that an installed cost less than $3500 for an installed two module PV-driven HPWH might be achievable.

Background

Water heating in residential buildings continues to pose a challenge as the overall efficiency of buildings improves over the last decade with energy efficiency code requirements for air conditioning, lighting and building envelope. Although modest improvement in the minimum energy efficiency for electric storage water heaters in the United States was implemented in 2015, much greater energy efficiency improvements remain desirable.

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 for water heating has been discussed in earlier research. In 1998-99, direct resistance water heating using PV was first 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 heating element

[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

to maximize power transfer. In recent years, similar resistance-based 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, PV has seldom been integrated with a heat pump for water heating. In one of the few examples, Aguilar et al. [7] 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 a uniform energy factor (UEF) as high as 3.4 as indicated under the advanced product list published by the Northwest Energy Efficiency Alliance (NEEA) [8]. The design and integration of PV and heat pump water heaters suggests 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) -- under contract with the National Renewable Energy Laboratory (NREL) -- has developed 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 can potentially be used with little grid interaction. With switching based on power electronics to isolate the electrical water heating system, any interaction with the grid can be eliminated, thus avoiding potential net metering issues that have recently emerged in some 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 nearly identical to manufacturer claims for the first generation unit [9]

The PV-HPWH prototype evolved with a series of implemented control improvements. Beginning on March 2016, the system was upgraded to autonomously change the thermostat setting from 52^{0}C (baseline) to 60^{0}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 an electronic controller and software developed at FSEC. The upper heating element was unchanged.

System Description

A diagram of the PV-driven HPWH as tested 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 ranges from 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^{0}C. The 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.

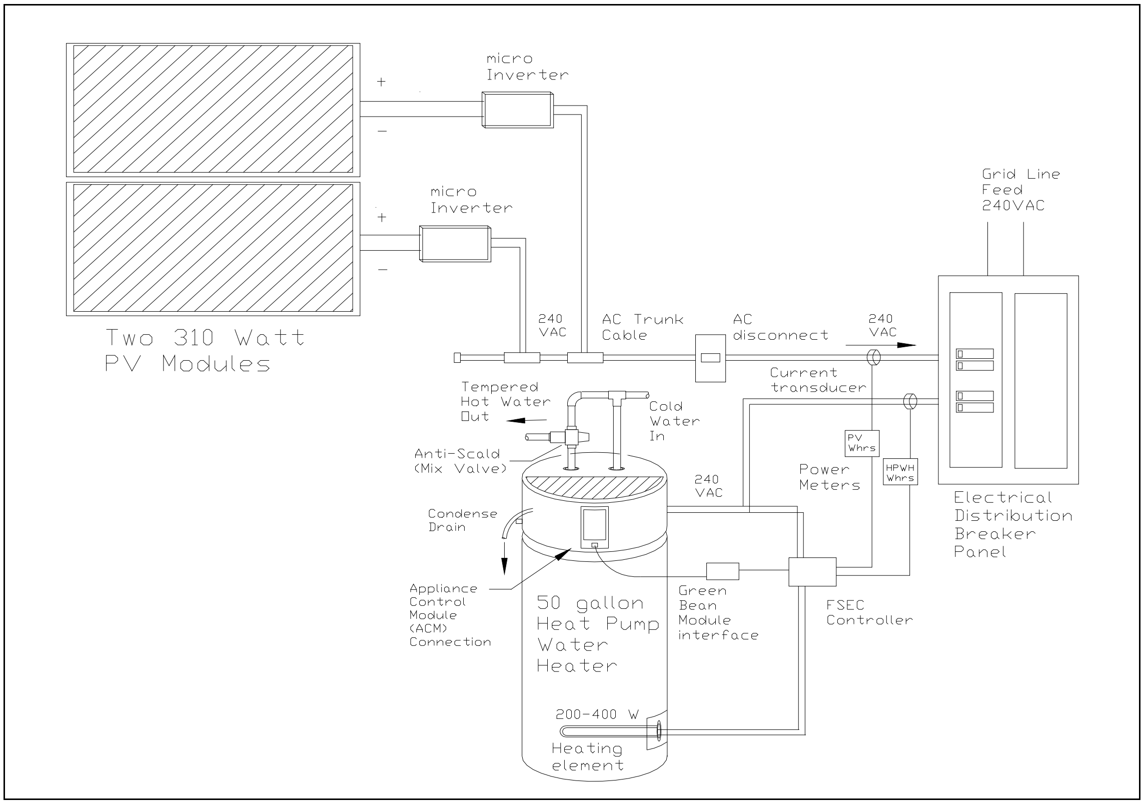

Figure 2: Schematic diagram of prototype PV-assisted HPWH.

