FLORIDA SOLAR ENERGY CENTER®

Creating Energy Independence

PV-Driven Heat Pump Water Heater

FSEC-CR-2043-16

Final Report
(Revised)

April 24, 2017

Submitted to:
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden CO 80401-3393

Submitted by:
Carlos J. Colon
Danny Parker
Email: carlos@fsec.ucf.edu

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1679 Clearlake Road
Cocoa, Florida 32922, USA
(321) 638-1000

www.floridaenergycenter.org

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Definitions

AC	Alternating Current
ACM	Appliance Control Module
BTU	British Thermal Unit
DC	Direct Current
EF	Energy Factor
GE	General Electric
GPIO	general purpose input output (microcontroller pin)
HPWH	Heat Pump Water Heater
HWS	Hot Water Systems
HVAC	Heating Ventilati0n and Air Conditioning
KWH	kilowatt-hour
NEEA	Northwest Energy Efficiency Alliance
Pmax	Nominal maximum power
PV	Photovoltaic
TRNSYS	Transient System Simulation Tool
WebGet	An experimental archived data base tool developed at FSEC

Acknowledgements

This research work was sponsored by the U.S. Department of Energy (DOE). The following individuals are recognized for their supporting role and efforts during the development, demonstration and evaluation of the PV-driven Heat Pump Water Heater concept presented in this report:

Eric Werling and Sam Rashkin, funding from the DOE's Buildings Technologies Office (BTO) Residential Buildings Integration (RBI) program

Craig Tsai (GE) –Advanced Systems Engineer Water Products, Louisville, KY for guidance hardware/software on appliance communication.

Tom Cummings (FSEC) – RaspberryPi2 and Javascript programming interface

Jeff Maguire (NREL) – TRNSYS simulations

Eric Schneller (FSEC) – ABB microinverter wireless communications initial launch

Tim Merrigan (NREL) – Research program coordinator, management and review

Safvat Kalaghchy (FSEC) – WebGet 5.0, data archive, communications link facilitator

William Wilson (FSEC) - Electrical/Electronics guidance

Allan Garnett (FSEC) - Facilities, Laboratory safety compliance

Executive Summary

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 successfully completed a demonstration of a photovoltaic heat pump water heater (PV-HPWH) prototype (see Figure 1). Operational performance data has been collected for 12 months ending in January 2017. The system integrates two 310 W_p solar photovoltaic (PV) modules and grid-tied microinverters with a commercially available 50-gallon HPWH. Testing and evaluation utilized an automated hot water load schedule totaling 59 gallons per day, typical of an average 3-4 person family. The project showcases innovative strategies for distributed PV systems that limit grid interaction and provide increased thermal energy storage.

Figure ES-1: Solar modules 310 Wp each (top) and 50 –gallon HPWH shown with added insulation.

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 which has been superseded in the market by a slightly more efficient unit (550W). The hot water tank was used to store an added 2.1 kWh of equivalent thermal energy above that of the baseline thermostat setting (125 ^{o}F). A mixing valve was utilized to limit hot water temperatures which can exceed the daily average of 144^{o}F. The system utilizes a custom appliance control module (ACM) interface to vary thermostat settings (up to 140^{o}F) depending solar radiation levels. It also prioritizes thermostat setbacks based on a time of day basis. By setting the thermostat down to 115^{o}F during early morning draws, it can disrupt compressor heating recovery normally set to 125^{o}F and shift the remainder of recovery to times where higher solar resources are available (i.e., after 10:30 am). On average, the fixed south facing photovoltaic modules produced

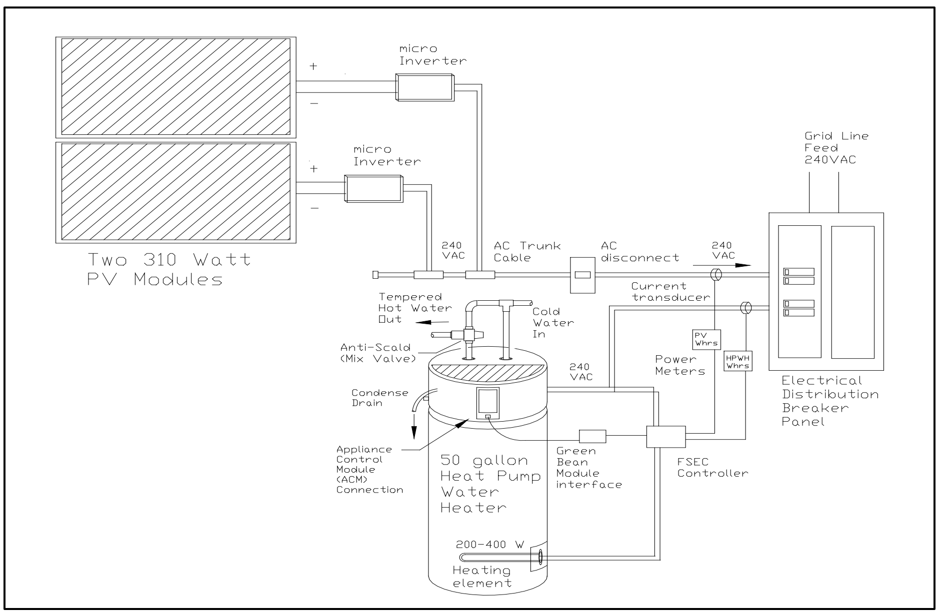

Figure ES-2: Overall diagram of component of a PV-driven HPWH.

around 369 Watts during mid-day hours (11:00 am – 2:00 pm). On a daily basis, tank heating in response to early morning hot water draws before 7:45am (22 gallons) was begun typically around 7:30 am, but the heating process was interrupted at 8:30 am by a thermostat setback to 115^{0}F. 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 125^{0}F 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 120^{0}F 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 115^{0}F 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.

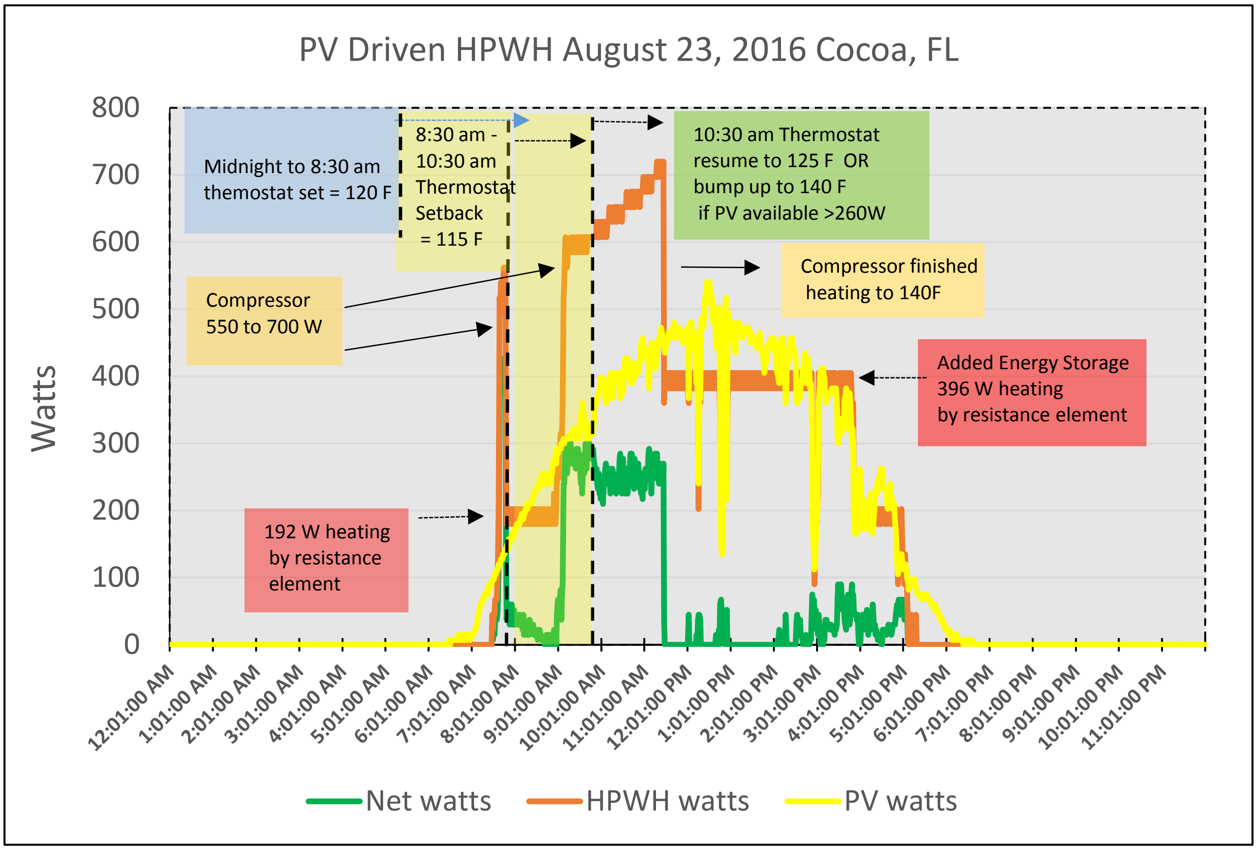

Figure ES-3: Illustration control techniques for compressor operation and auxiliary heating element interaction utilized in the PV-driven HPWH

Coefficient of performance (COP) thru January 2017 has averaged 5.2 in Florida, requiring grid power of only 1.2 kWh per day for a typical residential hot water load. The performance average includes all data beginning in February 2016, where optimization improvements were not yet implemented. By subtracting the PV-generated electricity produced from the total electricity used by the HPWH during real time intervals, the net grid electricity (as sourced from the grid) is used in the calculation of COP.

Measured performance recorded through January 2017 can be seen in Figure 4. 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.

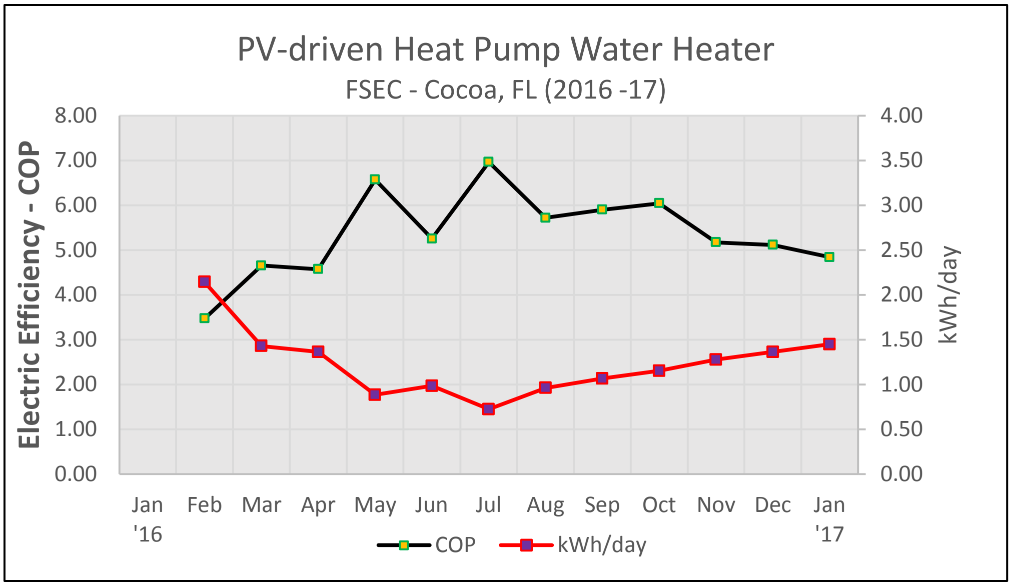

Figure ES-4: Performance of PV-driven HPWH from February to October 2016

Table 1 present a simple payback case scenario based on the retail cost of components of the PV-driven HPWH. A theoretical complete install cost of $3053 (assuming $1000 for installation) is used in the analysis for Florida, achieving a 12.1 year simple payback at $0.11/kWh. Earlier payback is achieved if the cost increment to replacing a standard premium electric water heater ($428) is assumed. Similarly, the annual energy savings (2321 kWh) and simple payback (5.5 yrs.) are presented for the state of Hawaii assuming $0.25/kWh. The Florida case calculates savings compared to an electric resistance water heater as measured simultaneously in the laboratory (7.2 kWh/day). The Hawaii case utilizes a baseline electric integrated value of 7.6 kWh/day as reported by UHERO in 2015. Both cases assume the daily average electricity consumption of 1.2 kWh/day as averaged during the PV-driven HPWH testing period.

Table ES-1: Theoretical simple payback for the PV-driven HPWH in Florida and Hawaii

	Florida Retail Cost ($)	**Annual Savings kWh @ $0.11**	**Simple Payback (years)**	**Hawaii Retail Cost ($)**	**Annual Savings kWh @ $0.25**	**Simple Payback (years)**
Equipment only	$2053	$251.7 (2288.5 kWh)	8.1	$2153	$571.4 (2321.4 kWh)	3.8
Complete Install	$3053	Same as above	12.1	$3153	Same as above	5.5

In summary, the PV-HPWH has demonstrated impressive performance by integrating photovoltaics with compressor-based refrigerant water heating, smart controls, and added energy storage. Table 2 provides a summary of its 12-month performance ending in January 2017.

Table ES-2: Summary of performance February 2016 – January 2017 by the PV-HPWH

Average Monthly Daily Electric Consumption		**Average COP Monthly (Min. /max)**	**PV generated Monthly Average**	**Added storage above 125°F**	**Hot water Average Daily (Max)**	**Average Daily Hot Water Delivered (w/ 125°F mix valve setting)**		
kWh/day	**Min-Max kWh/day**	**COP**	**kWh/day**	**kWh/day**	**°F**	**Gal.**	**Btu's**	**kWh**
1.2	0.7 – 2.1	5.4 (4.5 / 7.0)	2.8	2.1	144 (146)	56.9	20,727	6.1

Performance data collected from the PV-HPWH also indicates the highest efficiency electric water heating system, only using 1.2 kWh per day on average under the family realistic hot water load. Figure 5 places the PV-HPWH at the top of the chart when compared to other systems evaluated in recent years (2010-2017). Those include hybrid solar thermal with HPWH's of various gallons capacity evaluated under the Building America Partnership for Improved Construction (BAPIRC) program at FSEC.

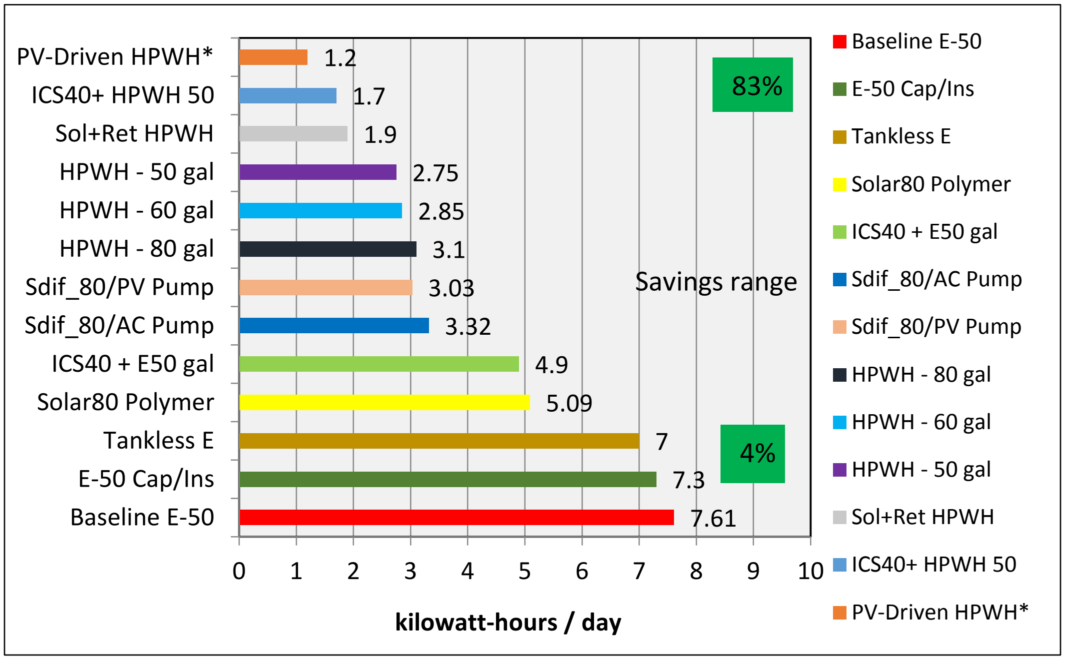

Figure ES-5: Representation of various electric water heating systems daily electric use as compared to a baseline (standard 50 gal. electric) and the potential for energy savings (4-83%)

1.0 Introduction

As part of the effort towards zero energy buildings and high efficiency, the Florida Solar Energy Center (FSEC) working under contract with the National Renewable Energy Laboratory (NREL) has successfully completed a demonstration of a PV-driven heat pump water heater (HPWH) concept. The system integrates two 310 Watt solar photovoltaic (PV) modules and grid-tied microinverters with a commercially available 50-gallon HPWH. The project showcases innovative strategies for ultra-high efficiency water heating. The PV-driven HPWH concept optimizes water heating controls which can be applicable to residential (or small commercial) systems. The PV-driven HPWH system demonstrates proof-of-concept in the following areas:

- Reduction of grid power consumption for water heating compared to a standard HPWH
- Reduction of PV power sent to the grid
- Thermal energy storage of PV-supplied energy
- Ultra-high efficiency water heating (COP range 4.0 -7.0; Average COP = 5.4)
- Adaptive thermostat control prioritizing compressor water heating relative to available solar resources (PV)
- Time-of-day operating windows (thermostat fallback/extended standby, optimization of solar resources while minimizing discomfort)

The high efficiencies demonstrated by the PV driven HPWH positions the rank of this hybrid water heating system at the top of FSEC laboratory performance charts, capable of supplying 60 gallons of hot water typical of three bedroom family home using less than 1.5 kWh per day.

