EXPERIENCES WITH USING SOLAR PHOTOVOLTAICS TO HEAT DOMESTIC WATER

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ABSTRACT

The solar photovoltaic (PV) industry continues to make progress in increasing the efficiency while reducing the manufacturing costs of PV cells. Economies of scale are being realized as manufacturers expand their production capabilities. Products are commercially available that integrate photovoltaic cells within building façade, fenestration, and roofing components. Legislation and incentive programs by government and commercial entities are supporting both reduced first costs and greater rates of return. The combination of factors support improved cost-effectiveness. As this trend continues, more options for using PV become possible. One such application is a stand-alone, PV-direct, solar water heating application.

Solar water heating can be effectively accomplished by directly using the DC power production from solar photovoltaic modules. A simple controller having multiple power relays connects the PV modules with different combinations of in-tank resistive elements. The controller actively changes the resistive combination so that the photovoltaic modules generate power at or near their maximum output.

The technology, which has been patented and licensed, is applicable to configurations that use a single water heater and to two water heaters that are piped in series. Prototypes using both tank configurations have been in operation at four field sites. This paper emphasizes the single-tank application and the field results from installations in Maryland and Florida.

INTRODUCTION

The key components of a solar photovoltaic water heating (PVWH) system are depicted in Fig. 1. The system consists of an array of photovoltaic modules, a microprocessor-based control module, a solar radiation sensor, one or more storage tanks, and multiple resistive heating elements. The control module connects the individual heating elements in different combinations such that the photovoltaic array operates at or near its maximum efficiency.

A PVWH water heating system may be configured as a single-tank or two-tank system. In a single-tank system (Fig. 1), water within the lower portion of the tank is heated exclusively using energy supplied by the photovoltaic array. A heating element that is connected to the utility grid is located in the upper part of the tank to assure a reserve of stored hot water and quicker recovery times. In a two-tank system, energy from the PV array is used to heat water stored in a separate, preheat tank. The preheat tank feeds water to a conventional electric, gas, or oil-fired water heater when a hot water draw is imposed.

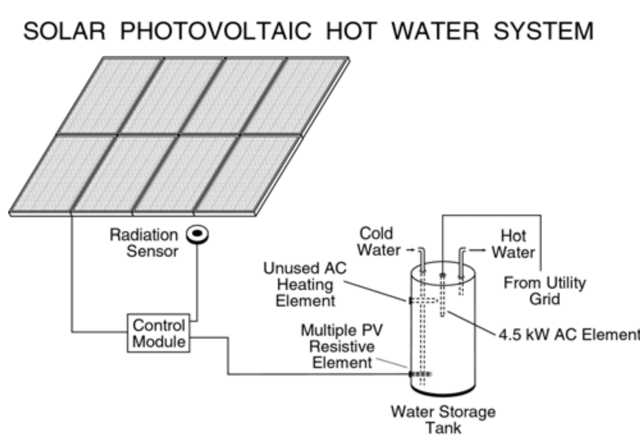

Figure 1 Single-tank PVWH Schematic

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The application for using the DC energy generated by a photovoltaic (PV) array to directly heat potable water was patented by the National Institute of Standards and Technology (NIST) in 1994 [1]. The first prototype systems used a two-tank configuration [2]. These two-tank prototypes were evaluated at test facilities located at the NIST in Gaithersburg, Maryland and at the Florida Solar Energy Center (FSEC) in Cocoa, Florida. The field performance of these prototype two-tank systems has been previously reported [3].

After completing the two-tank prototype studies, efforts to evaluate the PVWH technology as applied to a single-tank configuration were initiated. Prototype single-tank systems were installed and evaluated at both NIST and FSEC. Detailed performance data were collected. The results and experiences from this single-tank deployment are the focus of this paper.

During this same period, NIST also collaborated with two parties that were interested in demonstrating and evaluating the PVWH technology. In cooperation with the Tennessee Valley Authority and the National Park Service, a two-tank system was installed in late 1996 at the Sugarlands Visitor Center within the Great Smokey Mountains National Park (GSMNP). In November 1997, NIST teamed with the US Air Force to install a two-tank PVWH system at two military housing units in Okinawa, Japan. The electrical energy inputs – DC from the photovoltaic array and AC from the electrical grid – and the hot water usage at these three sites were monitored up until January 2000. The findings from the two Okinawa installations are summarized in this paper. The performance results for the GSMNP site are the subject of a separate technical paper [4].

THEORY OF OPERATION

The magnitude and shape of the characteristic current versus voltage (I-V) curve of a photovoltaic array changes continually over the course of a day, Fig. 2. The array's operating point depends upon the connected load. A load that coincides with the maximum power point on the I-V curve will result in maximum energy collection. In Fig. 2, these maximum power points are denoted as P_{max}. To continually operate a PVWH system at the maximum power point, a resistive heating element that was continuously variable would be needed. In practice, a finite number of discrete resistive elements provide an acceptable alternative. A PVWH system using as few as three heating elements is predicted to provide only 4 % less energy than a continuously variable resistive element [2,3]. The three elements are used to provide seven resistive loads by virtue of the four possible parallel wiring combinations.