To match the energy produced by 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 refinement of the developed controller led to techniques to maximize the compressor operation efficiency and store most PV energy as hot water with limited interaction with the grid and little waste of solar electricity produced. Once a full tank of 60^{0}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 ^{0}C, enabling the HPWH tank to act as thermal storage for the PV-generated electricity.

Increasing temperatures in the 189-liter tank from the 52 ^{0}C baseline beyond 60^{0}C is the thermal storage equivalent of 2.2 kWh. Data indicated that thermal storage levels above 60^{0}C appear during 75% of the days analyzed. Peak hot water temperatures reached beyond 65^{0}C in May and August as measured at the hot water outlet port during the 3:49 pm hot water draw and averaged 62^{0}C in late afternoons. This essentially allows the system to avoid any water heating electrical demand during evening hours—a help with the so called “duck curve” often associated with rapidly rising electrical demand from homes with PV systems during early evening hours [10].

On a daily basis, tank water heating in response to early morning cumulative hot water draws (83 liters) began around 7:30 am, but the heating process was interrupted at 8:30 am by a thermostat set up 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 setpoint. This process is illustrated in Figure 3 showing data and control thermostat setpoints recorded on August 23, 2016. During the example day, compressor turns on at 7:38 am for only 10 minutes, due to previous day storage and the 49°C thermostat setting, and then is followed by 192 Watts of electric resistance heating. The compressor resumes heating again at 9:07 am as solar output increases 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.

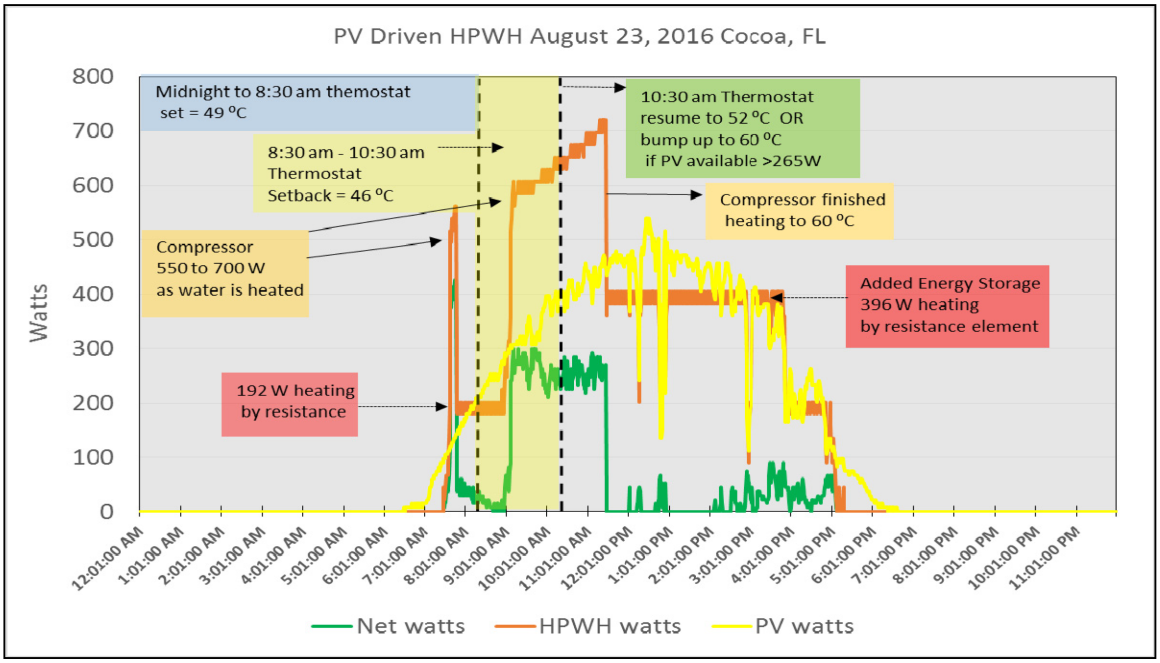

Figure 3: Example PV production and HPWH power usage in the prototype PV- HPWH

Results

Figure 4 illustrates test results from the prototype PV-assisted HPWH operating 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:

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

Figure 4 also shows the daily solar radiation from the two PV modules (dotted line) in Watt-hours per square meter per day on the right axis. As seen from the figure, COPs around 6.0 are typically achieved 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 further influenced by the solar irradiance on the preceding day as this determines the stored thermal energy over evening hours. Overnight tank thermal storage is particularly important for the efficiency of serving early morning hot water draws.