1.1 Heat Pump Water Heaters - General Overview

Today's residential heat pump water heaters (HPWH's) operate based on the same principles of mechanical refrigeration technology used for air conditioning and refrigerators. [1]An air source HPWH compressor utilizes electric energy and compressed hot refrigerant to transfer heat into a storage vessel. In the refrigerant process, heat contained in the surrounding air is absorbed into the HPWH evaporator and cold air is expelled along with removed humidity in condensation as a byproduct. HPWH technology appeared first appear in significant numbers in the mid 1970's due to energy awareness.[2] Early heat pump water heaters had poor reliability and most were removed from the market. A resurgence in the U.S. of about five major manufacturers began to appear offering HPWH products around 2010. Those include GE, Rheem, A.O.Smith, Stiebel-Eltron and Airgenerate.[3] These manufacturers offered residential type storage units in the range of 50 to 80 gallons. Other manufacturers such as Whirlpool and Bradford White outsource the production of HPWH's and re-badge the unit with their brand name.

1.2 Solar Photovoltaic Water Heating Today

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 in the area of air conditioning, lighting and building envelope occurred during the last decade. Although some improvement in the minimum energy efficiency for storage water heaters was implemented in 2015, energy efficiency improvements to other building components appear to provide significant energy savings compared to those applied to standard water heating appliances.

Photovoltaics has gained momentum in the U.S. with improvement in operating efficiencies as well as decreased cost over the last 10 years. The use of PV to heat poTable water has been recently discussed by many. [4,5] In previous years (1998-99) direct resistance water heating from PV was explored and tested at 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 improve on maximum power transfer to heat water. In recent years, PV system designs for dedicated poTable water heating have evolved into the market. Table 1.1 list two solar PV water heating systems that are currently certified and offered as whole scalable systems or as retrofit.

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[1] Hepbasli A, Kalinci, Y, A review of heat pump water heating systems. Renew Sustain Energy Rev (2008)
[2] Heat Pump Water Heater Technology presentation by Dr. Carl C. Hiller, P.E. Davis , CA, http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ns/b9_heat_pump.pdf
[3] General Electric announced during September 2016 that production of the Geospring HPWH in the U.S. would end in December 2016. At the beginning of 2015 Airgenerate decided to stop production and got out of the heat pump water heater business.
[4] http://cleantechnica.com/2013/09/30/pv-better-thermal-solar-water-heating/
[5] http://www.treehugger.com/green-architecture/does-it-make-sense-use-photovoltaics-heat-water.html
[6] Doughherty, Brian P.,Fanney, A. Hunter, "Experiences with Using Solar Photovoltaics to Heat Domestic Water", Journal of Solar Energy Engieering, May 2003, Vol. 125, pp. 195-202.

Table 1.1: Example of two U.S. manufacturers offering PV solar thermal systems and their specifications

PV Water Heating System	Heater capacity	Tank storage capacity	Current /voltage	Certification
Butler Solutions	PV Wand (DC) + 1.5 kW (6 x 250W_p)	50 gallons	50A DC / 30V	SRCC
Sun Bandit	MicroInverter scalable: 2-16 PV modules	30-120 gallons	Microinverter 450W each @ 240VAC	SRCC / FSEC

Compared to standard electric resistance, residential heat pump water heaters provide considerable energy savings due to their high efficiency. Currently, HPWH's ranging from 50 to 80 gallons are rated with an energy factor (EF) as high as 3.4 as indicated under advanced product list published by the Northwest Energy Efficiency Alliance NEEA (October 2016).[7] The use of PV to heat potable water has been recently investigated by others in Europe.[8] The design and integration of PV and heat pump water heaters provide a synergistic combination to improve overall efficiency at a reasonable cost.

1.3 Project Background

In September of 2015, the National Renewable Laboratory (NREL) and FSEC began to identify a cost effective integration of components and control operation logic for a PV-driven heat pump water heater (HPWH). There are two conventional ways to potentially drive a HPWH with PV – one approach using direct current (DC) powered compressor, the other one using an alternating current (AC) compressor. Both direct current DC and alternating current compressors were evaluated. A list of possible components for a DCDC-driven heat pump water heater was reported to NREL in the fall of 2015 under Task 4.2 (DC-Powered HPWH System Design and Specification). The brief 6-page report which includes possible compressor selections, capacity and efficiencies is found in Appendix A. It also listed component retail costs for power supply, heat exchanger tubing, evaporator and fan. However, a survey of currently available AC-powered HPWH's was performed, and due to a much lower cost, the project ultimately led to use the AC HPWH version. The most popular model sold and manufactured in the U.S. – GE's Geospring 50-gallon HPWH was selected for the evaluation.

NREL then evaluated the performance of HPWH's with dedicated photovoltaics with the latest TRNSYS simulation deck for the GE HPWH using central Florida weather. The HPWH simulation model previously developed by NREL, was upgraded to simulate the control logic created by FSEC. The system would employ two 300 Watt PV modules and microinverters and an electronic control that would automatically change the thermostat setting based on near real-time solar resources available. The simulation input deck was also set to deliver 125°F hot water outlet through a mixing valve. The hot water load averaged at around 43 gallons of hot water per day (gpd) ranging from 59 gpd in January to 24 gpd in August. Details of the initial design efforts and simulation were communicated in an internal NREL report released in January 2016.[9]

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[7] The advanced product specification is formerly known as the Northern Climate Specification http://neea.org/docs/default-source/advanced-water-heater-specification/qualified-products-list.pdf?sfvrsn=44

[8] 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

[9] T. Merrigan, J. Maguire, D. Parker, C. Colon, PV-driven Heat Pump Water Heater Analysis, Testing, and Development, Quarterly Progress Report, NREL / DOE Internal, January 2016

Simulation results covered in that report are shown in Table 1.2 for 50 and 80 gallon PV-driven HPWH against a 50-gallon HPWH and electric baseline. Further simulations were performed with three PV modules; however, results did not warrant the cost of a third PV module for Florida, leading to the conclusion that two modules provided the best optimized combination.

Table 1.2 Summary of NREL TRNSYS simulations results for one and two PV modules with HPWH's compared against a standard HPWH and electric 50-gallon baseline.

Water Heating	50 gal Electric Resistance	50 gal HPWH (without PV) Baseline	50 gal HPWH One PV module	50 gal HPWH Two PV modules	80 gal HPWH Two PV modules
Grid Energy Consumption (kWh)	2403	969	686	373	326
Net Savings over HPWH (%)			29%	62%	66%
Net Savings over ERWH (kWh)		1435	1718	2031	2077
Net Savings over ERWH (%)		60%	71%	84%	86%

Due to market availability of alternating current (240 VAC) HPWH's, lower cost, and encouraging simulation results, it was decided to develop and test a prototype PV-driven heat pump water heater at the FSEC hot water systems laboratory (HWSL) in Cocoa, FL.

1.4 System Description

The main components of the PV-driven water heating system are the residential type heat pump water heater (HPWH), two photovoltaic modules (310 Wp), each one connected to individual grid-tied microinverters. HPWH model GEH50DEEDSR is compliant under the 2012 DOE Energy Star Standards.[10] The units' HCFC 134a based refrigerant compressor is rated at 600 watts. The GE Geospring HPWH (Figure 1.1) has a storage capacity of 50 gallons and rated with an energy factor (EF) of 2.45. It is also capable of providing a first hour delivery at 65 gallons. The 140^{o}F thermostat setting is the highest factory-programmed temperature level a user is allowed to enter on the unit front keypad. Although testing conducted at FSEC was performed using the highest efficiency compressor only mode, data indicated the use of its auxiliary resistance heating element (4500 W) when ambient laboratory space temperatures dropped below 46^{o}F.[11]

Fig 1.1: GE's Geospring HPWH shown is capable of a 140^{0}F thermostat setting.

Table 1.3 provides a list of the main components used in the PV-driven HPWH as integrated and tested at the FSEC HWS laboratory. When sufficient power from the PV/microinverters is being generated and

[10] The latest version GE HPWH (GEH50DFEJSRA) manufactured as of June 2015 replaced previous version with a higher EF of 3.25. It is also rated as a 550 watt appliance, being 50 watts less than the model GEH50DEEDSR unit used.

[11] The GE Technical service guide for the GEH50DEED states a compressor operating temperature range between 45^{0}F and 125^{0}F to avoid liquid refrigerant into the compressor or compressor overheat.

detected, the thermostat setting was automatically increased to 140°F from its baseline setting of 125°F. The control of thermostat set point towards higher temperatures enables longer compressor operating times, essentially storing energy while using the efficient refrigeration cycle (more on HPWH control logic in section 2.0).

Table 1.3 Prototype PV-driven HPWH Components

Component	Model	Description
Heat pump water heater	GE GEH50DEEDSR GeoSpring	50 gallon Hybrid Water Heater
PV modules (x2)	CS Quartech MaxPower CS6X-310P	Polycrystalline 310 Watts
Microinverter (x2)	ABB Micro-0.3-I-OUTD	208/240 300W; 1.25A max.
Anti-Scald (Mix) Valve	Honeywell AM-101	Tempers hot water to 125°F
Current transducer (x2)	Continental Controls	0-0.333 VAC output
Controller	Raspberry Pi2	ARM Quad Core
Interface Controller	Greenbean	1B Firstbuild w/GE SDK

The integration of the prototype system components can be seen in Figure 1.2. The HPWH was connected to the laboratory electric distribution panel into a 30 amp 240VAC dedicated breaker. Copper plumbing (3/4") was utilized during installation with an added layer of pipe insulation. A mixing valve was used to temper hot water and adjusted to deliver 125°F hot water. The HPWH also required a flexible 3/8" tubing to dispose of the condensate byproduct typical of HPWH's refrigeration cycle.

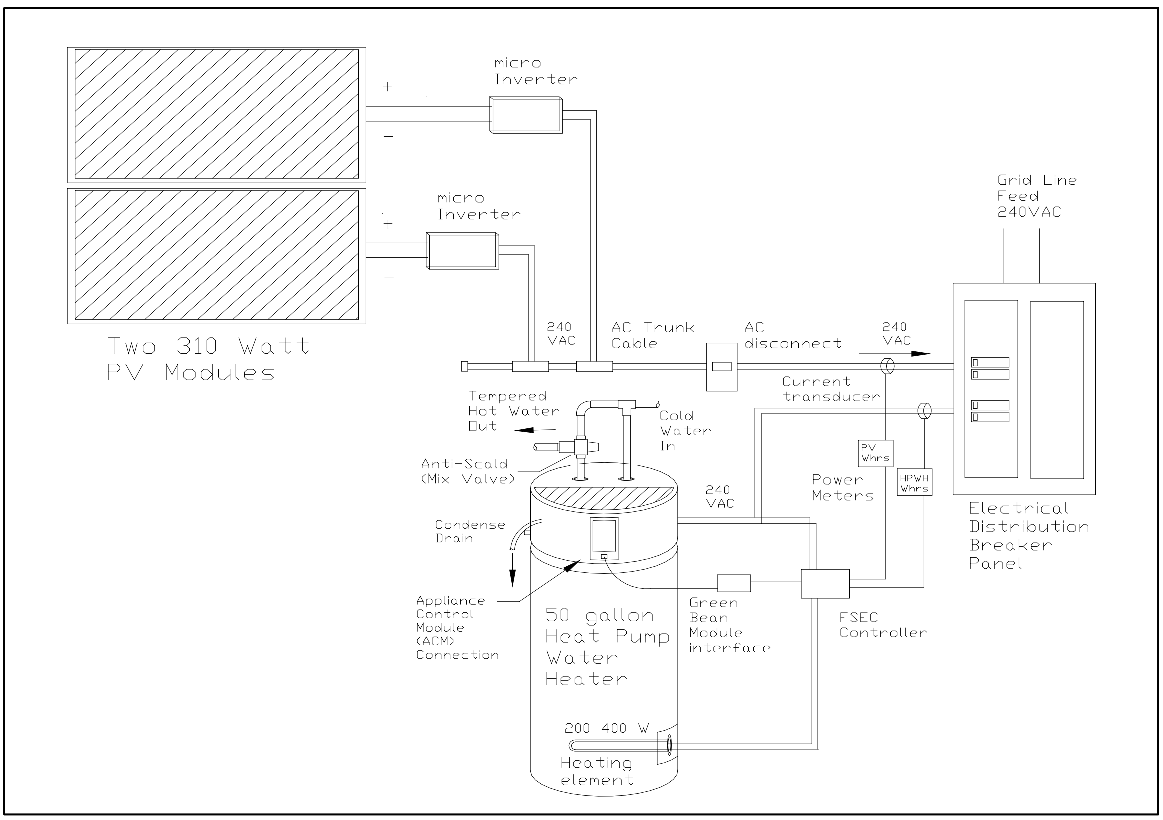


Figure 1.2 Diagram of connected components that make up the PV driven HPWH at FSEC's HWS laboratory in Cocoa, FL.

The diagram shows two photovoltaic PV modules which generate a direct current into individual microinverters. The two microinverters (Power One) convert the PV generated direct current into synchronized (60 Hz) 240 VAC and injects power into the same phase line at the distribution panel. The selection of microinverters required module compatibility check, specifically module operating voltages, due to the 72-cell composition of the modules selected. Connections from the PV modules to the PowerOne microinverter was accomplished by using the factory terminated Amphenol H4 PV connectors. The 240VAC current is delivered via proprietary trunk cable (41 inch) which connected the PV modules in the portrait arrangement allowing connection to the electrical distribution panel in the building. Table 1.4 list the physical and mechanical properties of the 310 watt photovoltaic Canadian Solar modules (CSGX) used in the PV-driven HPWH evaluation.

Table 1.4 CS6X Module Mechanical data

Cell Type	Polycrystalline, 6-inch
Cell arrangement	72 (6 x 12)
Dimensions	76.93 x 38.7 x 1.57 inch. (1954 x 982 x 40 mm)
Weight	48.5 (22 kg)
Front glazing	3.2 mm tempered glass
Frame material	Anodized aluminum alloy
Connectors	MC4

The Quartech CS6X PV modules by Canadian Solar claim the use of an innovative four busbar technology.[12] Busbars are metallic top contacts necessary to collect the current generated by a solar cell. The busbars are connected directly to the external leads. Electrical specifications of the CS6X modules are listed in Table 1.5.

Table 1.5: CS6X 301P Module Electrical Data

Electrical Data		Temperature characteristic
Nom Max Power (Pmax)	310 W	Pmax : -0.43%/deg C
Opt Operating Voltage (Vmp)	36.4 V	
Opt operating current (Imp)	8.52 A	
Open Circuit Voltage (Voc)		Voc: -0.34%/deg C
Open circuit voltage	44.9 V	
Short circuit current	9.08 A	Isc 0.065%/ deg C
Module efficiency	**16.16%**	

When integrating microinverters and photovoltaic, PV modules voltage output needs to be compatible with the voltage input range of microinverters for proper operation. The ABB 0.3 microinverter units are compatible with the output voltage range of the 72-cell (310 Wp) CS6X modules. The microinverter electrical specifications are listed in Table 1.6.

[12] Around 2002 three busbars were introduced, mainly by Kyocera and Mitsubishi. The latter decided to introduce 4 busbars a few years later and was followed by Canadian Solar. http://easysolar-app.com/en/solar-sales-tips-how-many-busbars-in-solar-cell

Table 1.6: Power One Micro-0.3-I-OUTD micro-inverter specifications

Nominal Output Power	300 W	Full Power MPPT voltage range	30-60 VDC
Max. usable DC Input Power	320 W	Maximum usable current	10.5 A (DC)
Absolute Maximum Voltage (Vmax)	65 VDC	Maximum Output current	1.25A (240 VAC)
Max. Allowed PV Rating	360W		
Startup voltage	25 VDC	Max efficiency	96.5
Operating voltage range	12-60 VDC	Standby Consumption	<50 mW

PV-Driven HPWH System Thermostat Logic

Control of the thermostat setting played an important role in the development of the PV-HPWH. Prior to building the system, a controls approach decision chart was drawn to help with initial simulation efforts which was part of a task analysis performed by NREL (T. Merrigan and J. Mcguire). Furthermore, a control strategy evolved around using a high thermostat setting (140ºF) for compressor heating when solar energy resources were available. Once the compressor reached its factory limited heating capacity (140ºF), electric energy produced by the PV and microinverters is directed to a resistive heating element in order to increase the hot water storage capacity past the 140ºF hot water levels.

A bottom heating element with external retrofit wiring (14 AWG, 600V wire) driven by its own dedicated controlled circuit (fused, 5A) was fabricated to replace the factory- installed 4500 Watt element. The internal wiring to the bottom element was electrically isolated and left unused. A feedback mechanism such as current transducers shown in the previous Figure 1.2 was utilized to measure the rate of electricity in near real time for both the PV electricity production and the total consumption of the HPWH unit. In the laboratory, this was accomplished using a watt-hour transducer (Continental Controls) via the Campbell CR10x logger/controller. As the project progressed from concept to prototype, other control strategies evolved as discussed through the remainder of the report.

