Field Test of a Photovoltaic Water Heater

A. Hunter Fanney, Ph.D.
Member ASHRAE

Brian P. Dougherty
Associate Member ASHRAE

John O. Richardson, P.E.
Member ASHRAE

ABSTRACT

A solar photovoltaic water heating system has been installed at the Great Smoky Mountains National Park. The system provides hot water for the restroom facilities at the park's main visitor center. This paper gives an overview of the technology, describes the installation, and summarizes the performance of the system.

The initial scope of the project was to install and monitor the performance of the photovoltaic solar hot water system for 12 months. As the study progressed, it was broadened to study the effects of water conservation measures.

INTRODUCTION

The average home or business uses a significant amount of hot water. The energy used to meet these hot water loads is more than most people realize. In the U.S., for example, energy consumed for water heating accounts for approximately 7.8 EJ (7.4 quads) of the site energy consumed by residential and commercial buildings (U.S. DOE 1997, 1999). According to the U.S. Department of Energy, an electric water heater supplying a typical U.S. family consumes approximately the same amount of energy per year as a medium-sized automobile driven 19,300 km (12,000 miles) per year (Divone 1993).

The primary energy sources used to generate hot water are nonrenewable. Regrettably, this condition remains despite efforts to develop and promote the use of renewable, solar thermal water heaters for over a century. Clarence M. Kemp, for example, patented the nation's first commercial solar water heater, the Climax, in 1891 (Butti and Perlin 1979a). His solar water heating system consisted of a metal tank within a glass covered wooden box. Kemp's concept is still in use today in the form of integral collector storage (ICS) solar water heaters. William Bailey advanced the art of solar water heating in 1909 (Butti and Perlin 1979b) by separating the solar water heater into two separate components: a solar heat collector and a water storage tank. Bailey's system was the first to use an insulated storage tank and relied upon the thermosyphon principle to circulate water between the solar collector and the storage tank. Later, following a freak cold spell in the winter of 1913 that severely damaged systems located in the Southern California area, Bailey added a coiled tube heat exchanger within the storage tank and used an alcohol and water mixture to transfer heat from the solar collector to the storage tank. Although vast improvements have been made since the early work of Kemp and Bailey, the basic concepts of solar water heating have remained the same.

There are currently over 90 million water heaters in use within the United States (Zogg and Barbour 1996). The number of installed solar water heaters, by comparison, is less than 1 million due to durability and installation issues, as well as relatively high initial costs. Durability issues have included freeze and fluid leakage problems, failure of pumps and their associated controllers, the loss of heat transfer fluids under stagnation conditions, and heat exchanger fouling. The installation of solar water heating systems has often proved difficult, requiring roof penetrations for the piping that transports fluid to and from the solar collectors.

The solar photovoltaic hot water system described in this paper avoids the durability and installation problems associated with current solar thermal water heating systems (Fanney and Dougherty 1997; Dougherty and Fanney 2001; Fanney et al. 1997). The system employs photovoltaic modules to generate direct-current (DC) electrical power that is dissipated in

A. Hunter Fanney and **Brian P. Dougherty** are mechanical engineers at National Institute of Standards and Technology, Gaithersburg, Md. **John O. Richardson, Jr.,** is manager of Energy Use and Industrial Ecology Technology at TVA/Public Power Institute, Chattanooga, Tenn.

multiple electric heating elements (Fanney and Dougherty 1994). These multiple elements replace the normal single element(s) within a conventional electric water heater. A microprocessor controller and a set of electrical relays periodically determine and then connect the resistive heating elements that best match the instantaneous operating characteristics of the photovoltaic modules. Although currently more expensive than existing solar thermal hot water systems, solar photovoltaic water heaters offer the promise of being less expensive than solar thermal systems within the next several years.

Studies to evaluate and demonstrate the solar photovoltaic water heating technology have taken place at four different sites (Fanney et al. 1997; Dougherty and Fanney 2001). This paper reports on one of those four sites—the installation at the main visitors center at the Great Smoky Mountains National Park (GSMNP). Measured performance from November 1996 to February 2000 is reported. One year into the project, efforts to reduce the hot water consumption at the site were initiated. Results from the original installation and three alternative hot water conservation options are included.