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 aims to maximize PV-supplied energy to be used by the system and to island the electric power if desired so that there is no interaction with the grid.

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.

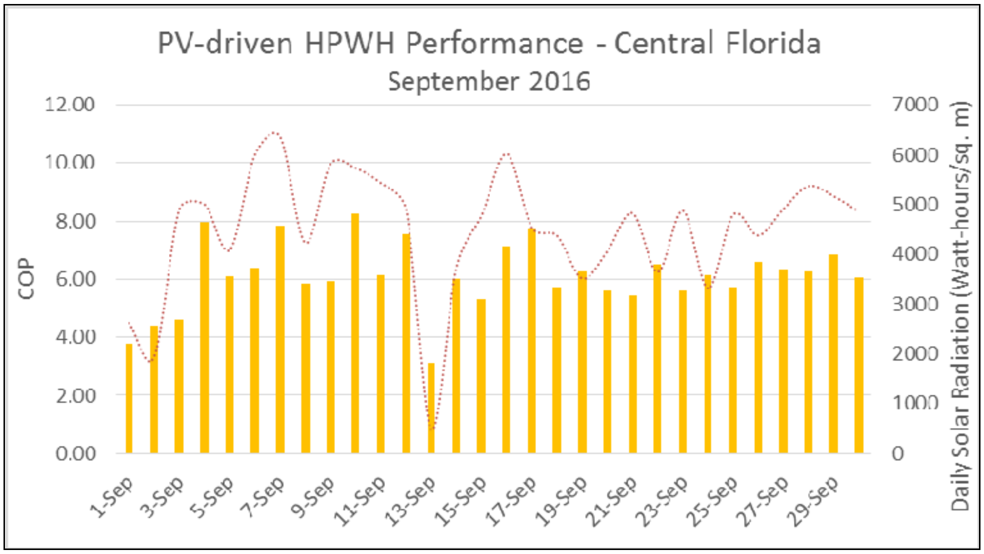

Figure 4: Prototype PV-assisted HPWH Performance in September 2016 in Central Florida

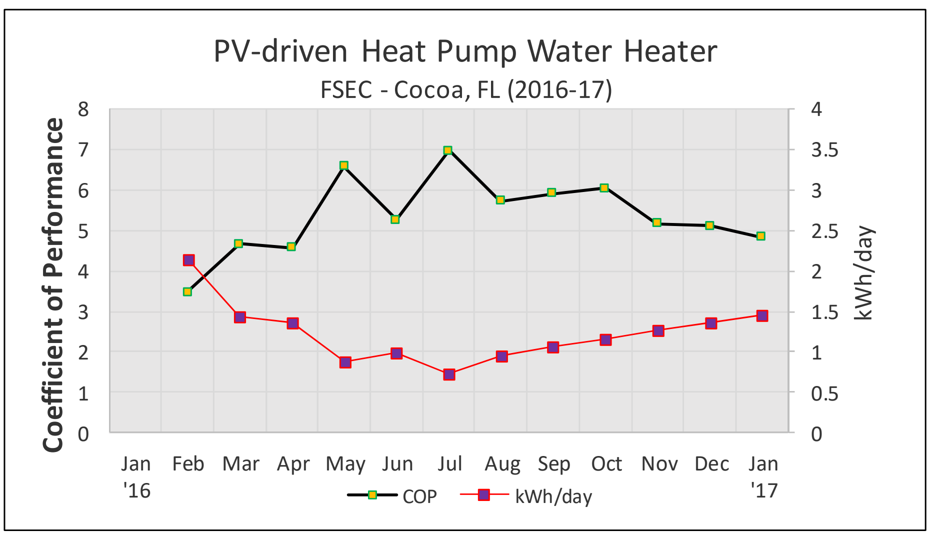

Figure 5: PV-HPWH monthly average COP and kWh per day (February 2016 – January 2017)

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.

The plot also shows the diversified water-heating only 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 [11]. 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 PV systems' decreasing electricity production.