2.0 Methodology

2.1 Heat Pump Operation and Controls

The GE Geospring HPWH offers 5 modes of operation (i.e., Heat Pump - Compressor only, Hybrid, High Demand, Electric and Vacation). The mode and thermostat setting of the HPWH is normally achieved via the built-in front user keypad on the unit. During testing, the HPWH was set to operate in compressor only mode where it is most efficient. Fortunately, the manufacturer of the HPWH (GE) provides a user interface input jack for communications and control via a proprietary module (i.e., Greenbean appliance module – discussed in next section). Customization of the PV driven HPWH control logic was developed to utilize as much of the compressor high efficiency operation. The PV driven HPWH was programmed to invoke thermostat settings based on the following conditions:

- Setback 120ºF (12:00 am – 8:30 am), 115ºF (8:30 to 10:30 am)
- Baseline 125ºF (resumed after 10:30 am)
- Forced Storage 140ºF (anytime PV solar resource produce greater than 290 watts)

Setback, baseline or forced storage was automated via control program based on specific time of day and PV solar electric production. The automatic baseline setting of 125ºF between 10:30 am and midnight would be maintained as long as daytime solar resources did not reach a predetermined minimum threshold. When microinverter electric energy production, as measured in near real time and averaged over 1-minute period amounted to greater than 260 Watts, a command is sent to the HPWH to raise the thermostat setting to 140ºF. This would in turn operate the compressor assuming its programmed thermostat deadband is not satisfied. The decision making to setting the thermostat to 140°F or lower it to 125°F, is continually evaluated every minute based on the averaged measured solar energy availability. The thermostat logic is presented in Figure 2.1.

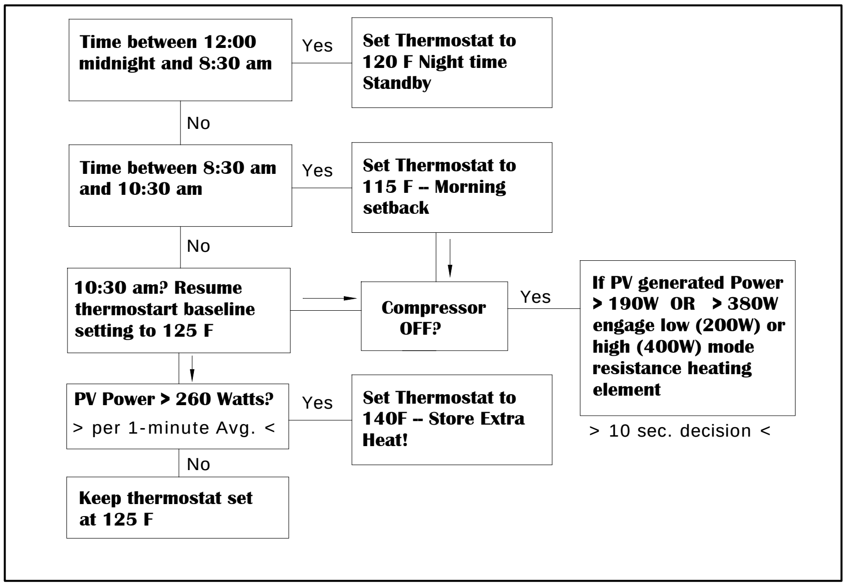


Figure 2.1: PV-HPWH Controller decision chart as tested at FSEC

2.2 Interface and Software Control

As mentioned in the previous section, automation of the varied thermostat temperature setting of 115°F morning setback up to 140°F on the HPWH was carried out via a proprietary hardware interface – Green Bean, Maker module ($19.95) marketed by FirstBuild.[13] The greenbean module (Figure 2.2) connects to a RJ-45 type port found on the front of the GE HPWH. This port is referred to by the manufacturer as the Appliance Control Module (ACM). The green-bean module was designed to interface with a variety of selected GE appliances which are listed on their website.[14] Among a list of kitchen and laundry appliances, the list also include two of their heat pump water heaters (GEHDEEDSR and GEHDEEDSC). The communications code to control appliances requires the use of a software development kit (SDK) which is supported by the Github

Figure 2.2: Greenbean controller board from Firstbuild used to communicate with GE heat pump water heater (HPWH)

[13]https://cocreate.firstbuild.com/mylescaley/greenbean-maker-module/activity/
[14] https://cocreate.firstbuild.com/greenbean/Green_Bean_Compatibility.pdf

open source development community.[15] The Raspberry Pi2 micro-controller server running a Linux operating system (Raspian) was used to host the SDK software after recommendations by a GE advanced systems engineer in Louisville, Kentucky. Further customization to the PV-driven HPWH controls software was hosted by the RaspberryPi2 server running both the SDK and JavaScript Node (JS Node). JS Node allowed the parallel communications between the proprietary SDK appliance software code and the custom controls code developed at FSEC. The process was achieved by writing to "socket" files on the on-board SD memory card (32GB) which also contained the Raspian operating system. Image files of the Raspian operating systems were obtained from the Raspberry.org which hosts a variety of essential files to run the RasberryPi2 micro controller system.

Physical communication between the green-bean module and the RaspberryPi2 server was performed via USB. The FSEC customized control software polled logic input received at the general purpose input/output pins (GPIO) of the RaspberryPi2 to make a decision of thermostat temperature setting. The actual thermostat set command sent by the SDK software via the green-bean module is performed by the transfer of hexadecimal characters temperature value preceded by the command $C as shown in Table 2.1. The hierarchy of software processes running on the Raspberry Pi2 server is shown in Figure 2.3

Table 2.1 Values passed to the HPWH by the Greenbean controller to set thermostat temperatures.

Command	Notes
C7D	Set thermostat to 125°F
C8C	Set thermostat to 140°F

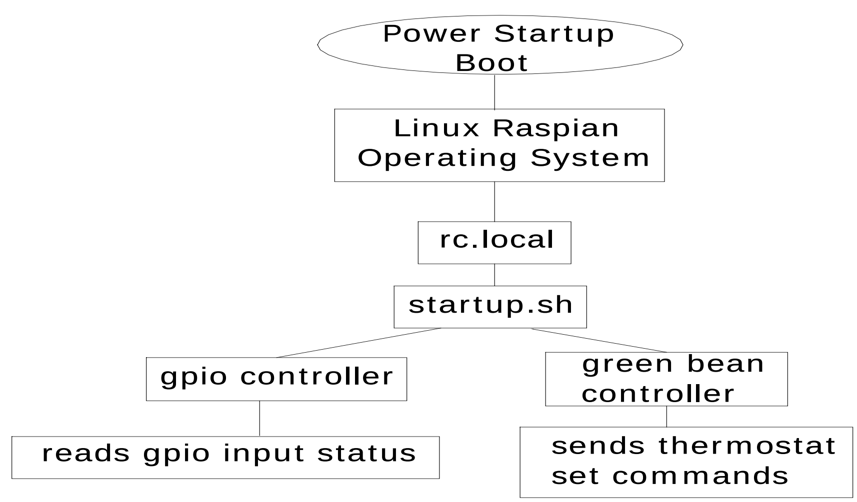


Fig x.x RaspberyPi2 operating system and script boot process

Figure 2.3 software process levels on a Raspberry Pi2 from startup to HPWH control execution

2.3 Instrumentation

Measurements and data collection at the HWS laboratory (Cocoa, FL) were accomplished by using a Campbell Scientific CR10X. Data was averaged or totalized over 1-minute intervals to help understand

[15] Gitbub Inc. states that "Millions of developers use GitHub to build personal projects, support their businesses, and work together on open source technologies". https://github.com/firstbuild/green-bean

the behavior of the controls mechanism. Data was routinely transferred and archived every hour from the data logger into FSEC's WEbGet 5.0 data base analysis tool.

Various sensors were utilized for measurements as listed in Table 2.2. Water temperature measurements at the cold hot outlet as well as the mixing valve outlet were accomplished by using differential thermocouples (Type T), ungrounded in stainless steel well probes positioned against the water stream. Mass flow of water was metered by using positive displacement flow meter with pulse output resolution of 0.145 gallons per pulse. The flow meter was installed at the cold inlet piping to the HPWH. Power measurements were made using WattNode watt-hour meters with associated current transducers. Solar radiation measurements were made with an Apogee pyranometer tilted at 25 degrees inclination from horizontal – approximately the same tilt as the PV modules during the spring and summer months.

Table 2.2 List of instruments utilized in the measurement of energy as used in the PV-HPWH prototype

Measurement	instrument	comment
Temperature	Type T thermocouple special limits	Using CR10X , differential mode
Water Mass flow	Elster positive displacement flowmeter (nutating Disc type)	Equipped with pulse output resolution 0.125 gal./pulse
Electric consumption	WattNode WNB-3D w /5A (PV) or 15A (HPWH) current Transformer	0.175 ore 0.350 resolution for 5A and 15A Current transformers
Solar radiation	Apogee SA110	0 to 2.5V output

A total of thirteen measurement data channels were archived into our experimanetal WebGet 5.0 data base designated as PVH (short for PV heat pump) The PVH data base archive account contains data beginning in February 8, 2016. The data channels are listed in Table 2.3

Table 2.3 Data channels as set in the FSEC experimental data base PVH under WebGet 5.0

Channel	Acronym	Measurement Description
1	REF107	CR10X Ref Temp 107 (C)
2	DISCHT	FAN/EVAP OUTLET AIR DISCHARGE TEMP (F)
3	HPWHOT	HEAT PUMP WATER HEATER HOT OUTLET (F)
4	HPWMIX	HEAT PUMP WATER HEATER MIXING VALVE OUTLET (F)
5	HPWCOL	HEAT PUMP WATER HEATER COLD INLET PORT (F)
6	TNK2SP	HEAT PUMP WATER HEATER TANK WALL (F)
7	NETHPW	NET HEAT PUMP WATER HEATER WATT-HOURS (WHRS)
8	FLOWGA	FLOWMETER WATER FLOW GALLONS (GAL)
9	HPWWHR	HEAT PUMP WATER HEATER WATT-HOURS (WHRS)
10	PVAWHR	PHOTOVOLATAIC WATT-HOURS (WHRS)
11	PYRNOM	PYRANOMETR WATT PER SQ. METER (W/M^2)
12	HPWBTU	HPWH HOT WATER DRAW (BTU's)
13	CRBATT	BATTERY VOLTS (V)

2.4 Testing and Evaluation

Testing the performance of the system was accomplished by a schedule of automated hot water draws representative of a typical family hot water demand. The draw schedule used was selected by utilizing an event schedule generator for residential buildings. The spreadsheet script-based software was set to generate a schedule representative of 3-bedroom home using central Florida weather (i.e., Melbourne). One daily draw schedule was selected to represent the average hot water load profile for the year. Furthermore, to simplify the criteria, a schedule with no draws between the early hours of 12:00am and 5:00 am was selected. The figure shown below (Figure 2.4**)** presents the draw schedule program into the data logger schedule of events which controlled the hot water solenoid valve. Since the test setup includes a 1.5 gallon per minute (gpm) flow regulator, consecutive draws that were separated by two minutes or less were integrated into a single event. Combined they made up of a total of 16 hot water draws during the day totaling around 52 gallons per day. The mixing valve was adjusted to deliver 125^{0}F on average.

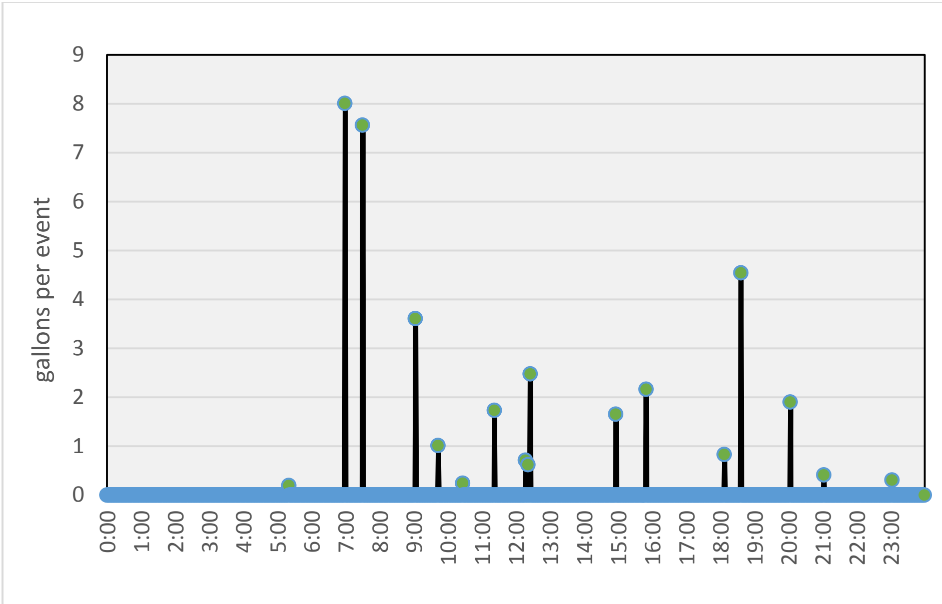


Figure 2.4: Hot water use schedule for simulation and laboratory testing

Thermal energy delivered by the system during the programed draw events was determined by calculating the inlet and mix outlet to inlet water temperature differential (ΔT) and water mass flow. The energy, as measured in 10 second intervals, was then totalized for every minute. The thermal hot water energy measured from the system is represented in the following equation:

Hot water energy (Btu's) = M Cp (T mix outlet – T inlet)*

Calculation of the overall average daily system efficiency (i.e., coefficient of performance or COP), was the derived from the measured thermal energy and electric power meter measurements. The electrical energy produced by the microinverters was metered by a dedicated power meter. This value was subtracted from the total electrical energy used by the HPWH every 10 seconds. This net electrical value was then utilized as denominator in the COP efficiency calculation as follows:

COP = thermal energy output / Net electric input

In addition to the instrumentation performed on the PV driven heat pump water heater, simultaneous operation and measurements on a 50-gallon standard residential electric water heater (EF=0.91) were performed. The standard electric water heater was submitted to the same hot water draw profile so seasonal performance could be compared.

2.5 Chronological Sequence of Events

Integration of the PV driven heat pump water components and instrumentation was accomplished during the month of January 2016. Data acquisition from sensors installed on the system to measure performance was begun in February 7, 2016. Table 2.4 shows the sequence of events that took place describing the operation and improvements made to the PV-HPWH through August 2016.

Table 2.4 Chronological events of PV-driven Heat Pump Water Heater testing.

Sequence of Events	Description	Notes
Feb. 7 – Feb. 29	Manual setting of thermostat setpoint	125°F or 140°F as noted
March 1 - March 30	Begin automated (Auto) thermostat setting: 125°F or 140°F with ACM greenbean + controller interface	Automatically changed between 125°F and 140°F depending on PV micro-inverter power production (140°F when > 302 watts injected)
April 1	Begin energy storage above 140°F via dedicated low wattage (390 W) bottom heating element control	0.75 kW resistance heat element was activated replacing 4.5 kW heat element. Lower watts accomplished via current restricted RC network.
April 19	Automated standby thermostat setting to 120°F after midnight, and 115°F 8:00 to 10:00 am followed by 125°F or 140 F depending on PV energy produced.	Morning (am) setting of 115°F to reduce compressor operation then resume after 10:30 am when solar resources are typically higher
April 25	PV modules inclination angle changed to 26 degrees from zenith	PV modules inclination angle prior to 4/25 was 52 degrees
May 5	Single wrap insulation with 0.5 inch airspace around HPWH tank shell installed	Double bubble foil type insulation (R<2.0) + 0.5 inch airspace (R = 1)
August 8	Two level electric resistance heating implemented via parallel capacitance switch (20uf, 15 uf) increase or decrease as needed.	When compressor OFF resistance heating activated at either 192W or 390W depending on solar power availability.

3.0 Results

3.1 Early Performance Results

Data archived into FSEC's experimental data base system (WEBGET 5.0) was periodically analyzed to determine the performance of the PV-driven HPWH beginning on February 7, 2016. During the first days of initial experimental testing, one of two thermostat setpoints (12^{0}F or 140^{0}F) were manually entered at the unit front keypad. Performance between the baseline thermostat setting of 125^{0}F was compared to a higher 140^{0}F setpoint. During the last two weeks of February the thermostat was set at 140^{0}F during workdays then to a lower setting of 125^{0}F at the end of Friday, lasting throughout the weekend. Automation of the thermostat setpoint was not put into operation until March 1st. Figure 3.1 is a representation of the daily performance obtained from February 7 through 29th. Analysis of data indicated resistive heating element (4.5kW) activation during three days in February (8th, 10th and 11th day), represented by the red-colored bars on the plot. During two consecutive days, average morning low temperatures reached down to 44^{0}F and 41^{0}F respectively. Furthermore, laboratory notes indicated that the heat pump water heater thermostat temperature was also set to the highest setpoint at 140°F. Yellow and blue bars indicate manual setting of thermostat at 140^{0}F and 125^{0}F respectively. For reference on solar resources, the dotted line indicates the daily moving average integrated daily solar radiation (Wh/m^2/day).