SYSTEM OVERVIEW

Unlike the vast majority of solar photovoltaic applications, a photovoltaic water heating (PVWH) system requires neither a battery for energy storage nor an inverter to convert the DC power supplied by the photovoltaic array into an alternating-current (AC) power. The DC power supplied by the photovoltaic array is fed to one or more resistive elements that are immersed in a water storage tank. The stored hot water acts as the system flywheel or battery, readily overcoming the mismatch between when the solar heating is available and when the end user needs the hot water. Notably, the storage tank may contain an additional heating element connected to the electric utility. In lieu of the auxiliary heating element, an additional water heater, heated by electricity, gas, or oil, may be connected downstream of the solar storage tank. The purpose of the auxiliary heating element or second water heater is to ensure an adequate hot water supply.

The electrical current versus voltage (IV) characteristics of a photovoltaic array vary depending on such operating factors as array temperature, incident solar radiation, angle of incidence, and air mass. Of these factors, solar irradiance dominates. Two representative current versus voltage curves are shown in Figure 1 for a photovoltaic array subjected to two different levels of solar irradiance—200 W/m^2 and 1000 W/m^2. The higher level is representative of midday clear sky conditions. The lower irradiance level could be experienced during cloudy conditions or early morning and late afternoon hours on clear days.

The power output from the photovoltaic array depends on the connected load. Referring to Figure 1, every IV curve contains a single point where the product of the current and voltage gives the maximum power output, P_{max}. To achieve maximum conversion efficiency, the load must pass through the current versus voltage curve at this point. Failure to do so results in a reduction in the power generated by the photovoltaic array. For example, in Figure 1, an electrical resistance of 13 Ω passes through the maximum power point of the photovoltaic array when the irradiance is 1000 W/m^2. As the irradiance deviates from 1000 W/m^2, the 13 Ω load line no longer coincides with the maximum power point. At an irradiance of 200 W/m^2, the power output of the photovoltaic array would be 100 W. If, however, the resistive load were 67 Ω instead of 13 Ω, the particular photovoltaic array would produce 445 W. Thus, in order to capture the maximum possible energy for all meteorological conditions, a variable resistive load is needed.

In considering the PVWH application, the authors are unaware of a submersible heating element whose resistance is continuously variable. Fortunately, six heating elements wired in parallel can reasonably approximate a variable resistive load. The use of six resistive elements results in an annual photovoltaic energy output that is only 4% to 6% lower than the performance obtained using a theoretical, continuously variable resistive element (Fanney and Dougherty 1997; Fanney et al. 1997).

At the GSMNP installation, up to six photovoltaic (PV) heating elements can be connected to the photovoltaic array at any given time. One of the heating elements is hard-wired to the photovoltaic array; the other five elements are connected, when needed, using mechanical relays. The decision as to which elements to connect at any given time depends solely on the solar irradiance measured in the plane of the PV array. The sensor used to measure irradiance supplies a voltage signal to a microprocessor-based controller. The controller takes this signal, executes the simple logic that decides which resistive elements to connect, and then outputs low-voltage signals to toggle the appropriate relays. At the GSMNP site, the controller repeats this process every minute.

At low sunlight conditions, a high resistive load yields the greatest power output. The highest resistive load is achieved by using only one of the six resistive elements, the hard-wired