The second part of the design process is selecting which resistive element(s) to connect at any given time. Solar irradiance, PV cell temperature, angle of incidence, and air mass all influence the current-voltage curve, and thus the instantaneous maximum power operating point. An attempt could be made to develop a resistive load control strategy that

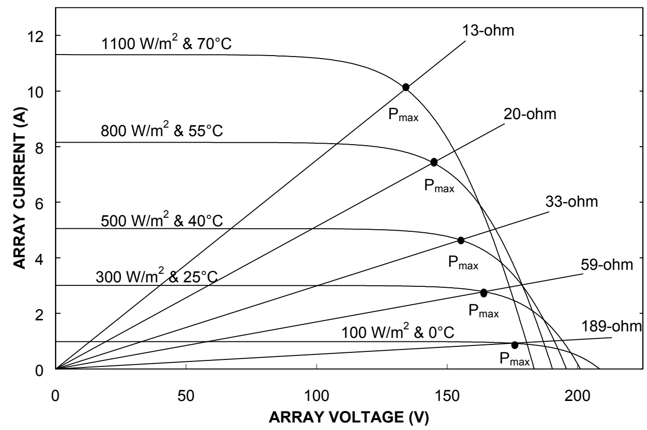

Figure 2 Select current versus voltage curves showing how the resistive load would have to change to operate at the maximum power point.

factored in all four parameters. The researchers, however, have found that acceptable performance can be achieved by keeping the system simple and making decisions based on the primary I-V curve driver, solar irradiance. Specific information is given in the next section on how the irradiance-based control strategy is implemented.

THE DESIGN PROCESS

System design is an iterative process of selecting a PV array configuration, choosing a combination of resistive elements, and then deciding upon the irradiance interval over which to use each resistive heating load. To make these decisions, a method for predicting the I-V curves for the particular PV array is required. For the PVWH systems reported here, a single-diode, four-parameter model [5] has been used. This PV model was combined with a computer model of a storage-type water heating system. The resulting computer program conducts yearlong simulations of a hypothetical PVWH system.

Beginning with a candidate PV array, the I-V curve model is used to generate a version of Fig. 2 to select resistive elements that individually, and when combined, will partition the range of possible maximum power point I-V combinations. During this initial screening process, hardware limitations related to the resistive elements (e.g., available ohm-ratings, maximum current limits), mechanical relays (e.g., how many are needed, maximum current limits), the complexity of the resulting power wiring, and the local solar resource are considered. The outcome of this first step is a selection of heating elements and a decision on whether to use all or a subset of the potential series/parallel resistive combinations.

Once the magnitude and sequence of the resistive loads are known, the next step is to exercise the I-V curve model to determine which resistive load is predicted to yield the highest

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power output for a given irradiance and PV cell temperature. The outcome is a decision table that lists the irradiance range for connecting each resistive load. Typically, the I-V curve model is further exercised to see how the decision table irradiance endpoints (which become switchpoints in the eventual control strategy) are affected in one direction or the other by cell temperature. This cell temperature check may lead the designer to slightly adjust the irradiance intervals assigned to each resistive load within the decision table.

The final step is to conduct the yearlong simulation. The user must input information that defines the PVWH system, including information on the water heater(s) and the daily hot water draw schedule. The simulation provides information on the system's overall performance. The most critical parameter is the predicted annual energy generation of the PV array. Another important output is the predicted electrical fraction, which is defined as the energy supplied by the PV array divided by the combined energy input to the water heater by the PV array and the AC grid. Once the PV array is chosen, the goal is to select resistive elements and irradiance switchpoints that maximize these two output parameters.

Work to streamline and improve the design process has been addressed by researchers at the University of Wisconsin [6]. For the field installation reported in the paper, however, the less refined process described above was used.

THE SINGLE-TANK CONFIGURATION

A schematic of a single-tank solar photovoltaic water heating system is shown in Fig. 1. The balance-of-system components include a control module, a solar radiation sensor, a PV heating element assembly, and an electric, residential water heater. Other balance-of-system components would include the rack used to mount the PV modules, an electrical combiner box that is installed in close proximity to the PV array, and an electrical breaker box that is installed in close proximity to the water heater. The combiner box houses the blocking diodes required for the series strings and provides a location for combining these series strings in parallel. The reader is referred to previous publications for information and schematics that are specific to a two-tank configuration [2,3].

The PV heating element is comprised of multiple resistive elements. The assembly is designed to replace the normally used AC heating element without any modification to the water heater. To date, two configurations of the PV heating element assembly have been tried, Fig. 3. The upper assembly in Fig. 3 uses off-the-shelf resistive elements and a fitting that allows three elements to be installed into the heating element port of an electric water heater. This assembly is referred to as the 3-cartridge heater assembly. The lower assembly is a custom-fabricated, single sheathed cartridge that contains three parallel wired resistive segments and is referred to simply as the 3-in-1 assembly.

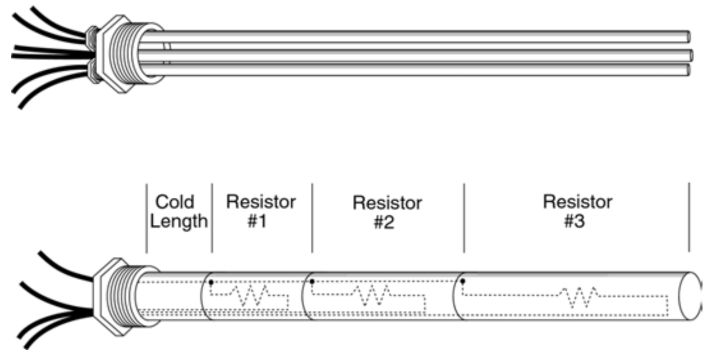

Figure 3 Two types of multiple resistance, PV heating element assemblies

The control module contains mechanical relays that connect the appropriate heating elements with the PV array. The control module also includes the electronics that sample the radiation sensor signal, effect the simple decision-table control logic, and generate the low-voltage signals to the control side of the mechanical relays. For the single-tank configurations used at FSEC and NIST, a single PV heating element assembly is used. A normally-open mechanical relay is wired in-line with each resistive element. The elements are wired in parallel and, through the control of the relays, seven different resistive load combinations are provided.