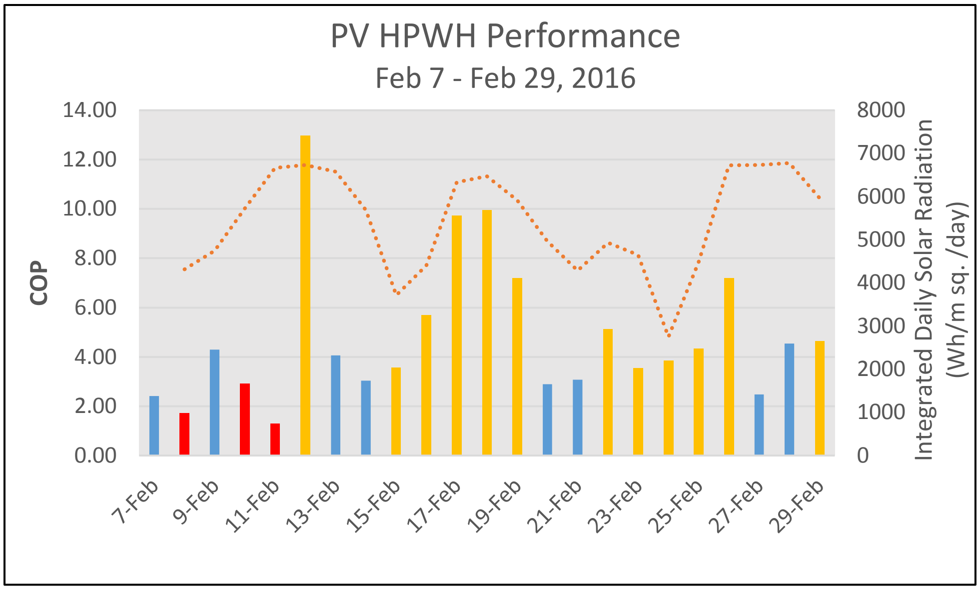


Figure 3.1: Coefficient of performance of a PV-driven Heat Pump Water Heater for the month of February 2016, Cocoa, FL.

Efficiency (COP) of the system is compared in Table 3.1 during February, for a number of days (n) at 125°F and 140°F thermostat settings. It is also averaged for those thermostat settings while ignoring the PV contribution. The impact on efficiency for those days where the electric resistance heating was briefly energized led to an average COP of 1.29. The average solar radiation for those days can be compared in the right-most column. Higher COPs are generally obtained with the 140°F setting due to the length of run time coinciding with higher solar resources as they increase during the day.

Table 3.1 Heat Pump operating efficiency compared in February with two thermostat settings.

		PV driven HPWH		Ignoring PV Contribution		Solar Resources
Thermostat setting	**Sample # of days (n)**	**Avg. Net Electric consumption kWh/day**	**PV driven HPWH COP**	**HPWH Electric consumption kWh/day**	**HPWH COP**	**Avg. integrated Solar radiation kWh/sq.m./day**
125°F	8	2.38	3.17	3.41	2.21	5.30
125°F w/part resistance Heat	3	4.53	1.77	6.20	1.29	5.98
140°F	12	1.39	5.54	2.97	2.59	5.31
All Feb	**23**	**2.14**	**3.58**	**3.54**	**2.17**	**5.40**

Beginning on March 2016, the system was upgraded to autonomously change the thermostat setting from 125°F (baseline) to 140°F depending on the power produced by the PV/microinverters. The thermostat setting was triggered by a minimum PV power threshold of 260W as averaged over one minute.

At the end of March 2016, the HPWH bottom heating element was replaced with that of a lower wattage (750 W). Resistance for a typical 240 VAC 4500Watt heating element is usually in the order of 12.8 ohms, where a heating load runs about 18 amps as shown in Table 3.2. The Table also shows the current values of the 750 Watt resistance heating element when powered at 240 VAC.

Table 3.2: common resistance heating element and their electrical properties

Heat element wattage (W)	Resistance – Ohms (Ω)	Current (A) @ 240 VAC
750	76.8	3.1
3800	15.2	15.8
4500	12.8	18.8
5000	11.5	20.8

The 240 VAC - 750 Watt heating element was the lowest wattage commercially (readily) available heating element found. This wattage value is still above the highest power that could be produced by the 620-Watt pair of PV and microinverters. As a result, a simple electrical circuit utilizing the resistance-capacitance (RC) network concept was implemented. Medium voltage (260-400VAC) plate capacitors, widely used in the HVAC industry for fan motor and compressor start applications, are available at a fair cost. Table 3.3 shows a list of electrical parameters, for various capacitors in series with a 76 ohm resistance heating element. The list shows the calculated capacitive reactance (Xc) circuit impedance (z), power factor (PF), current phase (Φ), current amps and dissipated power in watts.

Table 3.3 Resulting power for a 75-ohm series RC network and respective capacitive reactance values

Capacitance (ufd)	Capacitive Reactance (Xc) Ohms @ 60 Hz	Impedance (Z) Sqrt ($Xc^2 + R^2$)	PF (R/Z) Cos Φ	Φ deg. (current leads voltage)	Current I@240VAC	Power dissipated watts
20	132.6	152.3	0.49	60.5	1.58	186.0
22	120.6	141.9	0.53	58.2	1.69	214.1
24	110.5	133.5	0.56	55.9	1.80	242.0
26	102.0	126.6	0.59	53.7	1.90	269.3
28	94.7	120.8	0.62	51.7	1.99	295.8
30	88.4	115.9	0.65	49.7	2.07	321.3
32	82.9	111.7	0.67	47.9	2.15	345.7
34	78.0	108.2	0.69	46.2	2.22	368.8
36	73.7	105.1	0.71	44.5	2.28	390.8

During April 2016 a single value capacitor (30 uf) was used initially in the RC network. It eventually progressed into a two-stage power heating element in August 2016 by switching the two capacitors as needed. Capacitor values were chosen as 20 and 15 uf resulting in about 192 watts and 396 watts with 240 VAC, when switched as single (20 uf) or paralleled (35 uf) by a power relay circuit. The LTSpice schematic and simulation shown in Figure 3.2 shows the circuit Voltage and current transfer when switched from 20 uf (192 watts), then adding 15 uf to the circuit for a total of 35 uf (396 watts) when connected in series with a 75 ohm resistance heat element.

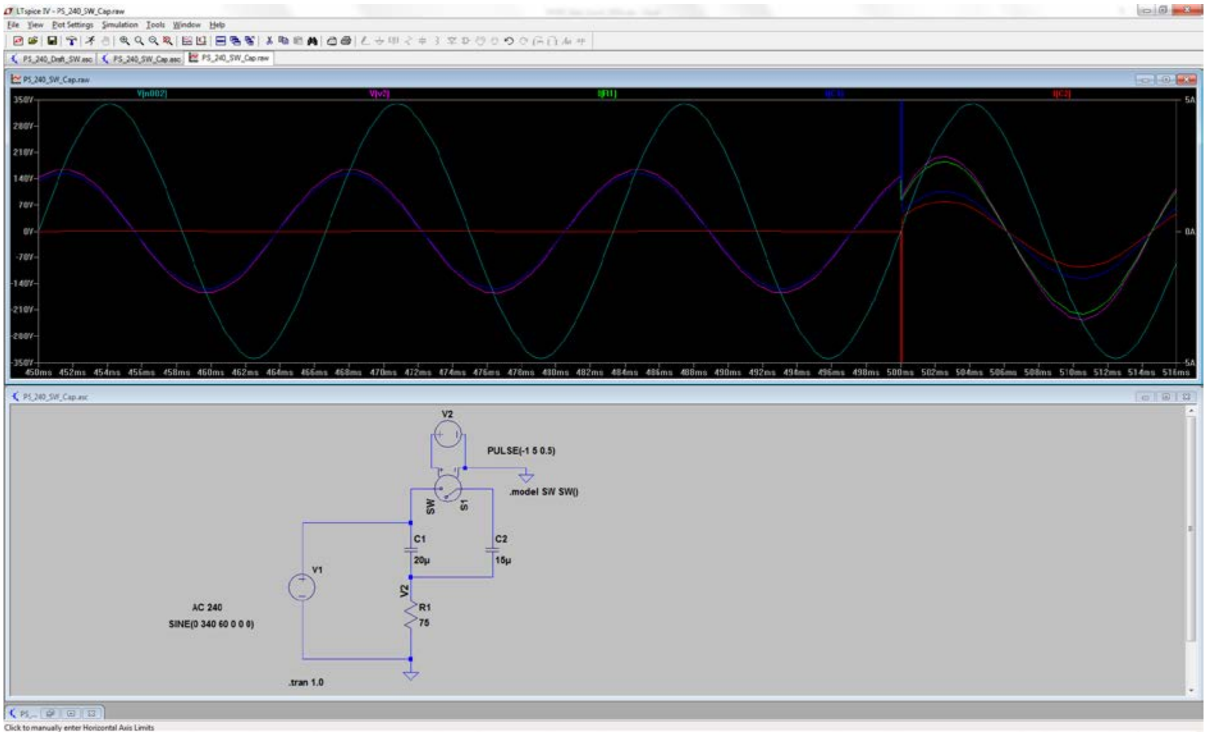


Figure 3.2: Schematic and simulation of RC network used for the two-stage heat element.

3.2 Monthly and Average Daily Results

Figure 3.3 indicates the COP efficiency of the PV-drive HPWH as the optimization of control details progressed the plot indicates the average monthly efficiency of the unit throughout the testing periods.

As Figure 3.3 indicates, the auto thermostat setting feature was begun in March and the added electric resistance heating in April 15. The dip in efficiency data seen in June was likely due to overcast days and rain typical of Florida weather where on average 4.6 kWh/m^2/day of integrated solar radiation was measured, compared to 5.5 kWh/m^2/day in July.

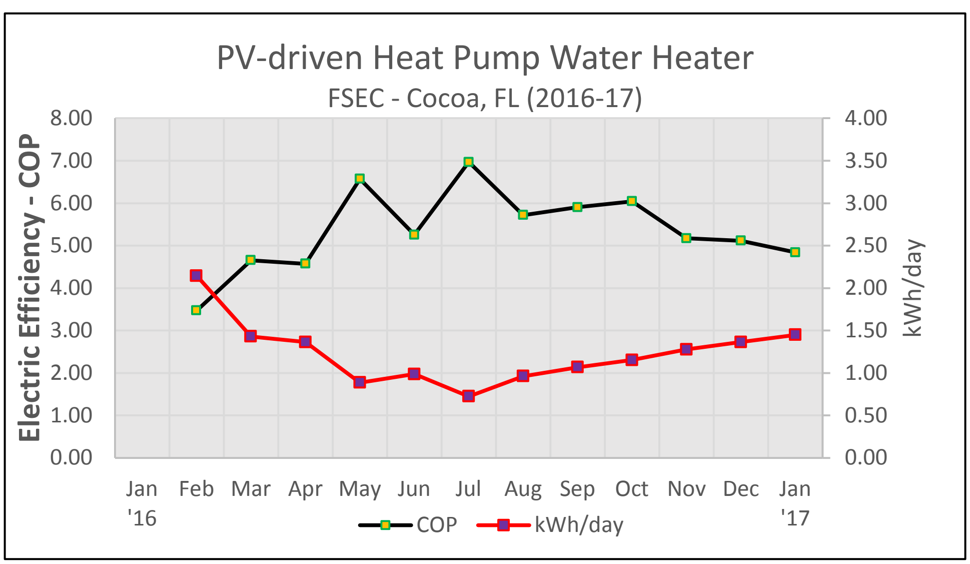


Figure 3.3: Monthly Coefficient of performance and average daily electricity used by the PV-HPWH.

A summary of the total monthly hot water energy output delivered (and equivalent kWh's) and total electricity used is provided in Table 3.4. Columns on the right indicate the average daily hot water energy delivered and electric net energy input.

Table 3.4: Summary of monthly energies and average daily energy data as measured from the PV-HPWH

Data	Month	Monthly Total		Total Net Electric Input	Daily Hot water Delivered		Avg. Net Daily Electric Input
Days		BTU	kWh	Whrs	Btu	kWh	kWh
n/a	Jan						
23	Feb	584737	171.2	49307	25423.3	7.44	2.14
30	Mar	681897	199.7	42874	22729.9	6.66	1.43
30	Apr	596208	174.6	38179	19873.6	5.82	1.36
31	May	616222	180.4	27456	19878.1	5.82	0.89
30	Jun	530768	155.4	29565	17692.3	5.18	0.99
31	Jul	534092	156.4	22446	17228.8	5.04	0.72
31	Aug	581874	170.4	29791	18770.1	5.50	0.96
30	Sep	645706	189.1	32031	21523.5	6.30	1.07
29	Oct	679345	198.9	32915	23425.7	6.86	1.15
30	Nov	676760	198.2	38312	22558.7	6.61	1.28
31	Dec	714974	209.3	40917	23063.7	6.75	1.36
30	Jan	726316	212.7	43930	24210.5	7.09	1.45

3.3 Side by Side Comparison to Standard Electric Resistance Water Heater

The bar type plot in Figure 3.4 compares the average daily electric consumption (kWh/day) of a standard 50-gallon electric water heater against the 50-gallon PV-HPWH as they operated side-by-side in the laboratory through January 2017. Figure 3.5 compares the average daily hot water gallons as they measured during the course of the evaluation. Note that beginning in August 2016 the total daily quantity of hot water deviated substantially for the PV-HPWH, where the problem was corrected at the end of October. Inconsistent operation from a solenoid valve was found to cause the discrepancy.

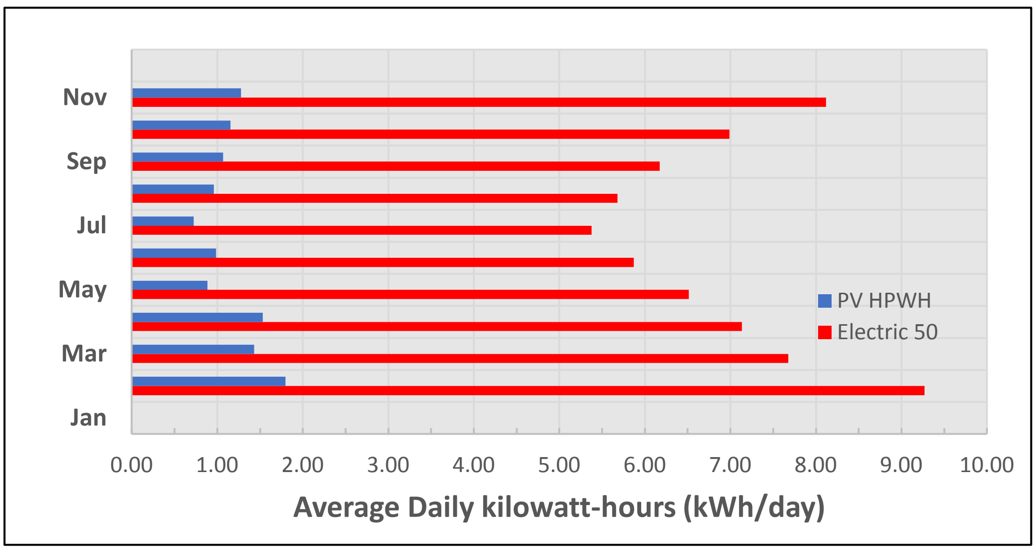


Figure 3.4: Averaged daily electric consumption by month for a standard 50-gallon water heater vs the PV-HPWH in Cocoa, FL.

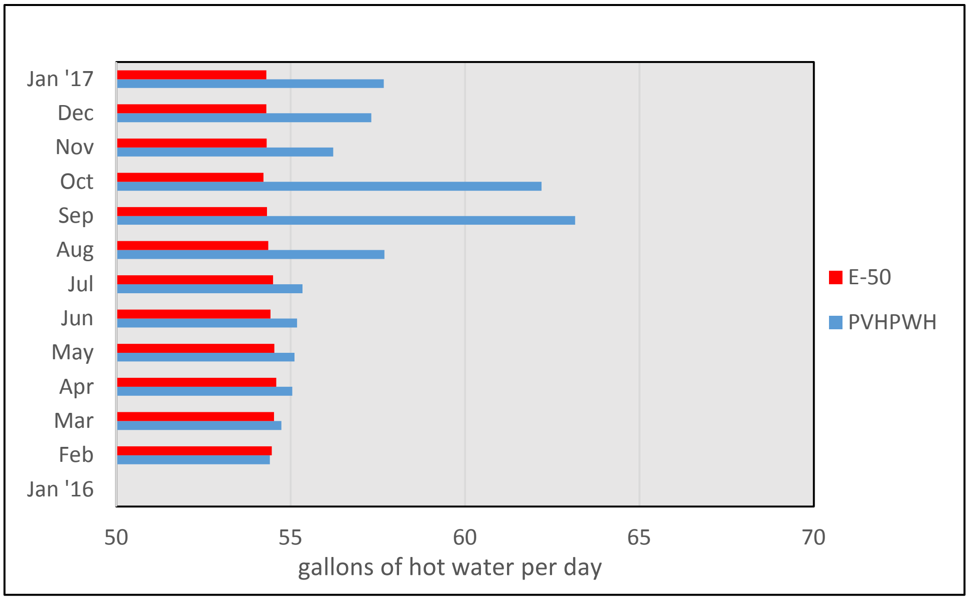


Figure 3.5: Average hot water gallons drawn per day by month.

3.4 HPWH Added Insulation Layer

Figure 3.6: Foam rings applied prior to tank shell insulation layer

On May 5, 2016 the 50-gallon HPWH was outfitted with a single layer of double wrap "bubble wrap" insulation which features metallic foil type layer on both sides. The wrap insulation covered the exterior wall of the tank from a height of about 48" below the controls input panel to the floor. The insulation layer was installed using two half-inch (1/2") weather strip foam rings applied around the circumference of the tank (Figure 3.6), leaving an airspace between the outer tank shell and the double bubble wrap. The wrap material is made of a reflective material with total R-value of about 2.04, assuming a perfect assembly and no dust on the reflective outer surface. The R-value was derived (not tested) by adding a half-inch air space insulation value (vertical) to published laboratory results (R=1.01) as reported in a on-line document reporting on this type of insulation (Reflectix). [16] [17] The ASHRAE handbook of fundamentals list an R-value of 2.03 for vertical airspace (1/2") having an effective emittance of 0.05 with a mean temperature of 90^0F and temperature differential of 10^0F. [18]Data was analyzed for the overnight period of May 3rd and May 4th, 2016. It included a period of 6.3 hours between 23:03 pm (last draw of day) and 5:21 am (first draw) of the following day. Table 3.5 is a summary of finding leading to the conclusion that heat losses (U) were reduced from 5.65 to 5.25 Btu/hr-F. Temperatures shown were those recorded during the 1-minute interval, as measured during the schedule hot water draws

Table 3.5: Data used for the pre and post wrap insulation layer heat loss analysis.