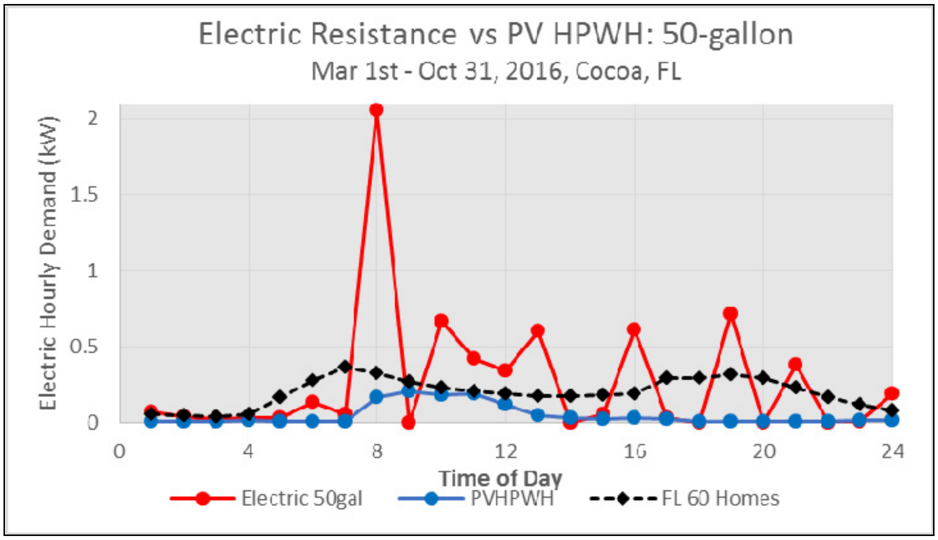

Figure 6: Time of day load profile of PV-HPWH compared to a single 189-Liter electric water heater and the load profile of 60 Florida homes with electric resistance water heaters

Table 1 summarizes 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.[2]

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 U.S. DOE Building America program thru 2016 [12]. 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 an integrated annual COP of approximately 0.8. Accordingly the prototype PV-HPWH saved 83% of the energy typically needed for conventional electric resistance water heaters.

[2] The unit modified to a PV-HPWH was a first generation HPWH with a Uniform Energy Factor (UEF) of 2.45. Many second generation HPWHs have UEFs of 3.1 - 3.7. It should be noted that the COPs described here are actually much more impressive than would be at first obvious since the UEF test procedure largely allows tested HPWHs to avoid use of the electric resistance heating elements which can significantly degrade real-world performance. This is accounted for in the TRNSYS simulations described here, however.

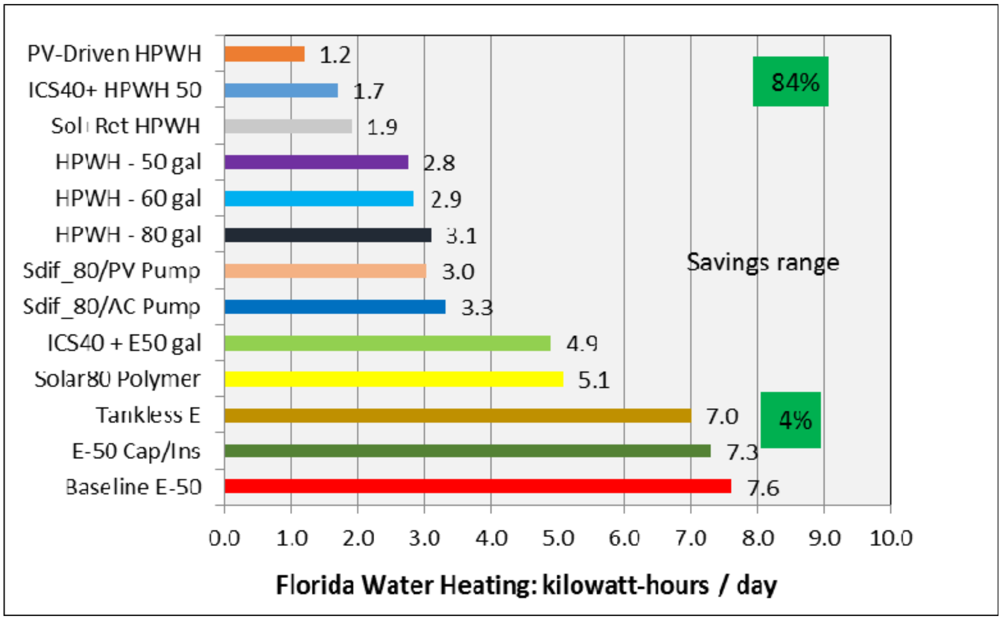

Figure 7: Representation of various electric water heating systems daily electric use compared to a baseline (standard 189 L electric) and the potential for energy savings (4%-84%)[3]

Simulation of PV Assisted Heat Pump Water Heater Across Climates

To evaluate the technology across North America, we performed a simulation analysis using a calibrated TRNSYS model of the system. The model featured a detailed description of the tank, PV modules, and inverter systems. The heat pump was modeled using a performance map based on detailed laboratory testing [13]. A custom controller was used to account for when the heat pump and electric resistance elements were powered, based on the tank temperature and PV production. We compared the predicted performance in Orlando using TMY3 weather data to the measured. The daily hot water consumption was simulated using the same 213 L per day draw profile used in the field. An electric resistance water heater was also simulated to evaluate comparative performance. The Orlando result was very close to the measured performance. The simulation predicted an annual system COP of 5.3 against the 5.4 measured at the FSEC laboratory over the year.