A photovoltaic reference cell is used to provide a measurement of the instantaneous solar irradiance. The output from this reference cell is connected to a precision resistor. The voltage drop across the precision resistor is fed to the control module. The relationship between irradiance and voltage drop was determined via calibration using a precision spectral pyranometer.

As with most solar water heating systems, a design consideration is to minimize hot water runouts during times of extended poor solar meteorological conditions and periods of higher-than-normal hot water use. The researchers wanted to use a readily available electric water heater. A two-element electric water having a nominal volume of 450 L was selected. The upper AC heating element of the chosen water heater was found to heat approximately 106 L. The researchers wanted a single-tank configuration that provided an AC heated reserve comparable to a typical residential application, i.e., a reserve in the 135 L to 170 L range. In order to increase the reserve volume, a cartridge heating element having a total length of 56 cm was installed in the water heater port that is usually used for the anode rod. (An anode designed for installing in the hot water outlet port was used instead.) The active part of the heating element was restricted to the lower 25 cm of the heating element. This configuration resulted with the highest active part of the heating element being positioned approximately 1 cm below the horizontal plane where the upper thermostat is attached. This relative positioning is important to assure that the water temperature at the very top of the tank is equal to the thermostat temperature setting. The total volume heated by the vertically oriented heating element was approximately 157 L.

In practice, using a vertically oriented heating element has the disadvantage of creating a temperature profile within the volume containing the active portion. For the purposes of this initial, controlled investigation, the authors felt that the vertical heating element was an acceptable mechanism for increasing the AC heated reserve. The possibility of using a bent AC heating element in the upper water heater port, as shown in Fig. 4, was considered after initiating the two single-tank field studies but never implemented. Finally, with the AC heating being performed by the vertically installed heating element, the option of using the upper heating element port for a second PV heating element assembly was investigated. The idea was abandoned after modeling revealed a strong tendency for overheating the upper part of the tank.

FIELD-EVALUATED SINGLE-TANK PVWH SYSTEMS

A summary of the single-tank configurations that were evaluated at NIST and FSEC are provided in Table 1. The PV array at both installations used the same model of single-crystalline PV module. The modules were rack mounted. The rated output of the NIST and FSEC arrays were 1590 W (peak) and 1060 W (peak) at an irradiance of 1000 W/m^2 and a module temperature of 25 °C.

Table 1. Key features of the single-tank PVWH systems evaluated at NIST and FSEC

System Location	NIST Gaithersburg, Maryland	FSEC Cocoa, Florida
Latitude	39.1° North	28.4° North
Longitude	77.2° West	80.8° West
Tilt	40°	24°
Azimuth	0°	0°
Photovoltaic Array Size (m^2)	12.8	8.54
Number of Modules in Series	10	10
Number of Series Strings in Parallel	3	2
Rated Maximum Power Current (A)	9.1	6.1
Rated Maximum Power Voltage (V)	174	174
Nominal/Measured Tank Volume (L)	450/406	450/405
Water Heater Rated Energy Factor	0.83	0.83
AC element thermostat setpoint (°C)	57	54
Tank Heat Loss Coefficient (W/°C)	2.12	2.12
Daily Hot Water Draw Volume (L)	243	243
Unique PV Resistive Elements (S)	75, 60, 50	177, 97, 51
PV Resistive Loads	75, 60, 50 75||60 → 33.3S 75||50 → 30.0S 60||50 → 27.3S 75||60||50 → 20.0S	177, 97, 51 177||97 → 62.7S 177||51 → 39.6S 97||51 → 33.4S 177||97||51 → 28.1S
Decision Table: Solar Irradiance Range, H_T (W/m^2), for Each Nominal Resistive Load (S)	75 : $0 \le H_T < 257$ 60 : $257 \le H_T < 317$ 50 : $317 \le H_T < 436$ 33.3: $436 \le H_T < 558$ 30 : $558 \le H_T < 620$ 27.3: $620 \le H_T < 770$ 20 : $770 \le H_T$	177 : $0 \le H_T < 190$ 97 : $190 \le H_T < 326$ 62.7: $326 \le H_T < 448$ 51 : $448 \le H_T < 568$ 39.6: $568 \le H_T < 704$ 33.4: $704 \le H_T < 838$ 28.1: $838 \le H_T$

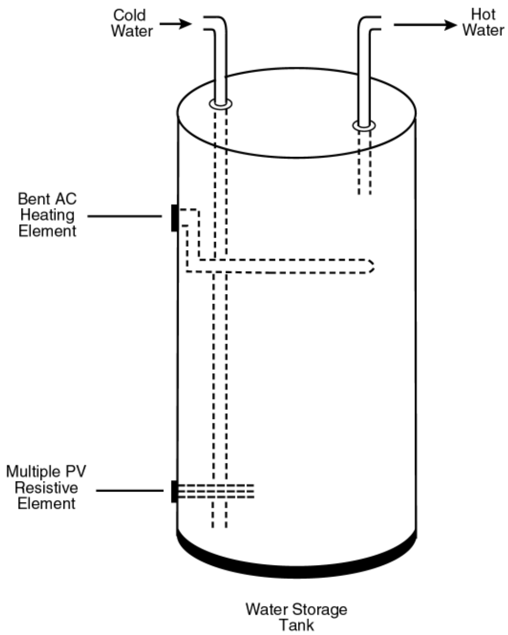

Figure 4 Alternative single-tank configuration

The three resistive elements selected for the NIST PV heating element assembly were 75 S, 60 S, and 50 S. The three resistive elements selected for the FSEC PV heating element assembly were 177 S, 97 S, and 51 S. The FSEC installation used a 3-cartridge heater assembly (Fig. 3). The NIST installation used a 3-cartridge heater assembly for the majority of the monitoring period. An evaluation of a custom-fabricated, 3-in-1 assembly was conducted at the NIST site beginning in July 1999.