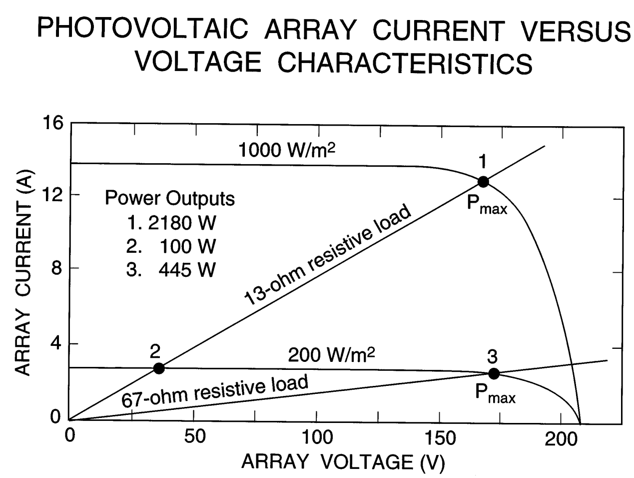

Figure 1 *Electrical characteristics of a photovoltaic array.*

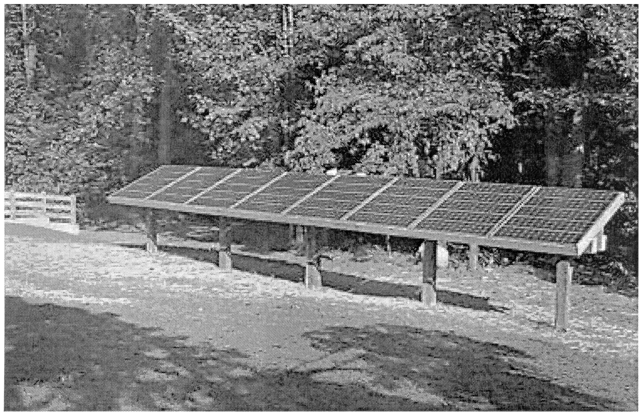

Figure 2 *Photovoltaic array, Gatlinburg, Tenn.*

resistive element. As the solar irradiance increases, the other heating elements are sequentially connected in parallel. An in-depth discussion of the procedure used for selecting the electrical resistance of the PV heating elements and for determining the irradiance levels at which to change the connected load is described elsewhere (Fanney and Dougherty 1997; Williams 1996).

The PVWH system at the Great Smoky Mountains National Park, which is located at 35.5° north latitude and 71° west longitude, provides hot water to high-use bathroom facilities and a janitorial closet found within the park's main visitors center. The photovoltaic array (Figure 2) faces true south with a tilt angle of 23°. Although a tilt equal to latitude is often recommended for solar installations, this lower tilt offers slightly better performance during the months of highest attendance at the park (May to October) in exchange for slightly lower performance during the colder months, while impacting annual performance negligibly. The array consists of forty single-crystalline photovoltaic modules interconnected in a manner that results in four parallel strings of ten modules connected in series. The rated power output is 2120 W_{peak}.

Two water storage tanks are used at the GSMNP installation (Figure 3). The grid-connected auxiliary tank is an unmodified 200 L (52 gallon), two-element, electric water heater. The solar storage tank is a 300 L (80 gallon) electric water heater in which the standard upper and lower heating elements have been replaced with PV heating element assemblies (Dougherty and Fanney 2001). Each assembly contains three independent resistive elements. The upper assembly contains resistive elements having nominal ratings of 70, 85, and 115 ohms. The nominal resistances of the three elements in the lower assembly are 70, 95, and 115 ohms. These elements provide total resistances that vary from 15 to 70 ohms. Although implemented after the close of the monitoring period, overheating of the water is prevented by passing the photovoltaic array's current through the thermostat normally used to control the lower resistive element. If the temperature sensed by this thermostat exceeds its setpoint, the flow of

Figure 3 *Solar storage and auxiliary tanks.*

current to all PV resistive elements ceases until the same thermostat again "calls" for heating. As a safety precaution, the water heater's high-temperature safety limit thermostat was connected within the PV electrical circuit as part of the initial installation process. This thermostat, which must be manually reset, acts to prevent pressure vessel failures brought on by very high stored water temperatures.

INSTRUMENTATION AND MEASUREMENT UNCERTAINTIES

Key system performance parameters were recorded throughout the multiyear monitoring period. An integrating water meter measured the quantity of hot water supplied by the system. A digital power analyzer recorded the energy provided by the photovoltaic array to the PV heating elements. A second digital power analyzer recorded the electric utility-supplied energy to the 200 L (52 gallon) auxiliary water heater. Precision spectral pyranometers measured the incident solar radiation on the solar array and on a horizontal surface. A personal computer scanned the instrument signals every 10 seconds. The data, after being converted into engineering units and, if applicable, integrated, were saved every hour. The data were forwarded to NIST periodically by park personnel for final reduction and analysis.

Two key derived quantities are the electrical fraction and the photovoltaic system conversion efficiency. Electrical fraction is defined as the electrical energy supplied by the PV array divided by the sum of the electrical energy supplied by the PV array and the utility AC grid. Photovoltaic system conversion efficiency equals the electrical energy supplied by the PV array divided by the total radiative energy incident on the array. The denominator, in this case, is the product of the incident solar radiation measured in the plane of the array and the total area of the PV array. As noted in the introduction section of this paper, the electrical power supplied by the PV array depends not only on the array but, on the connected load and the degree that this load tracks at or near the maximum power operating point of the array's IV curve.