[16] http://www.greenbuildingadvisor.com/blogs/dept/qa-spotlight/bubble-wrap-duct-insulation-good-idea
[17] http://www.greenbuildingadvisor.com/community/forum/energy-efficiency-and-durability/30705/why-reflective-insulation-still-being-sold-hd
[18] Heat , Air, and Moisture Control in Building Assemblies – material properties, Table 3 ASHRAE

	No Wrap Insulation	After Wrap Insulation
Hot temp prior to standby (5/3/16 23:03 pm)	135.0 □F	134.2 □F
Temp after standby (5/4/15 5:21 am)	130.1 □F	129.1 □F
Overnight Hot water temperature loss (ΔT)	4.9 □F	5.1 □F
Ambient to tank temp differential (ΔT)	57.27 □F	64.27 □F
Losses (BTU/hr).	324	377
U (Btu/hr F)	5.65	5.25

4.0 Analysis

As mentioned previously the GEH50DEEDSR (Geospring 2012 model) HPWH is rated at 600 Watts. However data indicates a linear increase in power consumption based on hot water storage temperatures as observed with a thermostat setpoint of 140^{o}F. As an example, data during the month of February in Cocoa, FL routinely indicated 430 watt power consumption at startup following morning draws, and reaching 540 watts at the end of operation with a 125°F thermostat setting. However during peak summer days, when the full control to make use of extended storage temperatures was implemented, power consumption routinely began at 580 watts and reaching as high as 707 watts.

A data plot describing the flow of electric energy and daytime operating performance of the PV-driven HPWH during summer is shown in Figure 4.1. The one-minute data is multiplied by sixty converting the y-scale into instantaneous system wattage perspective. The red data points indicate hot water temperatures into the mixing valve due to scheduled hot water draw activity. The yellow curve beginning after 6:00 am in the morning and tapering through 6:30 pm depicts the combined electric production of the two microinverters and associated 300Watt PV modules. During this particular summer day, compressor heating was activated at 7:38 am for only about ten minutes (orange data points). The storage tank had enough hot water stored from previous day to stop heating activity via compressor, since the thermostat setting at that time of day is set at 120^{o}F. Immediately following compressor shutdown, electric resistance water heating begins after 7:39 at a rate below 200 Watts by the lowest level stage of the heating element. The system thermostat is then changed to 115^{o}F at 8:30 am to attempt delay of heating recovery by compressor until solar resources are stronger, typically after 10:30 am.

However, at 9:08 am compressor resumes heating due to the impact of hot water use in the morning, as it can be observed hot water temperature outlet is reduced below 125^{o}F. Compressor shuts down at around 11:28 am at the time is satisfied based on thermostat setting of 140^{o}F. Resistance then resumes at 400 Watts momentarily reducing to the lower heating stage (192 W or less) during cloud passages. At around 3:52 pm the level of power being produced by the microinverter can no longer support the 396 watt load of the heating element highest stage and drops down to 192 watts, until it drops in and out through 5:20 pm. The net electric consumption or grid electricity used by the PV-driven system is plotted and represented by the green line. The unused power produced by the PV/microinverters and injected into the grid is plotted in blue –color below the horizontal x-axis shown as negative y-axis values. During this day, 10.7% (0.363 kWh) of the PV/micro-inverter electricity produced was fed into the grid.

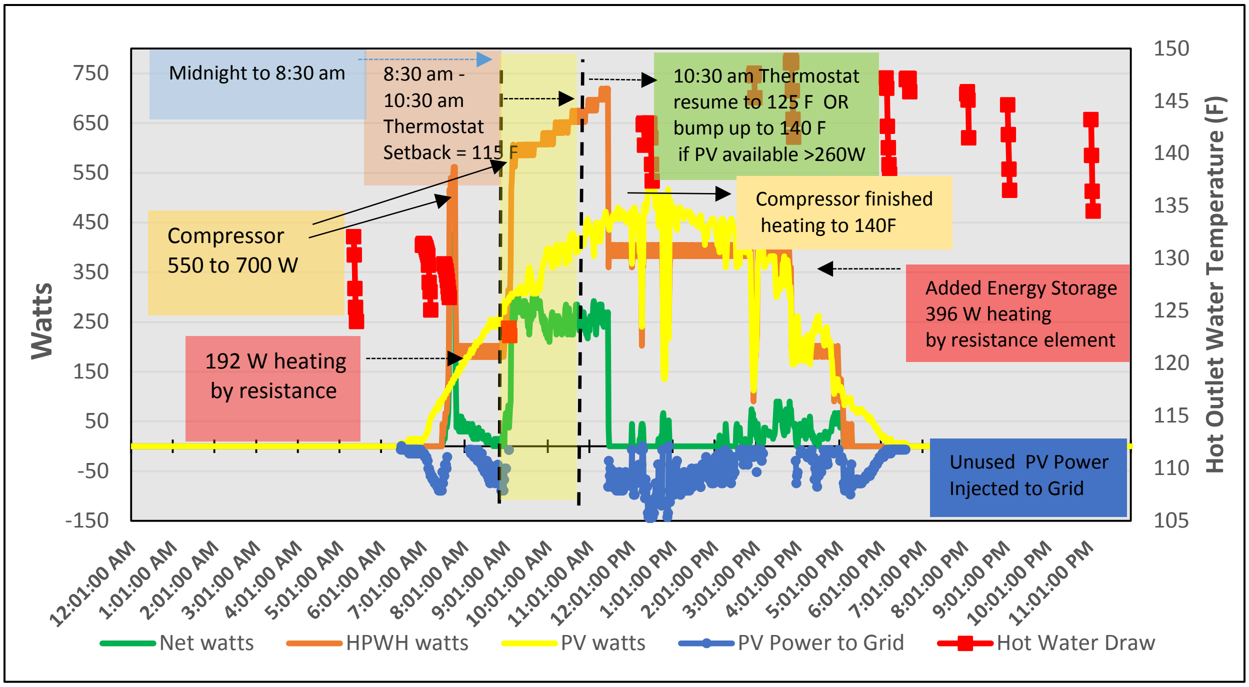


Figure 4.1: Typical operation example of the PV-HPWH as controlled by time of day and solar resources on August 23rd, 2015

4.1 Electricity generated by PV and Micro-inverter modules

Electricity generated by the two 310Wp PV modules and associated microinverters was measured by a dedicated power meter in-line to the electrical distribution panel. The total daily electricity produced by the two microinverters amounts to 2.86 kilowatt-hours on average. The average daily electricity produced by the micro-inverters as it varied by month can be observed in Figure 4.2.

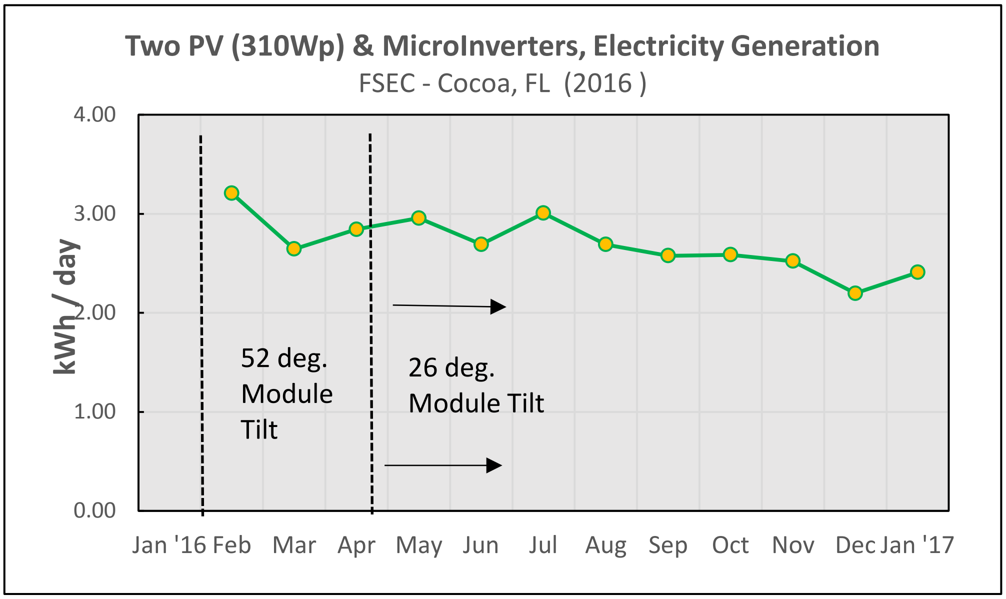


Figure 4.2: Electricity generated by two PV modules (620Wp) and two microinverters as measured in Cocoa, FL through August 2016.

As mentioned earlier, the PV modules were initially set to a tilt angle of 52 degrees from zenith. On April 25, 2016 the tilt positioning angle was adjusted on the exposure rack to 26 degrees from zenith. The effect of tilt angle and effects on overall efficiency of the PV and microinverter can be observed in Figure 4.3. Efficiency was calculated by using total PV solar collection surface area of 3.63 square meters (m^2). However the solar radiation sensor was fixed at a tilt of 26 degrees. Regardless of the solar radiation sensor adjustment, the plot illustrates the range of efficiencies obtained and the drastic change detected when the tilt angle was moved in April 2016. The negative slope of data points reflect the effects of the sun angle as it passes from spring equinox to summer solstice in Florida. The dark circled data points show temperature extreme effect on coldest and hottest days, where the temperature coefficient of the PV modules reduces current production.

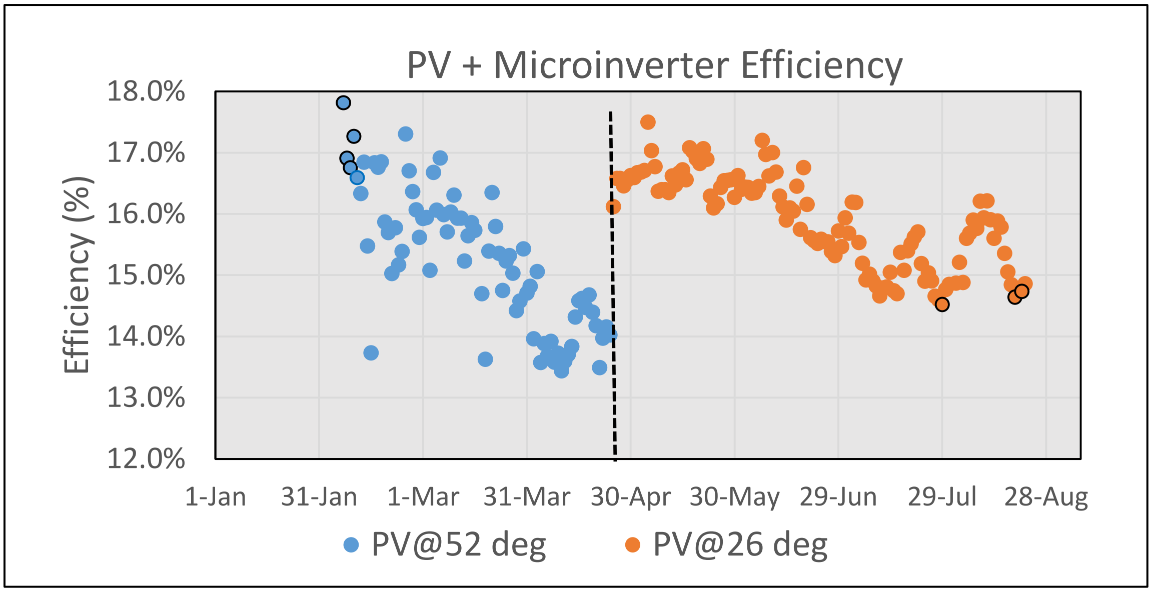


Figure 4.3: PV module efficiency showing a difference when tilt angle was adjusted from 52 and 26 degrees.

4.2 Single vs Two-Level Electric Resistance heating

Water heating was further improved by selecting from a two-level load of the heating element resistance-capacitance (RC) network at the beginning of August 2016. The two-level resistance heating was implemented either at low level heating (192 Watts) or a higher level at around 390 watts depending on the microinverter power generated as measured in real time every ten seconds. Minor power variation also depends on the grid voltage and heating element resistance changes at various time of day where the power can be slightly higher or lower. Figure 4.4 shows two data periods representing single level resistance heating (red data points) and the two level auxiliary resistance heating (black data points) after the change was implemented.

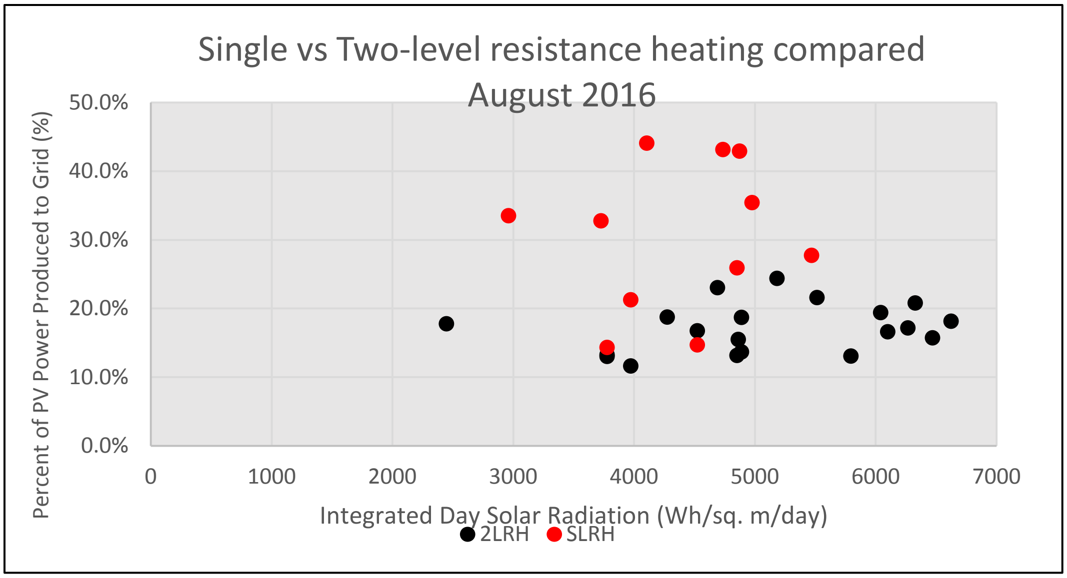


Figure 4.4 Comparison of net power used by the PV-HPWH comparing pre and post two-level heating element.

Data points indicate a tighter cluster of daily performance for those days where solar integrated radiation totaled between 3000 and below 5000 watt-hours per square meter. The y-axis indicate the percentage of total daily energy as measured from the micro-inverters that is not utilized for water heating and injected into the grid. The low level heating was used to address early morning and late afternoon low levels of solar radiation conditions and heating opportunity during cloud passages. To accomplish zero grid interaction, 100% of the energy should be used to heat water making the PV/micro-inverter with HPWH a behind the meter system with no net metering implications. The concept is being further investigated to allow implementation into microinverter design by the power electronics group at the University of Central Florida (UCF). The concept of no grid interaction would require feedback from the appliance to the micro-inverter as demonstrated in this project.

4.3 Thermal Storage

As mentioned throughout the report, the PV-driven HPWH is utilized as an efficient mechanical system for thermal storage by extending its compressor runtime past the baseline thermostat setting of 125^0F towards 140^0F hot water. The actual volume of hot water, as measured during initial fill-up, reveal that the 50-gallon HPWH storage tank totaled slightly less at around 48 gallons. The extra thermal energy stored in the storage tank by the compressor, considering the baseline of 125^0F to 140^0F temperature difference (6009 Btu's) is the equivalent of 1.76 kilowatt-hours (kWh). Temperatures shown in Figure 4.5 for the month of May 2016 indicate a further increase in thermal storage (past 140^0F) by the bottom resistance heat element activation.