For both single-tank systems, the controller sampled the output from the reference PV cell every 20 s. Each minute, these measurements of instantaneous irradiance were averaged and then used in deciding whether the connected resistive load should be changed. The decision tables used to select the resistive load are given in Table 1.

Except for the necessity of only instrumenting one water heater rather than two, the data acquisition and control system used to collect the performance data and to impose the hot water draw schedule was the same as reported previously for the two-tank configurations studied at NIST and FSEC [3]. The daily hot water draw schedule imposed on the single-tank installations was the same as used previously for the two-tank study.

The NIST single-tank system became operational in January 1997. Data collection continued until December 31, 1999. During the 3-year period, the system was off-line for the majority of March 1997 while confirming the accuracy of the energy measurements and improving the determination of the jacket heat losses from the storage tank. During May and June of 1999, a newer generation controller was installed, troubleshot, and finally made operational. The 3-in-1 element was installed at this time. Because of these events, coupled with the authors' preference to report results for complete 12-month periods, performance measured over the 24-month period beginning April 1997 and ending March 1999 is reported in this paper. During the entire time of operation, the single-tank PVWH system experienced no malfunctions or equipment failures.

The FSEC single-tank system was installed in April 1997. Data collection on this system was terminated in January 2000. A few months into the monitoring effort, slightly lower than expected performance – conversion efficiencies and electrical fractions – was noted. FSEC and NIST personnel diagnosed that the 20-panel array included a faulty PV module and that the measured resistance of one of the PV heating elements had shifted from 51S to 78S. The defective PV panel and resistive element were replaced by January 1998.

During the first half of 1998, the volume of hot water automatically removed from the solar photovoltaic water heating system at FSEC began to slowly decrease. By the time the reduction was identified in July 1998, the average daily draw volume had decreased 16 % from the daily target value of 243 L. The reduction, which was caused by a flow control valve that had become progressively restricted due to sediment build up, was corrected in late July.

A few other events that occurred during the remaining 17 months of monitoring impacted the data collection process and efforts to impose a repeatable draw schedule on the water heating system. The biggest nuisance stemmed from the data acquisition system locking up during severe thunderstorms despite being protected by an uninterruptible power supply. The authors preference to present results for 12-month blocks coupled with seeking the 12-month period with the highest data collection rates leads to the selection of September 1998 to August 1999 as the interval reported here. It is important to note that the solar photovoltaic water heating system, with the exception of the January 1998 replacements of the faulty PV module and the shifted resistive element, did not experience any operational problems during the 33-month interval of evaluation at the FSEC facility.

FIELD-EVALUATED TWO-TANK PVWH SYSTEM

The two residential PVWH systems installed in Okinawa, Japan were identical. The two-tank systems used the same preheat and auxiliary water heaters, the same size and configured PV arrays, and the same pair of 3-in-1 PV heating element assemblies. Furthermore, the heating element assembly selected for the upper and lower water heater ports were the same. Each assembly contained three 96 S resistive elements.

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The same model of single-crystalline PV module as described above for the single-tank systems was used for the two Okinawa installations. Each of the arrays is composed of three strings of eight series-wired modules. The rated output of these arrays is 1272 W (peak). A summary of the key design parameters that were common to both demonstration sites is provided in Table 2.

As compared to the systems evaluated at NIST and FSEC, the Okinawa sites included only minimal instrumentation. Two digital power meters monitored performance at each housing unit. One meter measured the DC current, voltage, and power provided by the PV array; the second meter measured the equivalent parameters associated with operating the grid-connected, AC resistive elements. Instrumentation to monitor the local meteorological conditions were not used. Generalized weather reports for the area (e.g., partly sunny, rain, etc.) were recorded to gain a qualitative assessment of the meteorological conditions.

Table 2. Key features of the two-tank PVWH systems evaluated in Okinawa, Japan

System Location	Okinawa, Japan
Latitude	26.4° North
Longitude	127.8° East
Tilt	25°
Azimuth	0°
Photovoltaic Array Size (m^2)	10.2
Number of Modules in Series	8
Number of Series Strings in Parallel	3
Nominal Preheat Tank Volume (L)	303
Nominal Auxiliary Tank Volume (L)	303
Water Heater Rated Energy Factor	0.85
Auxiliary Tank Thermostat Setpoint (°C)	55
Preheat Tank Upper Heating Elements: Nominal Resistance (S) Operating Sequence	96 –1 96 –5 96 –6
Preheat Tank Lower Heating Elements: Nominal Resistance (S) Operating Sequence	96 –2 96 –3 96 –4
PV Resistive Loads	96 → 96.0 S 96‖96 → 48.0 S 96‖96‖96 → 32.0 S 96‖96‖96‖96 → 24.0 S 96‖96‖96‖96‖96 → 19.2 S 96‖96‖96‖96‖96‖96 → 16.0 S
Solar Irradiance Range, H_T (W/m^2), for Each Nominal Resistive Load (S)	96 : $0 \le H_T < 198$ 48 : $198 \le H_T < 346$ 32 : $346 \le H_T < 493$ 24 : $493 \le H_T < 640$ 19.2: $640 \le H_T < 786$ 16 : $786 \le H_T$

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The two-tank systems were installed in November 1997. Data collection was terminated in January 2000. Data collected during 1998 and 1999 are reported here. No problems were experienced with either PVWH system. With the exception of data lost for System II for seven days in November 1999 (due to a faulty uninterruptible power supply that protected the data acquisition components), the only data loss was due to a scheduled, partial-day power outage on March 9,1998. For System II, the same family resided in the home during the entire monitoring period. By comparison, two different families resided in the second home, System I. The home was unoccupied and no hot water was used from January 14, 1999 to January 27, 1999.