To extend the results, at least one location was used to represent each of IECC climate zones 1-6. For consistency, and to study interactions with a residential home, the HPWH was assumed to be in a utility room on the interior of the house by with a thermal interaction factor of 0.68 based on work by Widder et al. [14]. The water heaters were simulated in 232 m^2 homes that comply with 2009 IECC code requirements served by a SEER 13, HSPF 7.9 ASHP. Additional details on the building models are provided in [2].

Table 2 summarizes the results from the simulation analysis for cases with 2 PV modules. The table provides a comprehensive evaluation from the TRNSYS simulations:

1. Annual HPWH electricity use (kWh)
2. Delivered energy from the hot water tank (kWh)
3. Solar electricity produced by the two 300 W PV modules (kWh)
4. Annual energy use of 189L (UEF) 0.91; electric resistance water heater (ERWH).
5. Delivered energy of the ERWH to load (kWh)

[3] Key: ICS40: Integrated collector storage solar system (40 gal); Sol+Ret: Solar heating of HPWH tank; HPWH: heat pump water heater of various sizes (50,60,80 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).

6. Net change in annual space conditioning energy (kWh) based on interaction with HVAC
7. Net HPWH electricity use, including solar production & space conditioning impact (kWh)
8. Net PV-HPWH electricity savings over ERWH (kWh)
9. Net PV-HPWH COP including interaction with HVAC system

Table 2 Simulation Results of PV-Assisted Heat Pump Water Heater with 2 PV Modules

Location	IECC Climate Zone	HPWH Energy Consumption (kWh)	HPWH Delivered Energy (kWh)	PV production (kWh)	Net Electricity Consumption (kWh)	Net System COP	Net Change in Space Conditioning Energy (kWh)	Net Electricity Consumption With Space Conditioning (kWh)	ERWH Energy Consumption (kWh)	ERWH Delivered Energy (kWh)	Net Electricity Savings (kWh)
Honolulu	1A	961	1881	910	51	37.0	-219	-168	2158	1794	2326
Miami	1A	989	1922	859	131	14.7	-165	-34	2200	1845	2235
Orlando	2A	1120	2201	813	308	7.2	-120	188	2502	2136	2314
Houston	2A	1262	2362	797	465	5.1	-111	354	2671	2306	2318
Phoenix	2B	1127	2020	1051	76	26.4	9	86	2313	1941	2227
Atlanta	3A	1510	2749	838	672	4.1	66	738	3069	2708	2330
Las Vegas	3B	1395	2434	1034	360	6.8	68	428	2738	2371	2310
Los Angeles	3B	1459	2731	918	540	5.1	122	662	3046	2677	2384
Sacramento	3C	1516	2832	905	611	4.6	125	736	3149	2787	2413
San Diego	3C	1390	2649	954	436	6.1	71	507	2952	2585	2445
San Francisco	3C	1658	3045	871	787	3.9	254	1041	3374	3006	2333
New York City	4A	1726	3065	737	989	3.1	120	1109	3396	3041	2287
Baltimore	4A	1724	3111	752	972	3.2	140	1112	3436	3082	2324
Albuquerque	4B	1828	3078	1010	818	3.8	120	938	3388	3032	2450
Seattle	4C	1848	3285	621	1227	2.7	268	1495	3643	3286	2148
Chicago	5A	1943	3434	703	1240	2.8	242	1482	3777	3429	2295
Boulder	5B	2087	3418	855	1232	2.8	200	1432	3744	3394	2312
Minneapolis	6A	2192	3676	716	1477	2.5	278	1755	4014	3672	2259
Helena	6B	2300	3735	756	1544	2.4	308	1852	4074	3730	2222

As seen in the tabular results, the PV-assisted HPWH performs best in cooling dominated and milder climates. The net system COP used here is defined as the hot water energy delivered over the electrical energy consumed less the PV contribution:

$$COP_{sys} = \frac{E_{del}}{E_{cons} - E_{pv}}$$

In warmer climates, the net energy consumption is negative as the PV and space conditioning benefit is larger than the HPWH energy consumption. The net system COP tends to drop in cooler climates due to the higher load, less favorable space conditioning impact, and lower PV production. However, the larger loads in colder climates lead to relatively consistent energy savings across all climates.