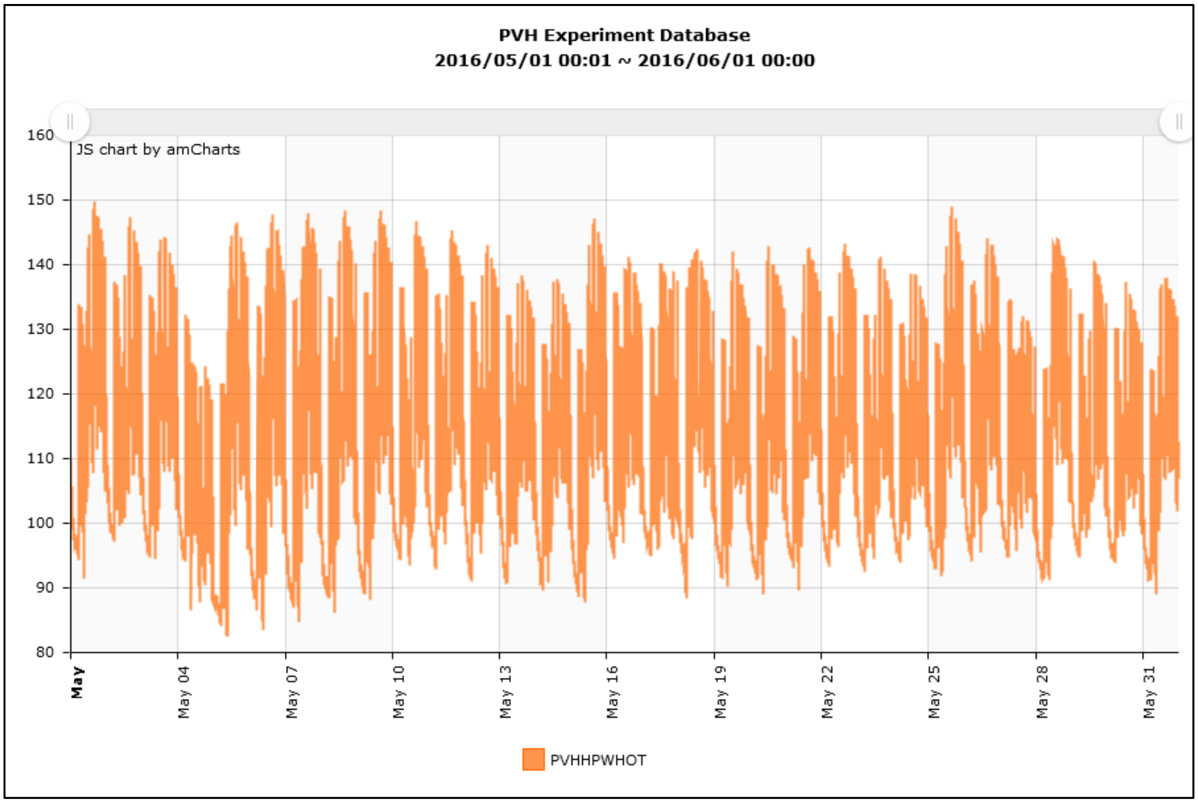


Figure 4.5: Hot outlet port temperatures recorded by the PV-driven HPWH in Cocoa, FL during the month of August 2016. Y-axis scale shown in degrees Fahrenheit (^{0}F).

A data query using our analysis web-based software (GET 5.0) was performed to determine the average daily one-minute temperatures representing each month. The query was process using filtering capabilities for those intervals where the temperature of hot water stored exceeded 140^{0}F. The resulting averaging of one minute data interval where elevated temperatures are easily distinguished where hot water draw events took place. The right column on Table 4.1 is a count on number of days for each month where stored temperatures exceeded 140^{0}F hot water due to extra energy stored from the resistance heating element. The left columns display the results by month, indicating the maximum hot outlet temperature recorded and the daily average for the minute where temperatures peaked. The maximum hot water temperature value usually appeared as a result of the 3:59 pm afternoon draw event.

Table 4.1 : Record of monthly average extra energy storage above 140 ^{0}F by electric heating element

	Maximum Hot outlet temperature recorded (F)	**Average Max Hot Water Temperature for days above 140 □ (F)**	**Equivalent Extra storage Energy above 140□F (kWh)**	**# Days in Month reaching over 140□F and percentage of instance for Month (%)**
April	147.67	143.5	0.407	19/23 (82.6%)
May	149.71	145.1	0.604	23/31 (74.2%)
June	147.49	143.4	0.394	16/30 (53.3%)
July	148.75	146.1	0.721	27/31 (87.1%)
Aug	149.81	144.2	0.496	27/31 (87.1%)
Sep	147.24	143.3	0.387	23/30 (76.7%)
Oct	146.26	142.5	0.293	15/24 (62.5%)
Avg		**144.0**	**0.472**	**150/200 (75%)**

It is concluded in the above analysis case that the added energy stored is at least the equivalent of 2.16 kWh per day – not counting standby losses. The thermal energy storage is achieved by adding the compressor energy storage past the baseline 125^{0}F (1.76 kWh) and the electric resistance heating element (0.472 kWh/day) past the 140^{0}F, but only on for 75% of the days that data was collected in Cocoa, Florida.

On the subject of minimum comfortable hot water temperature delivered, Figure 4.6 plots the hot outlet and mixed outlet temperatures as measured present at the mixing valve. Since data was recorded at one minute intervals, it represents an accurate indication of temperatures at time of hot water draw events as shown by the peak values.

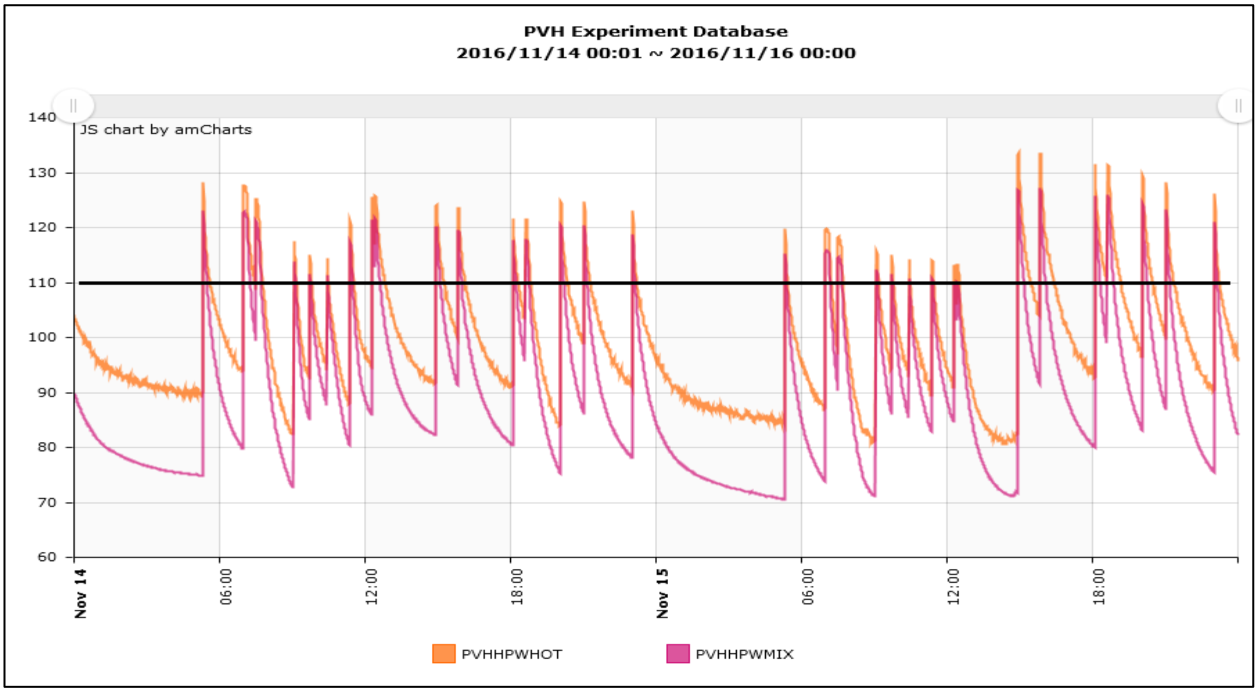


Figure 4.6: Hot outlet and mixed outlet delivered temperatures for two low solar radiation days consecutive days in November 2016

The hot water temperatures during November 14-15 were selected for scrutiny because they represent a period of two consecutive days experiencing low daily integrated solar radiation – 1279 and 1943 Whrs/m^2/day respectively. On those two days a system COP performance of 3.0 and 3.5 was measured, being the lowest recorded for that month. The plot includes a reference line (black) representing what is considered the lowest desirable temperatures to be delivered by the system into a residential hot water distribution lines. The reasoning being a loss of 5^{0}F between hot water tank and point of use would leave 105^{0}F for a comfortable showering level. The lowest temperatures delivered appear at 10:27 am (111^{0}F) the first day and at 12:30 pm (110^{0}F) the second day, but not during the early morning hours where it would be most critical in terms of comfort. More data is to be analyzed in near future as the winter season progresses and the most critical data is yet to be collected.

4.4 Time of Day Performance

The time of day electric demand shown in Figure 4.7 was generated by integrating one-minute data and averaging hourly over the period of February and October, 2016. The plot compares the electric demand of a standard 50 gallon water heater (EF=0.91) simultaneously ran in the laboratory with the PV driven heat pump water heater.

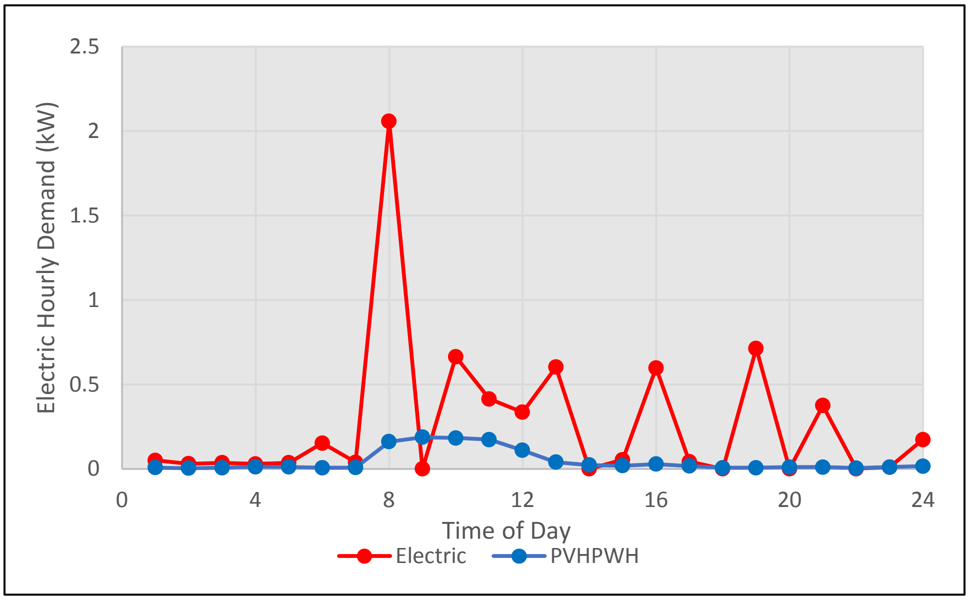


Figure 4.7: Hourly demand profile for a laboratory 50-gallon electric water heater compared to the PV-HPWH prototype (February thru October 2016).

The bar plot Figure 4.8 represents the maximum percentage (%) of electric demand reduction as measured in Cocoa, Florida, for the hot water load imposed (59 gal/day).

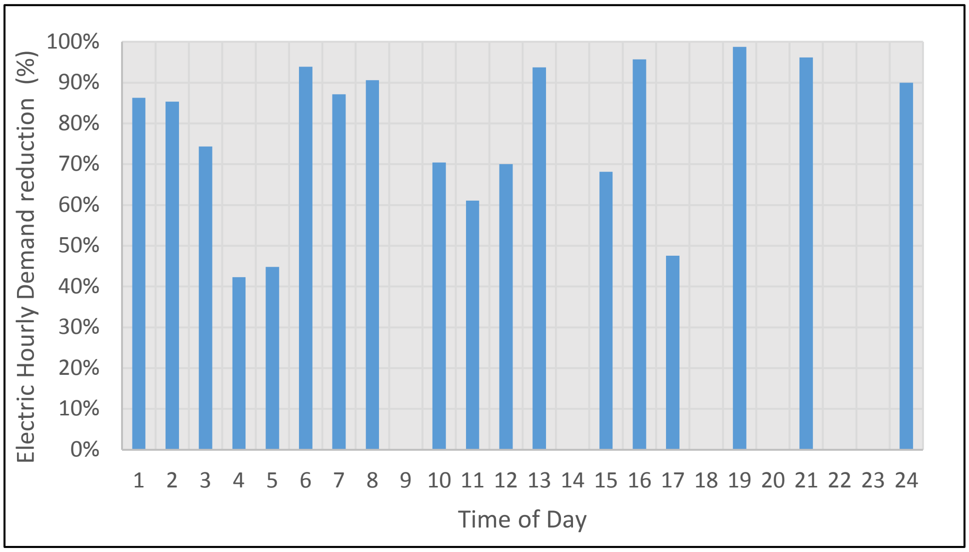


Figure 4.8: 50-gallon electric resistance water heater vs PV-driven HPWH hourly peak demand reduction demand (February thru October 2016).

However, the demand of a larger sample of water heaters with standard electric resistance heating elements used for this region (4500W), is better diversified due to times and much faster rate of recovery. Figure 4.9 compares the diversified electric water heating demand for 60 homes in Brevard County, Florida to the single PV-HPWH prototype. Similarly Figure 4.10 compares the electric water heating demand profile in Hawaii to the single PV-HPWH prototype demand profile.

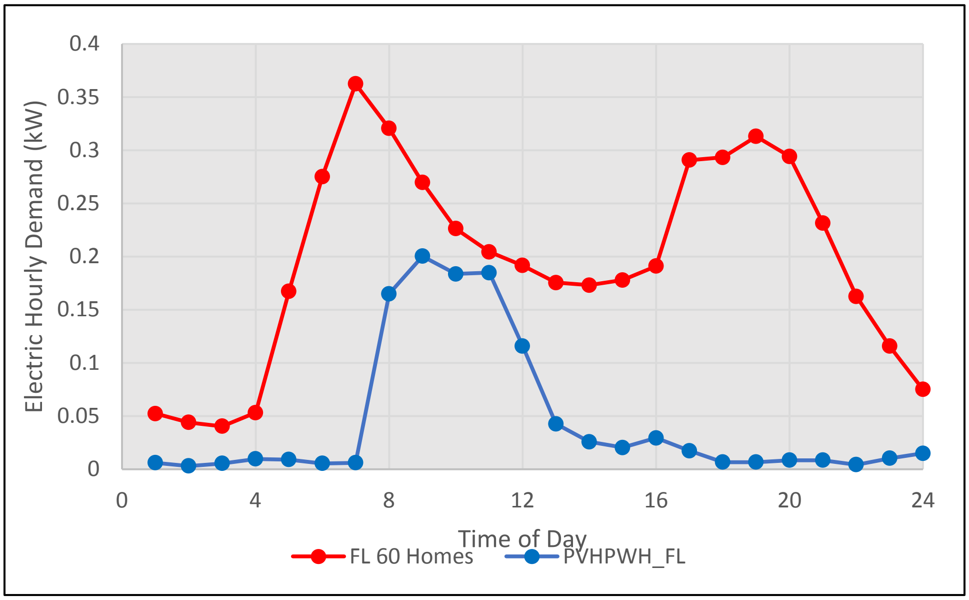


Figure 4.9: Hourly demand for water heating from 60 homes in Brevard county FL (2014) plotted against the PV-HPWH reduction demand (February thru October 2016).

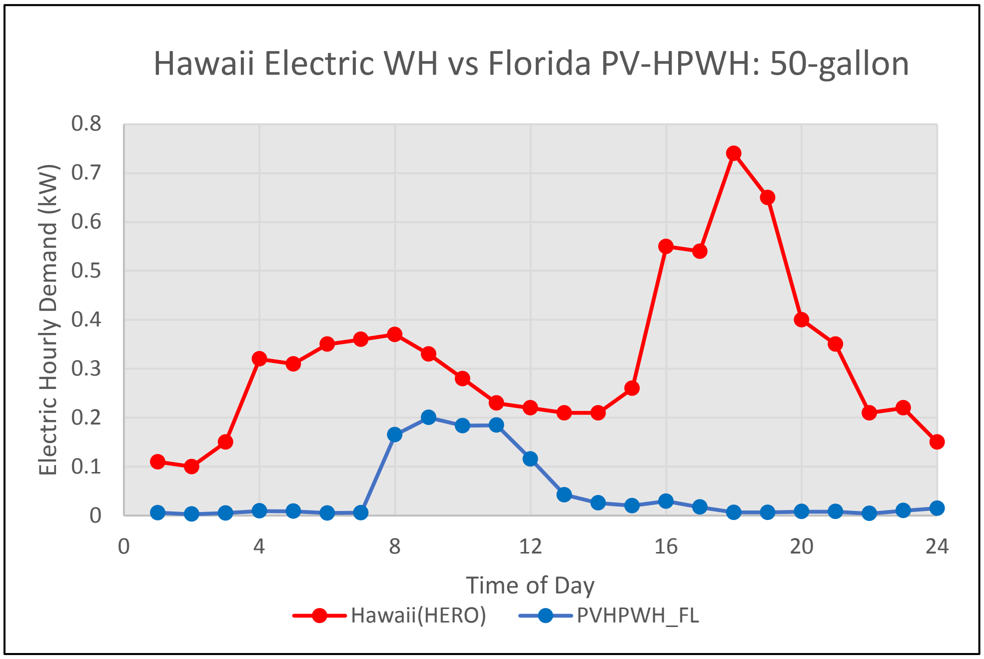


Figure 4.10: Hourly demand for residential water ehating in Hawaii (source HERO) as it compares to the PV-HPWH

4.5 Economic Analysis

The PV-driven HPWH prototype integrates a variety of components which costs can be further reduced in mass scale production by a water heater manufacturer. For the purpose of a simplified economic analysis, the retail cost of those component items purchased is utilized. Table 4.2 list the single-quantity cost of major components that make up the PV-driven HPWH.

Table 4.2 itemized list of component costs that make up the PV-driven HPWH

Component	Model	Price/Unit	Cost
Heat pump water heater	GE GEH50DEEDSR GeoSpring	$999	$999 (shipping included)
PV modules x 2	Canadian Solar Quartech MaxPower CS6X-310P	$241.80 each ($0.78/watt)	$483.60
Microinverter	ABB Micro-0.3-I-OUTD, 300W	$147.52 each ($0.54/watt)	$295.04
Anti-Scald (Mix) Valve	Honeywell AM-101 Thermostatic Valve ¾”	$80	$80
PV wire trunk cable	ABB AC-Trunk	$18.08 (portrait)	$36.16
Resistance heating element	#Grainger 2E458	$12.22	$12.22
Subtotal			**$1906**

Table 4.3 lists all controller and power switching related devices that were used as interface or retrofitted into the system.