Using the electrical energy measurements, a few spot measurements made by Air Force personnel of the make-up water temperature, and information on the thermostat setpoints and the rated energy factor of the two electric water heaters, NIST estimated the daily hot water volume used by the families that resided in the two military housing units. To validate these estimates, water meters were added for the last 11 months of the monitoring period.

FIELD RESULTS

Single-tank installations

The measured performance of the NIST and FSEC single-tank systems is summarized in Tables 3 and 4, respectively. For the twenty-four month period reported for the NIST system, 99.3 % of the available daily data was collected. For the twelve month period reported for the FSEC, 350 days worth of data, or 95.9 %, was collected.

An energy balance was performed to ensure that the measurements were accurate. The energy balance for each month is given in Table 3 and Table 4. The NIST installation appears to have offered smaller random variation but a small, systematic bias. The magnitude of the monthly energy balances for FSEC, by comparison, were greater but were split evenly as to their sign.

The FSEC installation provided a slightly higher electrical fraction for the cumulative period than the NIST installation, 51.8 % versus 49.0 %. The high and low monthly electrical fractions for the NIST site were 60.3 % and 30.7 %. The comparable values for the FSEC site were 63.2 % and 40.8 %. Uncertainties associated with the electrical fraction and other reported parameters are listed in Appendix A.

The comparable electrical fractions for the two sites come about as a result of offsetting factors. The FSEC PV array is two-thirds the size of the NIST array. This size difference is offset by the comparatively lower loads – the hot water load and the tank (jacket) heat loss – that occur at the FSEC site. The average daily energy of the hot water removed from the FSEC system was 70 % of the comparable average at NIST. The average daily tank heat loss from the FSEC tank was 66 % of the average loss from the NIST tank. The higher hot water loads at NIST are attributed to the comparatively lower make-up water temperatures and a slightly higher thermostat setpoint. The higher setpoint temperature, plus periods of lower surrounding ambient temperatures at NIST, contributes to the difference in tank losses.

Although not to the same degree of offset, the better solar resource at the FSEC installation is slightly offset by the higher conversion efficiency of the NIST system. The average daily incident solar energy measured at FSEC was 18,267 kJ/m^2. This average is 15 % higher than the NIST average of 15,865 kJ/m^2. The photovoltaic conversion efficiency of the NIST system was 4 % higher than the FSEC system, 10.6 % versus 10.2 %. It should be noted that the photovoltaic system conversion efficiency accounts for departures from maximum power point tracking that result from using a finite number of resistive loads and choosing to exercise the control logic at one minute intervals.

The electrical fractions and the photovoltaic conversion efficiencies for the NIST system were better for the second 12-month interval: 50.7 % versus 47.3 % and 10.7 % versus 10.5 %. The difference in electrical fraction is due to the comparatively higher solar input and the lower average daily hot water load. The difference in the hot water loads was caused by other, unrelated testing in the same laboratory space. This other testing called for a fixed water temperature of 14.4 °C from the conditioning loop that supplied the make-up water. When not set to 14.4 °C, the water conditioning loop at the NIST site was set to the average monthly make-up water temperature previously recorded for Gaithersburg, Maryland.

One additional comparison is offered in Table 5. Here the photovoltaic conversion efficiency of the two-tank system previously evaluated at NIST is compared to the second of the two 12-month intervals reported for the single-tank configuration. Both systems were evaluated using the same PV array. The average daily irradiances based on the 12-month totals are found to differ by less than 1 %. Comparing on this same basis, the two-tank system is observed to offer a 0.3 % higher conversion efficiency. In fact, with the exception of the February comparisons, the two-tank system consistently outperformed the single-tank system. This difference is attributed to the better tracking of the maximum power point that was provided by using two, rather than one, PV heating element assemblies. Another contributing factor is that decisions on changing the connected resistive load were made more frequently for the two-tank system, every 20 s.