The expanded uncertainties for the electrical fraction and photovoltaic system conversion efficiency were derived from the standard uncertainties of the applicable input quantities using current international guidelines (ANSI 1997). The expanded uncertainties correspond to a coverage factor (k) of 2, which approximates a confidence level of 95%. The expanded uncertainties associated with the electrical fraction and photovoltaic system conversion efficiency are ±1.6% and ±3.2%, respectively. The standard uncertainties (k=1) of the input quantities are as follows: ±0.4% for the AC electrical energy measurement, ±0.9% for the DC energy supplied by the photovoltaic system, and ±1.4% for the solar radiation incident on the array. This last uncertainty also applies for the measurement of solar radiation incident on a horizontal surface.

Along with electrical fraction, the two key variables used in assessing the water conservation measures included the hot water volume and the quotient of the average daily AC energy supplied to the auxiliary water heater divided by the daily hot water draw volume. The expanded (k = 2) uncertainties associated with these two additional parameters are ±0.6% and ±0.9%, respectively.

FIELD MONITORING

The photovoltaic water heating system was installed in late September 1996. The first full month of field monitoring was November 1996. Although originally envisioned as a one-year project, performance monitoring continued into the first few months of 2000 in order to document the impact of various attempts to reduce the hot water consumption.

Four different hot water configurations were investigated. For the first two configurations, manually operated faucets were installed. For the original configuration, aerators having a nominal rating of 17 L/min (4.5 gal/min) were installed. For the second configuration, the aerators were replaced with ones having a nominal rating of 8.3 L/min (2.2 gal/min). The monitoring period associated with the first configuration was November 1, 1996, to October 1, 1997; the monitoring period for the second configuration was October 3, 1997, to October 18, 1998. Hot water delivery temperatures in the 45°C (113°F) range were recorded during spot checks during the first year of operation.

Between October 19 and 26, 1998, the manually operated faucets were replaced with sensor-operated faucets. The replacement faucets emit infrared light that is reflected back to the senor receiver when users place their hands under the faucet. When the reflected infrared light is sensed, the solenoid valve of the sensor-operated faucet opens. As part of the installation, the hot and cold water supplies are combined at a below-deck, mechanical mixing valve whose outlet connects to the solenoid valve. For the third configuration, which ran from October 27, 1998, to March 8,1999, new aerators having the same nominal rating as the aerators used for the second configuration, 8.3 L/min (2.2 gal/min), were installed. Finally, on Mach 9, 1999, these aerators were replaced with ones having a nominal rating of 1.9 L/min (0.5 gal/min). Data for this fourth configuration are provided for the period of March 10,1999, to February 29, 2000. A hot water delivery temperature of 41°C (106°F) was measured several months after the close of the fourth monitoring period at both the tank outlet and at a faucet outlet. Although never logged as being implemented, the lower delivery temperature suggests that the auxiliary tank thermostat was adjusted downward at some point.

In the "Results and Discussion" section that follows, the hot water volume measurements are grouped based on the intervals when the four hot water configurations—Configurations I, II, III, and IV—were implemented. The monitoring intervals for each of the four configurations include the months of November to February and so comparisons based on this common period are provided. Electrical fractions, which depend on hot water use, are also reported based on the monitoring intervals for Configurations I, II, III, and IV.

As long as the system is allowed to operate, the conversion efficiency of the photovoltaic system does not depend on the particular water conservation configuration. As a result, photovoltaic conversion efficiencies are reported by month and then overall comparisons are based on the calendar year.

For the 40 months of data used in evaluating the four water conservation configurations, 95% of the water draw volume data is reported. For the three years used in evaluating the photovoltaic system's conversion efficiency, 87% of the data is reported. Data losses ranged from a single hour to several consecutive days. Data losses were caused by computer software glitches, a few power outages, one partial failure of the data acquisition card, one complete failure of the card, and human error in managing data files. If data were lost for any hour of the day when hot water draws were likely to occur or when the array would have been irradiated, then the entire day was excluded. Other reasons for excluding daily data included: (1) days when either the faucets or aerators were changed, (2) days when periodic maintenance checks of the overall photovoltaic system were conducted, and (3) days when the photovoltaic system was not operating normally. Although definitely affecting the performance of the photovoltaic system, no exclusions were made due to times when the PV array was partially or completely covered by snow.

Between September 1996 and February 2001 (the time of the last on-site check of the overall system), four events occurred that caused the PV water heating system to operate less than optimally. The first occurred during a few days in March 1997. A fuse in the photovoltaic circuit became loose and prevented PV power from the array being supplied to the solar water heater. A simple bending of the fuse holder produced a tight fit on the fuse and fixed the problem. In 1998, the AC power to the PVWH controller was mistakenly unplugged from July 25 to September 20. The third event came about as a result of overheating the solar storage tank. On January 12, 2000, the water heater's high temperature limit thermostat tripped, thus preventing any PV water heating. The thermostat was manually reset on February 17. Apparently, within a day or two of this action, one of the original field wiring connections at the back of one PV module failed. The power production of the system was reduced by approximately 25 percent until a replacement module was installed.