A further evaluation was done with 3 PV modules to compensate for lower solar availability in northern climates. Cases with 3 modules were analyzed for IECC climate zones 3-6. Results are in Table 3:

Table 3 Simulation Results of PV-Assisted Heat Pump Water Heater with 3 PV Modules

Location	IECC Climate Zone	HPWH Energy Consumption (kWh)	HPWH Delivered Energy (kWh)	PV production (kWh)	Net Electric Consumption (kWh)	Net System COP	Net Change in Space Conditioning Energy, 3 PV Modules (kWh)	Net Electricity Consumption with Space Conditioning (kWh)	Net Electricity Savings (kWh)
Atlanta	3A	1482	2766	1217	265	10.4	76	341	2728
Las Vegas	3B	1357	2446	1432	-75	∞	76	1	2737
Los Angeles	3B	1393	2744	1313	80	34.4	109	189	2857
Sacramento	3C	1491	2843	1270	221	12.9	126	347	2802
San Diego	3C	1349	2659	1349	0	∞	67	67	2885
San Francisco	3C	1635	3063	1251	384	8.0	216	600	2775
New York City	4A	1710	3075	1086	625	5.0	128	752	2644
Baltimore	4A	1711	3133	1108	603	5.2	148	751	2685
Albuquerque	4B	1770	3089	1440	330	9.4	108	438	2950
Seattle	4C	1870	3301	919	952	3.5	243	1195	2448
Chicago	5A	1978	3458	1035	943	3.7	230	1173	2604
Boulder	5B	2055	3437	1256	799	4.3	192	991	2753
Minneapolis	6A	2197	3696	1067	1130	3.3	266	1396	2618
Helena	6B	2302	3755	1115	1187	3.2	282	1469	2605

The 3 PV module cases show higher system COPs than the 2 module cases due to the higher PV production. In some cases, the PV produces enough energy to completely offset the HPWH electricity consumption, leading to a system COP of infinity (∞). In these cases, less of the total PV production is "useful" and ends up as heat stored in the tank since the tank more frequently gets to the maximum setpoint temperature. The systems with more modules could benefit from larger storage tanks, which would increase the amount of energy that could be stored in the tank. Higher volume tanks may be considered for colder climates in future studies.

Simple paybacks were calculated for PV assisted HPWHs for both 2 and 3 PV module cases. Utility costs are based on 2016 state average utility rates [15]. Net installation costs are based on the new construction used in BEopt for ERWHs, HPWHs, and PV. A 30% federal incentive is applied to the PV costs, but state and local incentives are not included. The net installed cost of the ERWH, 2-module PV assisted HPWH, and 3 module HPWH are $480, $2819, and $3500 respectively. These net installation costs don't account for any potential savings in installation expense when installing the HPWH and PV as a packaged system. Simple payback for all cases are given in Table 4. The costs also don't account for the reduction of the packaged PV-HPWH systems that would likely occur for a mature product with large scale deployment.

Table 4 Simple Payback for 2 and 3 Module PV Assisted Heat Pump Water Heaters

Location	IECC Climate Zone	2016 State Average Utility Rate (¢/kWh)	ERWH Annual Energy Consumption (kWh)	ERWH Annual Electricity Costs ($)	2 PV HPWH Net Electricity Consumption (kWh)	2 PV HPWH Annual Electricity Costs ($)	2 PV Simple Payback (yrs)	3 PV HPWH Net Electricity Consumption (kWh)	3 PV HPWH Annual Electricity Costs ($)	3 PV Simple Payback (yrs)
Honolulu	1A	23.87	2158	515	51	12	4.7	-	-	-
Miami	1A	9.91	2200	218	131	13	11.4	-	-	-
Houston	2A	8.43	2502	211	308	26	12.6	-	-	-
Orlando	2A	9.91	2671	265	465	46	10.7	-	-	-
Phoenix	2B	10.33	2313	239	76	8	10.1	-	-	-
Atlanta	3A	9.59	3069	294	672	64	10.2	-	-	-
Las Vegas	3B	8.39	2738	230	360	30	11.7	265	22	14.6
Los Angeles	3B	15.23	3046	464	540	82	6.1	-75	-11	6.4
Sacramento	3C	15.23	3149	480	611	93	6.1	80	12	6.5
San Diego	3C	15.23	2952	450	436	66	6.1	221	34	7.3
San Francisco	3C	15.23	3374	514	787	120	5.9	0	0	5.9
New York City	4A	14.47	3396	491	989	143	6.7	384	56	6.9
Baltimore	4A	12.21	3436	420	972	119	7.8	625	76	8.8
Albuquerque	4B	9.12	3388	309	818	75	10.0	603	55	11.9
Seattle	4C	7.68	3643	280	1227	94	12.6	330	25	11.9
Chicago	5A	9.38	3777	354	1240	116	9.8	952	89	11.4
Boulder	5B	9.83	3744	368	1232	121	9.5	943	93	11.0
Minneapolis	6A	9.99	4014	401	1477	148	9.2	799	80	9.4
Helena	6B	8.84	4074	360	1544	137	10.5	1130	100	11.6