Table 3 Performance of NIST Single-Tank Photovoltaic Water Heating System

Month	Year	# Days	Data Capture Rate (%)	Incident Solar Energy (kJ/m2)	Photovoltaic System Output (kJ)	Photovoltaic System Conversion Efficiency (%)	AC Electric Energy Supplied to Tank (kJ)	Energy Removed From Tank During Draws (kJ)	Heat Loss From Tank (kJ)	System Energy Balance (%)	Electrical Fraction (%)
Apr	97	30	100.0	601896	822195	10.7	545175	1231771	138592	-0.4	60.1
May	97	31	100.0	606615	796937	10.3	590695	1259982	145675	-0.9	57.4
Jun	97	30	100.0	569101	715763	9.8	640280	1218856	138384	-0.3	52.8
Jul	97	31	100.0	623166	761962	9.6	625592	1254117	146397	-0.7	54.9
Aug	97	31	100.0	573286	736009	10.0	657429	1255713	142485	-0.7	52.8
Sep	97	30	100.0	531129	708219	10.4	623415	1214865	134402	-0.5	53.2
Oct	97	31	100.0	509663	714446	11.0	660236	1236011	133704	-0.4	52.0
Nov	97	30	100.0	271044	389981	11.2	881467	1190466	116024	-1.0	30.7
Dec	97	31	100.0	332064	497529	11.7	877569	1252480	122455	-0.7	36.2
Jan	98	31	100.0	299757	448837	11.7	922191	1256826	119708	-0.5	32.7
Feb	98	28	100.0	307753	440115	11.2	788601	1130764	117477	-0.9	35.8
Mar	98	31	100.0	465925	649925	10.9	740871	1233760	147555	-0.7	46.7
Apr	98	30	100.0	569098	773387	10.6	511599	1141880	156055	-0.7	60.2
May	98	31	100.0	514854	660144	10.0	673645	1182247	156992	-0.7	49.5
Jun	98	30	100.0	490151	616760	9.8	658291	1139891	149835	-0.6	48.4
Jul	98	31	100.0	604716	770575	10.0	566814	1182070	159175	-0.4	57.6
Aug	98	31	100.0	611211	795029	10.2	523138	1162785	158753	-0.6	60.3
Sep	98	30	100.0	574437	773388	10.5	523412	1145201	157660	-0.3	59.6
Oct	98	30	96.8	454123	641545	11.0	659654	1133137	151531	-0.2	49.3
Nov	98	30	100.0	383416	574917	11.7	753118	1197312	145577	-0.4	43.3
Dec	98	30	96.8	320011	469155	11.5	876209	1212948	139423	-0.6	34.9
Jan	99	28	90.3	325773	499641	12.0	713622	1095249	129458	-0.8	41.2
Feb	99	28	100.0	396523	583818	11.5	669834	1157858	126823	-1.0	46.6
Mar	99	31	100.0	566528	821731	11.3	625069	1286575	145809	-0.4	56.8
Cumulative		725	99.3	11502242	15662007	10.6	16307928	28772763	3379949	----	49.0
First 12 Months		365	100.0	5691400	7681916	10.5	8553522	14735611	1602857	----	47.3
Second 12 Months		360	98.6	5810842	7980090	10.7	7754406	14037153	1777091	----	50.72
Average Daily Values (Cumulative)				15865	21603	----	22494	39687	4662	----	----
Average Daily Values (First 12 Months)				15593	21046	----	23434	40372	4391	----	----
Average Daily Values (Second 12 Months)				16141	22167	----	21540	38992	4936	----	----

Table 4 Performance Results of FSEC Single-Tank Photovoltaic Water Heating System

Month	Year	# Days	Data Capture Rate (%)	Incident Solar Energy (kJ/m2)	Photovoltaic System Output (kJ)	Photovoltaic System Conversion Efficiency (%)	AC Electric Energy Supplied to Tank (kJ)	Energy Removed From Tank During Draws (kJ)	Heat Loss From Tank (kJ)	System Energy Balance (%)	Electrical Fraction (%)
Sep	98	30	100.0	464463	397965	10.0	462797	762632	90270	0.6	46.2
Oct	98	31	100.0	567107	490955	10.1	412056	806565	98155	0.2	54.4
Nov	98	30	100.0	476851	430659	10.6	504540	859018	87014	-1.0	46.1
Dec	98	31	100.0	452295	412709	10.7	598226	933757	92451	-1.2	40.8
Jan	99	31	100.0	500071	462782	10.8	575984	980239	85815	-2.2	44.6
Feb	99	28	100.0	509112	458042	10.5	491178	881340	81718	-2.0	48.3
Mar	99	31	100.0	671022	598846	10.4	439395	961682	95768	-2.1	57.7
Apr	99	28	93.3	625042	537550	10.1	313054	767411	93101	-0.9	63.2
May	99	25	80.6	513070	432768	9.9	325588	655662	81458	1.1	57.1
Jun	99	29	96.7	503128	425787	9.9	395673	730154	94306	1.0	51.8
Jul	99	25	80.6	522460	431960	9.7	286666	624631	85554	2.9	60.1
Aug	99	31	100.0	588873	486649	9.7	366823	755762	98820	0.5	57.0
Cumulative		350	95.9	6393494	5566672	10.2	5171979	9718855	1084431	----	51.8
Average Daily Values				18267	15905	----	14777	27768	3098	----	----

Table 5 Comparison of Single and Two Tank PVWH System Conversion Efficiencies

Single Tank PVWH System – NIST			Absolute Difference in Efficiency	Two Tank PVWH System – NIST		
Month	Photovoltaic System Conversion Efficiency	Average Daily Irradiance (kJ/m^2)		Month	Photovoltaic System Conversion Efficiency	Average Daily Irradiance (kJ/m^2)
Apr '98	10.6	18970	-0.6	Apr '96	11.2	17578
May '98	10.0	16608	-0.7	May '96	10.7	15918
Jun '98	9.8	16338	-0.5	Jun '96	10.3	20200
Jul '98	10.0	19507	-0.2	Jul '95	10.2	20827
Aug '98	10.2	19716	-0.2	Aug '95	10.4	20875
Sep '98	10.5	19148	-0.2	Sep '95	10.7	17078
Oct '98	11.0	15137	-0.3	Oct '95	11.3	17678
Nov '98	11.7	12781	-0.1	Nov '95	11.8	10937
Dec '98	11.5	10667	-0.3	Dec '95	11.8	12331
Jan '98	12.0	11635	-0.2	Jan '95	12.2	5616
Feb '98	11.5	14162	+0.1	Feb '95	11.4	12699
Mar '98	11.3	18275	-0.3	Mar '95	11.6	17302
12-month	10.7	15865	-0.3	12-month	11.0	15753

Finally, although not definitively quantified, a very slight degradation of the PV modules over time may be a factor.

Two-tank Installations

In Okinawa, the percent of electrical energy supplied by the solar photovoltaic water heating systems (i.e., electrical fraction) from January 1, 1998 to December 31, 1999 were 25.8 % for System I and 28.0 % for System II. Excluding the eight days where data on one or both systems were lost, System I produced 2942 kWh of DC electrical energy from its photovoltaic array and System II produced 3011 kWh of DC energy. System II consistently outperformed System I by approximately 2 %.