Table 4.3 itemized list of component costs for add-on power and interface controllers.

Component	Model	Cost ($)
Appliance Interface Module	Green Bean, maker module firstBuild (GE)	$19
Micro-Controller Processor	Raspberry Pi2 (Adafurit)	$39.95
Micro SD card 32 Gb	SanDisk SDHC Class10	$14.95
Intranet Interface wiring	Cat 5 type cord (7 ft.)	$5
Current transducer	Continental Controls	$32
20 & 15 ufd Run capacitor 370VAC	370VAC	$30
Relay Control Kit	Sparkfun kit 11042	$5.95
Subtotal		**$147**

The total system equipment retail cost amounts to $2053. However, in the event a manufacturer integrates some of the redundant controller items listed in Table 4.3, the system equipment cost could easily be under $2000 (retail).

Adding a theoretical up-charge cost of $1000 for installation, would position the total installed system cost at around $3000 well into the market. The $2053 total parts dollar amount indicates a $1625 cost increment relative over a standard electric resistance 50-gallon water heater[19]. Table 4.4 indicates the simple payback of cost of the system and total installed cost of the system for two cases: Florida ($0.12/kwh) and Hawaii ($0.25/kwh) which differ largely in cost of kilowatt-hours residential rate.[20] A daily electric use of 7.6 kWh per day for a standard electric water heater is used in the analysis which is realistic for both Florida and Hawaii climates[21] A cost increment of $100 is added to the Hawaii case analysis to allow for shipping of PV modules due to geographical location outside continental U.S. bringing the total equipment only cost to $2153. The cost for a 50-gallon HPWH appears the same ($999) as verified by pricing on-line under a Honolulu home improvement retailer website.

[19] For example, $428 for a premium 9-year Rheem 50-gallon electric water heater as priced on-line, Home Depot, FL store on 10/2016.
[20] Based on residential Hawaii rates for Oahu as of October 2016 (https://hawaiienergy.com/about/get-the-facts#1).
[21] A 7.6 kWh/day value was estimated by integrating the hourly demand for water heating in Hawaii from the report “Estimating the Opportunity for Load-Shifting in Hawaii: An Analysis of Proposed Residential Time-of-Use Rates” UHERO, August 2, 2016 (Figure 7, page 15).

Table 4.4: Actual cost and payback analysis of a PV-driven HPWH in Florida and Hawaii

	Florida Retail Cost ($)	Year Savings kWh @ $0.11	Simple Payback (years)	Hawaii Retail Cost ($)	Year Savings kWh @ $0.25	Simple Payback (years)
Equipment only	$2053	$251.7 (2288.5 kWh)	8.1	$2153	$571.4 (2321.4 kWh)	3.8
Complete Install	$3053	Same as above	12.1	$3153	Same as above	5.5
Complete Install over cost increment Electric WH	$3053 - $428	$251.7	10.4	$3153-$428	$571.4	4.8

As shown in the simple payback column for Florida and Hawaii, the PV-driven HPWH looks very attractive with a short payback of 12.1 and 5.5 years respectively for a complete install. The period is lowered to 10.4 and 4.8 years if the cost incremental over the standard electric water heater only is used in the analysis. Furthermore, PV modules and inverters may be operating past the life of the HPWH, which in case could be re-used in the next HPWH replacement say after 10 years, lowering the overall cost of water heating over a 20 year period.

4.6 Follow-up Work

Development of a PV-driven HPWH concept has led into a ultra-high efficient, smart and reliable water heating appliance in the laboratory. Some of the most notable and interesting improvements such as two-level auxiliary resistance heating and morning thermostat setback features were implemented during the latter months of the contract period. It is in the interest of FSEC and the research community to continue performance data collection to complete a full year of performance through February 2017 at the least. Smart thermostat control interface was begun in March 1st, 2016 and optimization with two- level auxiliary resistance heating feature was begun in August 2016. Extended data collection through the winter and summer of 2017 would yield a complete set of data with most accurate results representing that of a finished optimized prototype.

Optimization of renewable PV energy power transfer from the microinverter to the auxiliary resistance heating element can be accomplished by the development of a twin-output microinverter. This new secondary power output feature would replace the two-stage level power circuitry used on the resistive element which includes reactive power capacitors, solid state relays and microinverter current sensing circuitry. Micro-inverters have the ability to match solar energy resources via their maximum power point tracking (MPPT) to the fixed resistive element load. Most of what is accomplished externally in the circuit described above can be accomplished with simple microinverter re-design upgrades which would save an additional $70 putting the retail cost of the unit tested at FSEC under $2,000. FSEC has already discussed the design of a microinverter, incorporating a separate secondary 240VAC output independent from the grid with the power electronics division at UCF. The dedicated power output connections would switch from grid-tied mode into sending power to a fixed load such as a low power resistance heating element connected to a secondary set of wiring leads. The goal of such a control scheme would allow a redirection of available PV generated power (while compressor is in OFF state), into hot water storage, avoiding any interaction with the grid. As an example, consider the HPWH cycling through the day where a smart controller detects when power is being drawn by its compressor and fan. During the compressor operating cycle, power is injected normally into the site electrical distribution panel to provide as much renewable energy contribution towards the compressor electricity power needs. As soon as the compressor stops operation, microinverter power is redirected to a low power resistance heating element of the water heater which in turn pumps extra energy into the tank acting as an energy storage mechanism.

Hurdles in the Current PV-driven HPWH Prototype Design

The following discussion is a summary of hardware and software changes that would need upgraded by a manufacturer of HPWH's to deploy the PV-driven heat pump water heater into the field and meet code compliance. The changes would integrate optimization features into the unit as factory built instead of external non-code compliant retrofits like those applied to the laboratory prototype. In the event of a field deployment demonstration, occupants in a home could go on extended vacation days potentially leading to overheating (>170^{0}F) due to compounding of daily extra heating and lack of hot water draws. Temperature overheating protection can be implemented by either electro-mechanical disconnect protection or via software (opening a relay) by the factory HPWH central control unit.[22] The latter would only be upgradeable by the manufacturer as the factory operational control code is proprietary.

In the case of the Geospring HPWH, GE has communicated that if a lower wattage heating element is replaced as a retrofit (i.e., original 4500 W to a lower capacity 750 W) it may trigger an error upon trying to energizing the element. Speculation indicates that the unit would sense less current on a 750 W element as opposed to the 4500 W element thus raising a flag. The manufacturer would need to re-program HPWH internal controls to allow the operation of lower power heating element. In the laboratory no such incident has been encountered, however the 4500 W heating element was replaced with the 750 W element in April 2016 and the coldest ambient conditions (and water inlet temperatures) usually appear between December and February in Florida. The problem could be compounded further in northern climates.

An upgrade with directional power routing control to the bottom element would also be necessary unless the bottom element is to be left as renewable energy heating element only. This would leave the factory top position heating element as the only means of resistance heating in the event high hot water demand is called for. The solution may be as simple as double pole double throw relay connected to the bottom element which would permit power input selection either from the grid or power input from the dedicated micro-inverter in non-grid tied mode (which as today does not exist).

Compressor On/Off status detection is also needed as feedback to allow automatic switching by the microinverter AC output to either feed the electric distribution panel (grid-tied) or to the dedicated heating element load in which case would be non-grid tied.

As discussed above, the only upgrade that would meet electrical building code criteria that we can implement today is the thermostat control (via green bean controller) which does not involve physical component changes to the HPWH. Electrical component retrofits as performed in the laboratory would essentially fail electrical building code compliance and would only be accepted under special code variance in experimental sites (with proper documentation to deviate from code). All other non-factory control retrofit subjects discussed above also affect manufacturer's warranty on the HPWH.

We conclude that optimization features demonstrated in this project cannot be fully implemented without the participation and support of a manufacturer of HPWH's.

[22] A temperature protection limit of 170^{0}F can be accomplished by a "Open on Rise Limit Control DPST" offered by distributors of water heater control products such as Grainger item # 6XZV3 ($29).

5.0 Conclusions

The PV-driven heat pump water heater (HPWH) concept demonstrates a unique integration of photovoltaics and high efficiency compressor-based water heating. It also represents a major milestone in efficiency performance. The use of thermal storage with the integrated HPWH tank and mixing valve is utilized to its advantage leading to higher reserves of hot water. Furthermore, control techniques help optimize the use of available solar radiation during the day. In turn, the HPWH is better utilized by extending its efficient compressor refrigerant mode These efficiency improvements are the results of the setbacks of 120^0F during early hours past midnight and the further setback of 115^0F past the morning peak demand between 8:00 am and 10:30 am. When higher solar resources are typically available, compressor operation can resume which leads to less power energy consumption from the grid.

The use of solar energy to operate electric resistance heating past the compressor limit of 140 ^{0}F of the compressor is demonstrated. The redirection of available photovoltaic energy when the compressor is not operating is utilized to its economic advantage, as the hot water energy storage mechanism is relatively inexpensive. The concept of distributed photovoltaic energy as applied to a specific appliance having minimal or no interaction with the grid has also been demonstrated. The strategy can help market the concept further to those utility service territories that penalize or disrupt full rate energy buyback for injected electricity into the grid.

Data gathered from the operation of the PV-driven HPWH in Cocoa, Florida have indicated the highest efficiencies ever demonstrated for heating water at the FSEC HWS laboratory. On a daily average, the PV driven HPWH has measured a low electrical energy consumption (1.2 kWh/day – thru January 2017) as shown in the summary of performance Table 5.1 Electricity consumption is lower than that of the best record (1.6 kWh/day) as performed by a larger 90-gallon total storage HPWH (50 gal.) fed passively by an integrated storage solar thermal collector (ICS, 40 gal.) evaluated in 2012. But most important, operational optimization techniques were demonstrated, which represent an excellent potential for electric water heating by using the timing strategy utilizing solar resources which are higher during mid-day. 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 form the PV and microinverters averaged 65.6% of the total electric used by the system.

Table 5.1 Summary of performance for the PV-HPWH for the 10-month period ending in November 2016

Average Monthly Daily Electric consumption		Average COP Monthly (Min. /max)	PV generated Average	Added storage above 125 □F	Average Hot water Max Temp Stored	Average Daily Hot Water Delivered (w/ 125 □F setting)		
kWh/day	Min-Max kWh/day		kWh/day	kWh/day		Gal.	Btu's	kWh
1.20	0.72 – 2.14	5.43 (4.51 / 6.97)	2.92	2.1	144 □F	56.9	20,727	6.12

The performance of the 50-gallon PV driven HPWH daily electric consumption is compared against solar thermal hybrid systems previously tested at the FSEC HWS laboratory (2012). Although the weather conditions, cold inlet temperatures and amount of daily draws varied, the PV HPWH system appears to perform extremely well – considering that previous thermal systems tested had larger storage capacities between 80 to 90 gallons. It is also important to know that some of the optimization techniques explained in the report were applied to the PV-driven system during late spring and summer months. The true effect of those control techniques should reflect in lower electric consumption in the upcoming winter months of

December thru February where historically solar thermal solar systems have shown less than expected efficiency. The relatively high electric consumption of solar thermal systems during the winter months is illustrated in Figure 5.1. The performance of a baseline electric water heater during 2012 (red curve) and 2016 (brown curve) are shown on the plot allowing the comparison of seasonal (monthly) average daily energy use. The hybrid water heating systems are shown as follows: Solar thermal 80-gallon with retrofit mounted Airtap HPWH (Sol_AIRTAP, Orange), integrated collector storage (40-gallon passive) in series with 50-gallon HPWH (ICS_HPWH, Orange), and the PV driven HPWH (600 Wp PV + 50-gallon HPWH) covered in this report.

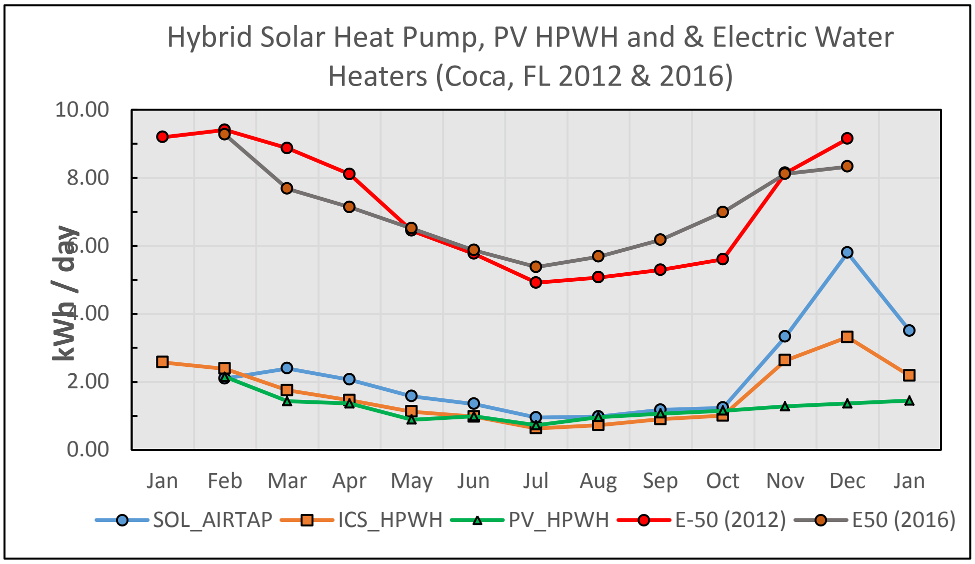


Figure 5.1: Performance of hybrid (w/compressor heating) solar thermal systems compared to the PV-HPWH

Results presented also demonstrate that a cost-effective photovoltaic systems dedicated for the use of water heating can compete favorably against solar thermal systems. The simplicity of electric energy transfer with no mechanical pumping components or fluids, piping, heat exchanger and with added benefits of no damage from freeze is highly desirable. Photovoltaics can also bring a synergistic benefits to the seasonal conditions. Cooler weather increases current in photovoltaics, leading to slight efficiency increase during winter season. Conversely, higher temperatures of summer season can curb module efficiency, reducing current due to the nature of their temperature coefficient.   Table 5.2 presents the monthly data plotted in Figure 5.1. Performance by averaged monthly-daily energy consumption for each system compared against the electric standard baseline water heater for the years shown (2012 and 2016).

Table 5.2 Average daily electric kWh performance (averaged monthly) for systems evaluated in 2012 and the PVHPWH in 2016

Month	Solar 40 ft^2 80-gal. + Airtap retrofit HPWH	Integratd Solar Collector 32 ft^2+ HPWH (90 gal. Total)	Standard Electric 50-gal. WH (2012)	PV (600Wp) + 50 gal. HPWH	Standard Electric 50-gal. WH (2016)
Jan	3.50	2.57	9.20		
Feb	2.10	2.39	9.41	2.14	9.27
Mar	2.40	1.75	8.87	1.43	7.68
Apr	2.06	1.46	8.11	1.36	7.14
May	1.57	1.12	6.45	0.89	6.51
Jun	1.35	0.98	5.76	0.99	5.87
Jul	0.95	0.63	4.91	0.72	5.38
Aug	0.98	0.73	5.07	0.96	5.68
Sep	1.18	0.90	5.29	1.07	6.17
Oct	1.23	1.00	5.60	1.15	6.99
Nov	3.33	2.63	8.14	1.28	8.12
Dec	5.80	3.31	9.20	1.36	8.33
Average				**1.19**	

Furthermore, in the future, the standard water heater working with scalable photovoltaics modules may be seen as a next stepping stone for electric water heating in the U.S. Currently, standard electric water heaters above 55 gallons require an energy factor (EF) of 2.0 and electric resistance heaters below 55 generally fall below a 0.945 EF. The range between 1.0 and 2.0 for electric water heaters could easily be filled with a boost from products utilizing PV energy to directly transfer electricity into stored heat energy.

Performance is yet to be analyzed during the most critical winter season which features the highest water heating loads given declining inlet water temperatures. The system may undergo further refinement in order to be demonstrated in a residential water heating field project. Manufacturers of HPWH also indicate in recent specifications that the latest generation of compressors can operate at least 50 Watts less compared to HPWH unit used in the PV-HPWH demonstration. In northern climates, larger storage (80-gallon) HPWH's could also be utilized along with additional PV modules although both of these potential improvements are yet to be demonstrated.

Appendix (Task 4.2 Report) - DC-Powered HPWH System Design and Specification

A1.0 Introduction

There are two conventional ways to potentially drive a HPWH with PV – one approach using a direct current (DC) powered compressor, the other one using an alternating current (AC) compressor. Heat pump water heaters which utilize AC compressors are readily available from a few manufacturers at competitive prices.[23] Heat pump water heaters which utilize direct current (DC) compressors are scarce or under limited market availability. However, commercial products which utilize DC compressors for cooling applications in the telecommunications industry and automotive applications do exist and are readily available in the marketplace. Some of these products utilize variable speed compressor in their design. Direct current compressors which operate at 24V and 48 V could be integrated for heat pump applications. These would also be suitable for integration with photovoltaic (PV) modules and a DC power supply (or batteries) which would be necessary to run the compressor at night. Forty-eight (48V) volt systems are preferable to 24 volts because it reduces current through all electrical components.

A2.0 DC Compressor Specifications

A list of small DC compressors is shown in Tables A2.1 and A2.2. Published data on compressor specifications from manufacturers Masterflux and Danfoss was examined. Ultimately the larger capacity DC compressors offered by Masterflux, a Tecumseh (U.S.) products division, was selected for further investigation. Masterflux offers a wide range of variable speed compressor with capacities as shown in the right-most column in Table A2.1.

Table A2.1 List of Masterflux DC compressors (48 volts).