The first and fourth events could potentially happen to any photovoltaic installation. Based on the authors' experience with other PV installations, such problems are rare. The second event was due to human error. The third event is easily avoided by using one of the tank's thermostats to prevent the unsafe, overheating condition. The events did support the need to eventually build into the controller some simple fault detection features that could alert and aid an owner with troubleshooting potential problems.

RESULTS AND DISCUSSION

The electrical performance of just the photovoltaic system is summarized in Table 1. The monthly photovoltaic system conversion efficiencies (column 5) ranged from 9.0% to 10.7%. The trend toward slightly higher efficiencies during the colder months is a characteristic of single-crystalline photovoltaic modules. The average annual conversion efficiencies were very consistent: 9.8% for 1997, 9.6% for 1998, and 9.6% for 1999. The overall conversion efficiency for the full three-year monitoring period was 9.7%.

Although conversion efficiencies tend to peak in the colder months, the average daily PV system energy production peaks during the warmer months, with a maximum value of 8.50 kWh/day being recorded in May (1999) — see Table 1, column 7. Given the relatively small monthly variation in conversion efficiency, the PV system energy production is driven mainly by monthly variations in the local solar resource. As shown in Figure 4 for the representative year of 1999, the solar resource at the GSMNP site and its south-facing, tilted array peaks in mid-spring and late summer.

In Figure 4, the measured incident solar radiation on a horizontal surface, expressed on the same average daily basis, is included to show the relative benefits from the 23° tilt of the array. For this case of 1999, the annual solar gain on the tilted surface exceeded that on a horizontal surface by 14%. A horizontal orientation outperforms the 23° tilted orientation only during a few weeks near the summer solstice, June 21. Times when the horizontal orientation is better are minimized somewhat at this site due to an obstructed view to the sky by hills and trees during these times when the sun rises and sets north of the east-west line. These obstructions also play a small part in the slight trough in the local solar resource observed during the months of June and July. Two other contributing factors include the tilt (even a zero tilt) not being optimal and, based on a review of the daily data, a trend of having comparatively more cloudy days during June and July versus May, August, and September.

A limited comparison with other PVWH field sites, all of which use the same model of photovoltaic modules as used at the GSMNP site, is offered in Table 2. The GSMNP system uses the most photovoltaic modules (40) of the listed sites and so has the largest rated power output (2120 W_{peak}). The GSMNP system's 9.7% overall conversion efficiency runs a little lower than the 10.0% to 11.0% efficiencies (column 3) recorded at the Maryland and Florida sites (Fanney et al. 1997; Dougherty and Fanney 2001). The difference in efficiencies suggests the resistive loads for the park system are not as optimally selected and sequenced. The difference is also consistent with the greater shading conditions at the park due to snow, leaves, and more gradual transitions each day from fully shaded to fully lit and then from fully lit to fully shaded.

Referring again to Table 2, the GSMNP system average annual energy production (column 4) is 2245 kWh. To better compare with the other PVWH installations, annual production is divided by the nominal power rating of each array. This ratio (column 5) varies from 1.06 to 1.52 kWh/W_{peak}. This site-to-site variation is attributed mainly to the differences in the local solar resource and then secondly to the differences in conversion efficiency. The GSMNP PV array is exposed to an average daily solar irradiance (column 6) of 13.42 MJ/m^2, which is 27% lower than the mean of the two values recorded for the Florida systems. Besides factors such as latitude, cloud cover, and precipitation, the location of the park visitor center in a valley also contributes to the park's comparatively lower solar resource. The other sites offer relatively flat terrain and the arrays are installed at local high points where the array is directly illuminated from sunrise to sunset (for times when the sun rises south of the local east-west line). The valley setting and the unfavorable elevations of the array relative to surrounding woodlands reduce the daily interval when the sun directly illuminates the GSMNP array.

Further evaluation of the PVWH system(s) can be aided by considering that the PV module used for the Table 2 sites has a rated efficiency at standard conditions of 12.4%. When compared to the range of field conditions, standard rating conditions are close to optimal: an irradiance of 1000 W/m^2, module operating at 25°C, a radiative spectrum associated with an air mass of 1.5, module oriented normal to the radiation source, and operation at the maximum power point. Thus, the difference between the rated efficiency of a PV module and field-measured annual efficiencies of the entire system shows the impact from operating over a wide range of conditions and powering a connected load that does not always coincide with the maximum power point.