The electrical fractions were lower than originally expected. This result is partly due to the hot water usage being higher than the 243 liters per day assumed when designing the system and sizing the photovoltaic array. For example, based on water meter measurements made during the last 11 months of 1999, System I residents used an average of 450 L of hot water each day. System II residents averaged 333 liters per day over the same period. A second factor that may have contributed to lower than expected solar fractions was the lack of data on the solar resources in Okinawa. For design purposes, the authors had assumed the meteorological conditions in Okinawa would be similar to Tampa, Florida. Tampa was chosen because of its similar latitude and historical outdoor temperature data. Based on monitoring of the weather forecast for Okinawa, however, the authors now believe that Okinawa experiences comparatively more overcast and cloudy days.

Collective Experience

One of the several secondary issues investigated in the course of this field-monitoring project was to see if and how the resistances of the in-tank PV heating element assemblies change over time. Table 6 reports the findings for the changes in the resistive loads of the 3-cartridge heater assembly used at the FSEC location. Table 7 reports the same for resistive loads of the 3-in-1 assembly used in Okinawa, Japan, System I. In both cases the resistive loads were observed to increase slightly over time. In the case of the 3-cartridge heater assembly, the increases ranged from 0.5 % to 5.7 % over the two year period that was checked. For the 3-in-1 PV heating element assembly, the percent increase ranged from 1.3 % to 3.0 %. Despite these slight increases, no loss in photovoltaic system conversion efficiency was detected. Nonetheless, when designing a system, the realization of this trend leads one to choose resistive elements that are slightly lower than the target values.

Table 6. Changes in the resistive loads of the cartridge PV heating element assembly used at the FSEC installation.

Nominal Resistor Combination	Measured Resistance of Each Resistive Load Combination				
	May 1997	May 1998	May 1999	January 2000	% Increase May '97 to May '99
177	177.2	177.0	178.1	179.3	0.5
97	97.1	99.6	101.8	102.1	4.8
177||97	62.7	63.8	64.8	65.2	3.3
51*	51.4	53.3	54.3	54.5	5.6
177||51	39.8	41.0	41.7	41.9	4.8
97||51	33.6	34.7	35.5	35.7	5.7
177||97||51	28.2	29.1	29.6	29.7	5.0

*Replacement element having a measured resistance of 51.4S was installed January 1998.

Table 7. Changes in the resistive loads of 3-in-1 PV heating element assembly used at the Okinawa System 1 installation.

Nominal Resistor Combination	Measured Resistance of Each Resistive Load Combination			
	December 1997	December 1998	December 1999	% Increase Dec '97 to Dec '99
96	96.2	98.5	99.1	3.0
96||96	48.0	48.8	49.0	2.1
96||96||96	32.0	32.3	32.5	1.6
96||96||96||96	23.9	24.2	24.3	1.7
96||96||96||96||96	19.1	19.3	19.4	1.6
96||96||96||96||96||96	15.9	16.1	16.1	1.3

COMPARISON WITH ALTERNATIVE SOLAR APPLICATIONS

Grid-connected PV Systems

Although, a PV water heating system could conceivably be considered for applications where grid power was unavailable, the majority of potential applications are foreseen in grid-connected homes and commercial buildings. In such cases, the customer has the alternative of connecting the PV array to the utility grid.

The grid-connected alternative offers the flexibility of using the PV generated power for more end uses than just water heating. But, the grid-connected option means higher balance-of-system costs. Although improving, grid-connected PV also yields comparatively lower system reliability, higher maintenance costs, slightly lower conversion efficiencies, and greater burden for permitting, interconnecting, and inspection [7-9]. Typical end user costs for 1 kW to 2.5 kW, grid-connected inverters range from $0.75 to $1.70/Wac [7, 10]. For the unique components of the PVWH system (control module, two PV heating element assemblies, and a PV reference cell), end user costs are estimated to be $400 to $450. For an application with a 1500 W (peak) array, these costs thus become $0.27/W and $0.30/W. As with inverters, the potential for reducing these costs does exist.

Inverters and power conditioning equipment in grid-connected systems are still prone to operational problems that range from a nuisance circuit breaker trips to a complete equipment failure [7]. The result is unscheduled maintenance, repairs, and change outs. Typical inverter warranties are between 2 to 3 years which, in certain cases, can be extended to 5 years [11-13]. The relatively simple PVWH controller, heating elements, and reference cell, as expected, have been comparatively robust. The lone system problem experienced during the field testing, the shift in the resistance of one heating element within the FSEC single-tank system, only marginally reduced the conversion efficiency. In general, the balance-of-system (BOS) of the PVWH system is expected to provide better reliability and therefore comparatively longer warranties. The PVWH BOS components create a better match with the PV modules, which have associated warranties as high as 25 years for the more established crystalline modules [14].

As compared to a grid-tied system, the PVWH system is much less likely to experience a hardware failure or trip that causes a complete disconnect. A PVWH system, however, will have periods of disconnects if the hot water usage is low compared to the solar input. As with a battery-storage system, proper system sizing should mitigate any reduction in the solar utilization due to a fully recovered water heating storage tank.

The efficiency of a grid-tied inverter approaches the overall system conversion efficiency of the PVWH system [2,3,15]. The gap can widen, however, depending on the maximum point tracking capability of the grid-tied system and whether the inverter's efficiency tails off at high or low loading. Because the PVWH system is a stand-alone application, in addition, it doesn't face the same safety and ownership considerations that are unique to grid-connected systems [7,16].