Manufacturer	Component	Model	Voltage	Refrigerant	Capacity
Masterflux	Compressor	Sierra 03-0434	48V DC	R134a	4k – 6.8k BTU/hr
Masterflux	Compressor	Sierra 04	48-100V DC	R134a	4.1k- 15k BTU/hr
Masterflux	Controller	025A0220	37-59.9 V DC	------	Full cable Soft Start

Table A2.2 List of Danfoss DC compressors (48 volts)

Manufacturer	Component	Model	Voltage	Refrigerant	Capacity
Danfoss	Compressor	BD350GH	48– 60V (max)	R134a	3.2k BTU/hr.
SECOP (formerly Danfoss)	Dual Compressor	BD250/250GH	48-56V DC	R134a	2.2k- 3.6K BTU/hr.

An application performance calculator, obtained from Masterflux was used to examine the performance of these compressors. Operating performance for the Sierra compressor 03-0434Y3 was evaluated using the calculator. Results shown in Table A2.3 led to the conclusion that the smaller of the two compressor shown in Table A2.1 would be sufficient as it has a maximum capacity at or above 6000 BTU/hr. The

[23] Typical 2016 heat pump water heater prices in the U.S. which operate at 240 VAC range from $999 (50-gallon GE) to $2625 (80-gallon Stiebel-Eltron)

maximum operating velocity of the compressor rotor is listed as 6500 RPM with capacity reaching 6800 Btu/hr. under maximum operating conditions. Performance at various operating conditions were examined and listed in Table A2.3.

Table A2.3 Compressor capacities (Btu/hr) and efficiency (COP) for Sierra 03-0434Y3 under stated operating conditions (RPM, Evaporator temp (Et), Condensing temp (Ct))

RPM	Et	Ct	Btu/hr.	Mass flow lbs/hr.	COP	Power	Current
6000	52	148	6002	108.4	1.85	901	19.8
5800	50	145	5726	100.9	1.95	859	17.9
5500	48	142	5350	86.51	2.15	634	13.2
5000	45	140	4649	66.4	2.32	519	10.8
4000	40	135	3613	56.7	2.42	437	9.1
3000	35	132	2572	37.9	2.36	314	6.5
2000	32	124	1542	22.5	2.02	223	4.6

A3.0 Heat Pump Water Heater - Condenser Heat Exchanger Design

Following current design practice of residential heat pump water heaters, a wrap-around heat exchanger on a standard steel hot water storage tank design approach is presented. Although refrigerant copper tubing immersed in thetank water or an external pumped heat exchanger designs have been explored by the industry, the wrap-around refrigerant heat exchanger generally has proven to be more reliable. A cutaway view of a leading HPWH product by a U.S manufacturer (GE) which utilizes wrap-around tank tubing, reveals the approximate line tubing length used in the refrigerant condenser. Copper tubing from the compressor discharge port is transitioned to aluminum tubing which is utilized as the wrap-around tank condenser. The tubing length was determined by calculating the circumference of a storage tank having 18 inches in diameter. The pictured HPWH (Fig A3.2) appears to utilize about 124 feet of refrigerant tubing including the suction and discharge vertical lines to and from the compressor. Heat transfer is mostly accomplished by conduction from the hot refrigerant aluminum tubing attached to the tank wall as it is grouped from bottom to mid tank height in 2-4-4 and 13 coil passes.

Automotive air conditioning and repair hardware catalogs list aluminum 3003-0 tubing which can be used with refrigerant R-134a in refrigeration systems.[24] Aluminum 3003 tubing of 5/16"(8mm) nominal size (fig A3.3) can be expensive at \$2.58 per linear foot. Automotive refrigeration parts catalogs list the tubing having a 0.049 in. wall thickness suitable for refrigerant pressures of a HCFC 134a system.

Figure A3.2 Cutaway view of modern HPWH design with wrap-around tank heat exchanger.

[24] http://ken-co.com/fmsi/catalog/catalog.pdf

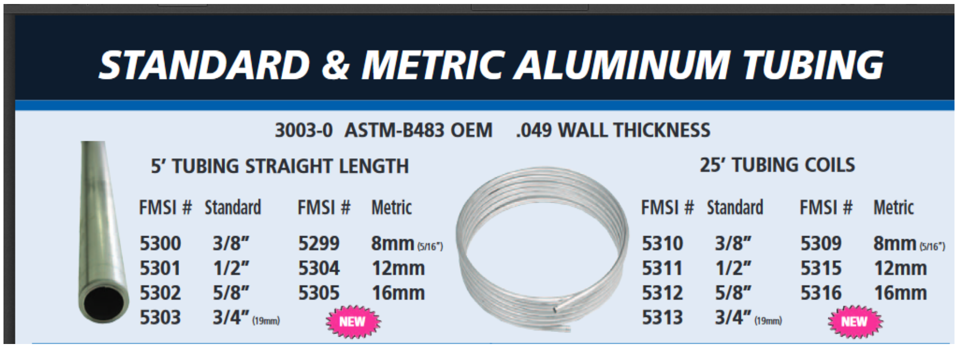
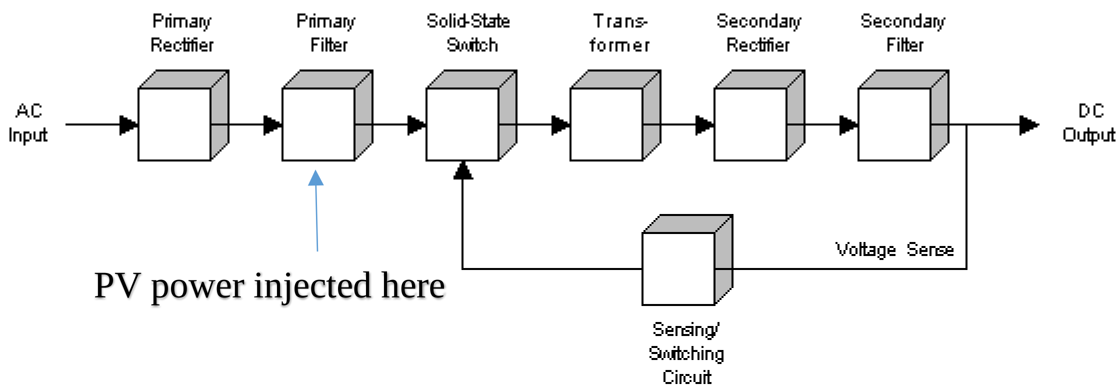


Figure A3.3 Top tank mounted compressor and wrap around-refrigerant heat exchanger. Aluminum tubing specifications used with 134a refrigerant.

A4.0 Power Supply Requirements

A direct current (DCDC) compressor requires a DC power supply to operate. Furthermore, the integration of direct current generated by photovoltaics (PV) in to a DC refrigeration appliance requires a careful design thought process. There are generally two design methods for conventional direct current (DC) power supply. The first is generally described as linear design, including linear voltage regulation. This type utilizes a voltage higher than is needed, then regulating it to a lower voltage. The extra energy or voltage drop across the control element is dissipated as heat. The second is a more efficient switching power supply circuit topology. A regulated switching power supply would be the preferred power source as it provides a higher regulation conversion efficiency. The integration of photovoltaic modules into a DC switching power supply effectively creates a hybrid AC-DC switching power supply augmented by direct photovoltaic current. The hybrid DC power supply can be accomplished by injecting power into a higher voltage capacitor at the primary filter stage of a switching power supply as shown in the block diagram (Figure A4.1) below.

Figure A4.1 AC/DC Switching Power Supply with PV integration Concept



Capacitance integration and DC voltage levels of the primary storage filter section would have to be designed for the PV modules that are selected in order to accommodate operating voltage levels. Using the optimal operating voltage level of 36 V (Vmp) typical of 300 watt PV modules as an example, this would yield an operating 72 V series string voltage.[25] The current supplied by incorporating a second parallel string in the PV module array design would supply around 17.0 amps at extreme peak sun

[25] Such as in the case of Quartech CS6X 305Wp PV modules which list 36.3 V (Vmp) and 8.41A (Imp) as optimal operating voltage and current

conditions (1220W). The balance of the total current needed when solar peak conditions are not available and the system demands more, would come from the 900W AC switching power supply connected to the utility grid. By design, the DC switching power supply would gradually provide a fade out supply of current at the beginning of a morning day and fade in as it approaches nighttime, then continuing to provide 100% power availability through the night. Listed in Table A4.1 are 48 VDC switching power supplies suitable for the DC-driven HPWH design and their cost per watt.

Table A4.1 AC / DC Power Supply

Manufacturer	**Model**	**Output Voltage /Max Current**	**Power**	**List price - $ ($/watt)**
TDK Lambda	HWS600-48	48VDC / 13A	624 W	$ 560 ($0.89/W)
TDK Lambda	HWS 900-48 Config 9QSMF	48VDC / 19A	900W	$ 783 ($0.89/W –est.)
TDK Lambda	HWS1500-48	48VDC / 32A	1.536 kW	$1305 ($0.85/W)

A5.0 Prototype Design - Main Components Cost

Table A5.1 provides a list of components suitable for the proposed DC HPWH design augmented by the integration and power of four PV modules. An additional capacitor bank connected to the PV modules would have to be designed for integration into the AC/DC power supply.

Table A5.1 Component List for a prototype DC driven heat pump water heater

Component	**Model**	**Description**	**BOM (List$ Retail)**
Compressor	Masterflux Sierra 0434Y3	48V DC compressor 6.8k Btu/hr.	$591
Controller DC	Masterflux 025A0220	Var. Speed DC	$292
Condenser coil	125 ft. aluminum tubing 5/16”	3003-0 ; .049 wall thickness	$320
Storage tank	Model #: E50R6-45-110 50 gallon, EF>0.94	Std. residential electric water heater min. EF>0.95	$389
Power supply	TDK Lambda HWS 900 9QSMF – 48 S	Vega 900 (W)	$783
Evaporator	Four Seasons 54474	Automotive Plate & Fin Evaporator Core	$ 65
Expansion device	Four seasons 39000	TXV direct fit	$35
Evaporator Fan	ebm-papst W1G200-HH01-52	Fan; DC; 48V; 260x225x80mm; Obround; 588CFM; 45W; 60dBA; Lead wires	$306
PV modules	Quartech Max Power CS6X 305W x 4 (1220 Watts Total)	2-Series, 2-parallel (72VDC)	$936
Total estimated Cost ($)			**$3717**

A6.0 Closing Remarks

The PV-driven direct current heat pump water heater concept presented in this appendix has a few design challenges, including the integration of components listed above in Table A5.1. A hybrid AC/DC power supply would have to be developed to incorporate the power supplied by PV modules. Control of power source would be self-automated by the power supply to transfer current from the AC grid only when solar

resources are not enough or not available (e.g., cloudy daytime conditions & night time). Typical maximum operating refrigerant temperatures for the Sierra Masterflux compressor 0434Y3 is limited to 150 °F, where the compressor capacity would be around 6 000 Btu/hr with 900 Watts of input power at a COP of 1.91. Adding renewable energy to the DC power supply would elevate the COP substantially and would raise the overall daytime electrical efficiency to ultra-high levels. Higher COP efficiencies above 2.3 (when using the grid power supply only) can be obtained by operating the compressor at lower RPM but that would limit the available refrigerant heat and subsequently limit the hot water temperature to well below 140 °F. However, b
(200W-1000W) heating element, once the limits of the compressor are reached, additional energy storage levels can be attained from the 1.2kW photovoltaic array. A diagram of the DC heat pump water heater prototype augmented by direct current of photovoltaics is shown in Figure A6.1.

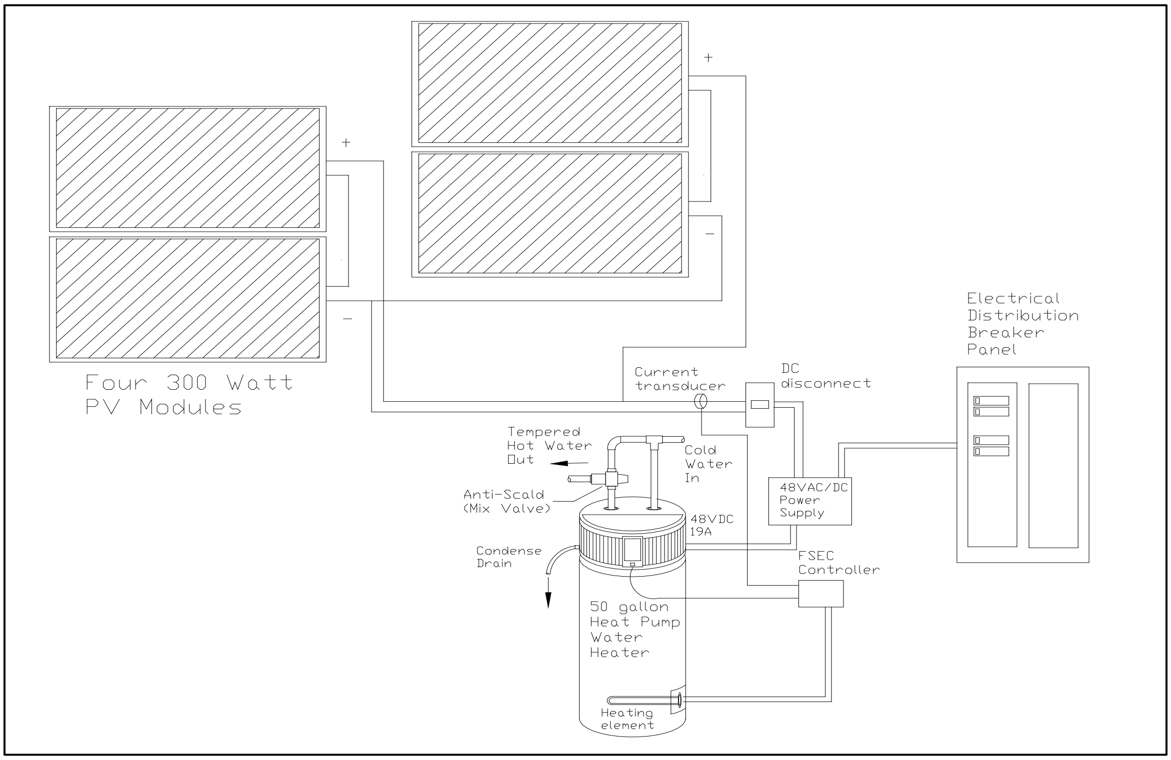


Figure A6.1 Photovoltaic augmented DC driven heat pump water heater diagram

Performance Characteristics for Sierra 48V DC Compressor

Copy of SIERRA03-0434Y3_Performance_Calculator_WEB.xls [Compatibility M...

MASTERFLUX
COMPRESSOR PERFORMANCE DATA

8/14/2013

SIERRA03-0434Y3	**SUCTION TEMP:**	18.33°C (65°F)	**TEST VOLTAGE:**	48 V DC
	SUB COOLING:	8.33°C (15°F)	**MOTOR TYPE:**	BLDC
R134a	**AMBIENT:**	35°C (95°F)		

COEFFICIENTS	**CAPACITY**	**POWER**	**CURRENT**	**MASS FLOW**
c1	-6.262409E+03	-1.006527E+03	-2.096931E+01	-8.990093E+01
c2	1.289884E+00	2.611476E-01	5.440575E-03	1.235807E-02
c3	-1.339645E-04	-1.677172E-05	-3.494109E-07	-1.248812E-06
c4	1.400445E-08	1.001703E-09	2.086882E-11	1.104119E-10
c5	1.125932E+02	7.195594E+00	1.499082E-01	5.665706E-01
c6	-3.175953E-01	4.015479E-01	8.365582E-03	3.326093E-03
c7	7.163275E-03	-1.267573E-03	-2.640777E-05	5.250719E-05
c8	1.415857E+02	1.597312E+01	3.327734E-01	2.105187E+00
c9	-1.120186E+00	-5.459110E-02	-1.137315E-03	-1.696991E-02
c10	2.708589E-03	-7.798935E-05	-1.624778E-06	4.347658E-05
c11	6.707360E-04	8.404594E-06	1.750957E-07	6.336705E-06
c12	1.456661E-08	2.719304E-09	5.665216E-11	1.868148E-10
c13	-8.915019E-08	9.614630E-07	2.003048E-08	1.151861E-08
c14	-3.446913E-06	-2.916520E-07	-6.076083E-09	-3.203895E-08
c15	-1.939086E-02	1.790520E-03	3.730250E-05	-1.210281E-04
c16	-4.568333E-03	-3.071264E-03	-6.398467E-05	-3.381422E-05
c17	-1.972551E+00	-2.766131E-01	-5.762772E-03	-1.273783E-02
c18	-1.830042E-06	-1.613385E-07	-3.361219E-09	-2.505208E-08
c19	1.389256E-04	-9.886370E-05	-2.059660E-06	5.808573E-07
c20	-4.486187E-07	7.396136E-08	1.540862E-09	-1.356880E-09
c21	2.687089E-05	1.418915E-05	2.956074E-07	1.864797E-07
c22	-1.563311E-03	-3.048626E-03	-6.351305E-05	-4.898309E-05
c23	8.628039E-03	2.009413E-03	4.186278E-05	6.248005E-05

		Allowable Range		
ENTER RPM:	2000	1800 to 6500		
ENTER Et (°F):	32	-10 to 55	**Et (°C):**	0.0
ENTER Ct. (°F):	124	80 to 150	**Ct. (°C):**	51.1

CAPACITY:	1542	Btu/hr
	452	Watts
POWER:	223	Watts
CURRENT:	4.65	Amperes
MASS FLOW:	22.51	Lbs/hr
	10.21	Kg/hr
EER:	6.92	Btu/watt
COP:	2.02	W/W

SIERRA03-0434Y3 24V | **SIERRA03-0434Y3**

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