Estimated simple payback varies between 5-15 years depending on the climate and average electricity costs. Almost all of the cases have a simple payback of less than 13 years, the average lifetime of an ERWH and HPWH. Increasing the number of PV modules installed reduces the simple payback in colder climates, where more of the PV energy generated can be used to meet the water heating load.

Table 5 shows greenhouse gas (CO_2) related emissions in the cases of interest with the TRNSYS runs expanded to include natural gas water heating. Emissions associated with electricity use are taken from the same EPA database used for cost data. In all cases evaluated, the best PV-HPWH option has lower annual GHG emissions than either electric resistance, gas storage or gas tankless water heaters. Thus, this particular technology has the potential of making large reductions in GHG emissions in the U.S. residential sector even in parts of the country where gas water heating dominates.[4]

[4] See Figures 2 and 18 in this NREL evaluation of RECS data: https://www.nrel.gov/docs/fy13osti/58594.pdf

Table 5. Greenhouse Gas Emission Impacts for Natural Gas Storage, Tankless and PV-assisted Heat Pump Water Heaters

Location	IECC Climate Zone	ERWH Energy Consumption (kWh)	HPWH-2 PV Energy Consumption (kWh)	HPWH-3 PV Energy Consumption (kWh)	Gas Storage Energy Consumption (kWh)	Gas Tankless Energy Consumption (kWh)	Electricity Emissions (lb CO_2/kWh)	ERWH Emissions (lb CO_2/yr)	HPWH-2 PV Emissions (lb CO_2/yr)	HPWH-3 PV Emissions (lb CO_2/yr)	Gas Storage Emissions (lb CO_2/yr)	Gas tankless Emissions (lb CO_2/yr)
Honolulu	1	2158	51		3734	2024	1.605	3464	82		1491	808
Miami	1	2200	131		3808	2086	1.019	2242	133		1521	833
Orlando	2A	2502	308		4189	2435	1.019	2549	313		1673	972
Houston	2A	2671	465		4415	2641	1.146	3061	533		1763	1054
Phoenix	2B	2313	76		3958	2211	0.901	2084	69		1580	883
Atlanta	3A	3069	672	265	4930	3126	0.992	3044	667	263	1969	1248
Las Vegas	3B	2738	360	-75	4511	2722	0.804	2202	290	-60	1801	1087
Los Angeles	3B	3046	540	80	4910	3088	0.525	1599	284	42	1961	1233
Sacramento	3C	3149	611	221	5040	3221	0.525	1653	321	116	2013	1286
San Diego	3C	2952	436	0	5040	2977	0.525	1550	229	0	2013	1189
San Francisco	3C	3374	787	384	5348	3088	0.525	1772	413	201	2136	1233
New York City	4A	3396	989	625	5354	3572	0.512	1739	506	320	2138	1426
Baltimore	4A	3436	972	603	5405	3572	1.100	3779	1069	663	2158	1426
Albuquerque	4B	3388	818	330	5347	3513	1.550	5252	1268	511	2135	1403
Seattle	4C	3643	1227	952	5681	3817	0.197	718	242	187	2268	1524
Chicago	5A	3777	1240	943	5845	3981	0.848	3203	1052	800	2334	1589
Boulder	5B	3744	1232	799	5805	3941	1.458	5458	1796	1164	2318	1574
Minneapolis	6A	4014	1477	1130	6151	4261	10.96	4400	1619	1239	2456	1701
Helena	6B	4074	1544	1187	6151	4330	1.304	5312	2014	1548	2456	1729

Conclusions

This paper describes a novel solar photovoltaic assisted heat pump water heater (PV-HPWH). The system uses two 300 Watt PV modules, micro-inverters and innovative controls to produce and store daily hot water. The system appears to have costs less than half that of solar thermal systems, with greater reliability, no freeze protection and potentially superior performance even in cloudy locations. Moreover, no net metering might be needed for 2-3 PV modules making for a simple installation.