The best prospects for a PVWH system is one where the array size is in the 1 to 2 kilowatt range, as would be typical on many residential installations. Next, the system would be best suited to cases where the residence has a moderate to high hot water load, which is preferably regular over the year. Finally, the end user would otherwise heat water using an electric water heater, as is the case in roughly 45% of the homes in the US [17,18]. If the daily energy supplied by the PV array is less than the energy used by the homes' grid-connected electric water heater, than the user would obviously be better off by using the PV array to directly heat water. The cost, complexity, and loss of efficiency of converting DC array power into AC power so that it can be used to heat water is avoided.

Solar Thermal Hot Water Systems

Solar thermal hot water systems are popular in some of the more temperate parts of the world like Israel and in the Caribbean. Solar thermal water heating, however, has failed to gain wide acceptance in many parts of the world, including most of the US. For those areas where solar thermal has found acceptance, the PVWH system is not yet competitive on a life cycle cost basis. The PVWH system offers a more reliable alternative with lower maintenance costs. Still, the first cost of the PVWH system will have to be reduced. As reported previously [2], the purchase price of photovoltaic modules would have to decrease to approximately $1.90 per peak watt for the cost of the PVWH system to be comparable to an equivalent solar thermal system. As this module price is approached, the opportunity for PVWH systems in areas where solar thermal systems are popular increases. More importantly, the potential market for PVWH systems expands to other locations where solar thermal has had limited acceptance mainly due to freeze concerns. For such locations, the more popular, simpler solar thermal systems (e.g., integrated collector storage, thermosyphon), can not be used without concern for catastrophic failure. With the PVWH system, living in a region that experiences freezing temperatures becomes a non-factor on whether a person who wishes to invest in solar energy can do so. More discussion on the relative merits PVWH system versus a solar thermal domestic water heating system is provided in reference [2].

SUMMARY

A photovoltaic solar water heating system has been developed and patented by the National Institute of Standards and Technology. Unlike other residential photovoltaic systems, no inverter or storage batteries are needed. The direct current supplied by the photovoltaic modules is supplied to a number of resistive heating elements by a control and power relay system that operates the array at a current-voltage combination that maximizes its power output.

To date seven prototype systems have been placed into operation and monitored. A previous paper reported on the performance of double-tank systems evaluated at NIST and FSEC. This paper summarizes the performance of two additional double-tank systems located in Okinawa, Japan and two single-tank systems evaluated at NIST and FSEC. Together these seven systems represent over seventeen years of field experience. To date, only two problems have occurred that resulted in slightly degraded performance, a faulty PV module and a shift in the electrical resistance of one heating element. Both probems occurred during evaluation of a single-tank system at the Florida Solar Energy Center and resulted in only a minor decrease in overall performance.

The NIST and FSEC single-tank systems provided 49.0 % and 51.8 %, respectiviely, of the energy needed to heat the 243 L of water withdrawn daily from each system. The photovoltaic array associated with the FSEC system utilized one-third less modules than the NIST system. The FSEC system's performance benefitted from a greater solar resource, a higher inlet water temperature, and reduced thermal losses from the tank.

Previously monitored two-tank systems were found to have a slightly higher conversion efficiency compared to the performance of single-tank systems presented in this paper. This difference is attributed to the use of six resistive elements in the two-tank systems compared to the three resistive elements used in the single-tank systems. The slight increase in performance must be weighed against the added cost of an additional storage tank, resistive elements, and power relays.

The two-tank systems in Okinawa, Japan, have performed flawlessly. The solar contribution of both systems to the total water heating load was significantly lower than originally projected. This lower contribution is attributed to the substantially higher hot water consumption (450 and 333 liters per day compared to the design value of 243 liters per day) and to extended periods of cloud cover.

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APPENDIX A

The primary measurements for the FSEC and NIST installations were the electrical fraction and photovoltaic system conversion efficiency. For the Okinawa sites, the primary measurement was electrical fraction. The expanded (k=2) uncertainties for these primary measurements were derived from the standard uncertainties of the applicable input quantities using current international guidelines [19]. Components that contribute to a standard uncertainty were combined by the method of propagation of errors.

For quantities where multiple entries are reported (e.g., for each month), an attempt was made to identify the case that yielded the highest standard uncertainty. Uncertainties derived from manufacturer's specifications were assumed to incorporate a coverage factor of unity (k=1). The resulting standard uncertainties were dominated by Type B evaluations.

The expanded (k=2) uncertainties of the primary measurements, which were derived from the single-sample laboratory and field measurements, are summarized in Table A-1. The standard uncertainties (k=1) of the input quantities are reported in Table A-2. The labels F, N, and O are used in the tables to designate the FSEC, NIST, and Okinawa installations, respectively.

Table A-1 Expanded Uncertainties of Primary Measurements

Quantity (Location: F, N, and/or O)	Expanded (k=2) Uncertainty (%)
Photovoltaic System Conversion Efficiency (F,N)	2.8
Electrical Fraction (F,N)	1.1
Electrical Fraction (O)	1.4

Table A-2 Standard Uncertainties of Input Quantities

Quantity (Location: F, N, and/or O)	Standard (k=1) Uncertainty (%)
Photovoltaic System Output (F,N)	0.5
AC Electrical Energy Supplied to Tank (F,N)	0.5
Incident Solar Energy (F,N) Average Daily Irradiance (F,N)	1.3
Energy Removed From Tank During Draws (F,N)	0.3
Heat Loss From Tank (F,N)	1.9
Tank Heat Loss Coefficient (F,N)	1.1
Daily Hot Water Consumption (O)	0.6
Measured Tank Volume (F,N)	0.4
Photovoltaic Array Size (F,N,O)	0.3
Measured Resistance of Each Resistive Load Combination (F,O)	0.3