The system was tested at Florida Solar Energy Center in Central Florida under realistic conditions with loads approximating a family of four. Relative energy savings compared to an electric resistance storage system were 83%, representing a near breakthrough for water heating efficiency. Realistic hot water draws were imposed with detailed data recorded on system performance. Daily COP has been as high as 8.0 during sunny summer days. 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 day – less than many refrigerators.

The prototype PV-HPWH showcases innovative strategies for distributed PV systems that limit grid interaction and provide increased thermal energy storage. Sophisticated 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. 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 settings on a time of day basis. By altering the thermostat down to 46^{0}C during early morning draws, the system can disrupt compressor heating recovery normally set to 52^{0}C and shift the remainder of recovery to times where adequate solar resources are typically available (after 10:30 am). 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, but is limited at that point. A mixing valve provides hot water at the target temperature (52ºC). By dynamically altering tank temperature, an equivalent of ~2 kWh of electrical energy is stored for use during evening hours. Typically, there is no water heating grid electricity demand during utility summer peak periods such that such a controlled water heating system would not aggravate the "duck curve" resulting from many residential PV installations.

The prototype PV-HPWH system equipment had a retail cost of $2053 (including the HPWH, PV, micro-inverters, controls and tempering valves), significantly less than traditional solar thermal systems. Key advantages of the PV-HPWH technology:

- Simplified installation likely to 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 promise greater long term reliability
- PV to thermal storage strategy typically produces 2.2 kWh of evening load shift relative to standard electric resistance systems.

Analysis of data from the original prototype suggests even better performance. We anticipate further refinement relative to controls within a heuristic control framework (learning prevailing household hot water load and weather patterns. Also, the latest generation of HPWH compressors operate at a power level of ~50 watts less compared to the unit used in our demonstration [12]. Further, in northern climates, larger hot water storage tanks (303-Liter) with the HPWH's could also be utilized along with additional PV modules to achieve performance advantages [2, 9].

To evaluate the technology potential across North America, we performed a simulation analysis using a calibrated TRNSYS model of the system. This simulation was found to very accurately describe the laboratory performance seen in Florida. With the PV-HPWH being located inside the conditioned space, performance was then estimated across 19 highly varied North American climates. The results showed strongly improved performance over standard HPWH systems. A 2 module PV-assisted system appeared adequate in warmer climates, but a three PV module system was best in colder regions. System COPs was 2.4 – 37.0 across climates in the 2 PV module configuration. Three PV modules were found helpful in the coldest locations (minimum COP was 3.2) and newer lower wattage compressors would likely improve upon current simulation results.

A preliminary evaluation was made of relative economics using an installed system cost estimate along with state-level electricity prices. Including provision for the federal solar tax credit on the solar element, the estimated simple paybacks were 6–11 years for the most appropriate configuration. Economics were best in locations with the highest electricity price such as Hawaii, California and New York. However, economics were positive in all locations. Finally, an evaluation of relative greenhouse gas emissions (GHG) showed the PV-HPWH technology could make significant reductions to emissions over electric and natural gas water heating of all types across each region evaluated.

A pilot demonstration of the PV-HPWH technology in a residential water heating field project seems the next logical step. Refinement based on results could lead to development of a new generation of residential water heating equipment addressing the combined needs for very high efficiency and effective energy storage while providing large reductions to associated greenhouse gas emissions.

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] 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.

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

[6] 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.

[7] 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.

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

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

[10] Denholm, P., O'Connell, M., Brinkman, G and Jorgensen, J., *Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart, NREL/TP-6A20-65023, National Renewable Energy Laboratory, November 2015.*

[11] 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

[12] The newer General Electric HPWH, the GEH50DFEJSRA (more recently produced by Bradford-White), has a 3.25 UEF with a compressor power of 550 watts: "Specs and Details" http://products.geappliances.com/appliance/gea-specs/GEH50DFEJSR

[13] Sparn, B. Hudon, K. and Christensen, D., *Laboratory Performance Evaluation of Residential Integrated Heat Pump Water Heaters. NREL/TP-5500-52635, National Renewable Energy Laboratory, June 2014.*

[14] Widder, S, C. Metzger, J. Petersen, and J. McIntosh. 2017, *Interaction between Heat Pump Water Heaters or Other Internal Point Source Loads and a Central Heating System*, PNNL-26447, Pacific Northwest National Laboratory, Richland, Washington.

[15] U.S. Energy Information Administration. 2018. *State Electricity Profiles.* U.S. Energy Information Administration. April 2018. https://www.eia.gov/electricity/state/