The accidental unplugging of the PV water heating system's controller from July 25 to September 20, 1998 (Table 1), provides insight into the impact of a utility-grid power

TABLE 1
Measured Performance of the Solar Photovoltaic Components

Month	Days of Data	Cumulative Solar Energy Incident on PV Array (MJ/m²)	Cumulative PV System Output (kWh)	PV System Conversion Efficiency (%)	Daily Average Solar Energy Incident on PV Array (MJ/m² per day)	Daily Average PV System Output (kWh per day)
Jan 97	31	298.5	150.8	10.7	9.63	4.86
Feb 97	28	283.3	141.5	10.5	10.12	5.05
Mar 97[1]	2	15.9	7.3	9.7	---------[2]	---------[3]
Apr 97	24	386.6	181.9	9.9	16.11	7.58
May 97	31	554.9	257.3	9.8	17.90	8.30
Jun 97	30	411.3	193.3	9.9	13.71	6.44
Jul 97	31	523.6	237.5	9.6	16.89	7.66
Aug 97	31	529.5	232.7	9.3	17.08	7.51
Sep 97	30	469.0	206.8	9.3	15.63	6.89
Oct 97	29	385.6	178.1	9.7	13.30	6.14
Nov 97	30	239.2	106.8	9.4	7.97	3.56
Dec 97	24	137.9	66.3	10.1	5.75	2.76
Jan 98	24	177.6	80.2	9.5	7.40	3.34
Feb 98	28	251.1	116.5	9.8	8.97	4.16
Mar 98	31	407.3	188.5	9.8	13.14	6.08
Apr 98	30	442.3	205.1	9.8	14.74	6.84
May 98	31	490.5	227.3	9.8	15.82	7.33
Jun 98	30	478.9	209.4	9.2	15.96	6.98
Jul 98[4]	24	369.5	164.6	9.4[5]	15.40[6]	6.86
Aug 98[4]	0	0.0	0.0	---------[5]	---------[6]	---------
Sep 98[4]	10	142.0	62.6	9.3[5]	14.20[6]	---------[2]
Oct 98	28	455.8	206.4	9.6	16.28	7.37
Nov 98	30	290.7	134.2	9.7	9.69	4.47
Dec 98	31	218.2	99.1	9.6	7.04	3.20
Jan 99	31	266.1	129.2	10.2	8.58	4.17
Feb 99	28	327.4	158.2	10.2	11.69	5.65
Mar 99	31	430.2	198.8	9.7	13.88	6.41
Apr 99	28	476.5	214.5	9.5	17.02	7.66
May 99	31	583.0	263.4	9.5	18.81	8.50
Jun 99	30	436.0	198.6	9.6	14.53	6.62
Jul 99	27	409.8	183.4	9.4	15.18	6.79
Aug 99	30	576.8	248.7	9.1	19.23	8.29
Sep 99	12	235.5	100.2	9.0	19.63	8.35

TABLE 1 (Continued)
Measured Performance of the Solar Photovoltaic Components

Month	Days of Data	Cumulative Solar Energy Incident on PV Array (MJ/m^2)	Cumulative PV System Output (kWh)	PV System Conversion Efficiency (%)	Daily Average Solar Energy Incident on PV Array (MJ/m^2 per day)	Daily Average PV System Output (kWh per day)
Oct 99	31	455.3	206.9	9.6	14.69	6.67
Nov 99	29	368.3	171.5	9.8	12.70	5.91
Dec 99	31	321.4	153.8	10.1	10.37	4.96
1997	321	4235.0	1960.3	9.8		
1998	297	3724.0	1693.9	9.6		
1999	339	4886.0	2227.2	9.6		
1997 to 1999	957	12845.0	5881.4	9.7	13.42[7]	6.15[7]

1 Data acquisition channels for solar radiation measurements failed on March 3.
2 Insufficient data to calculate daily average for the complete month.
3 PVWH system energy production was available for 24 days in March 1997; daily average output equaled 8.53 kWh per day.
4 PVWH controller accidentally unplugged from July 25 to September 20, 1998; PVWH system operated at reduced efficiency.
5 The photovoltaic system conversion efficiency during the period that the PVWH controller was unplugged was 4.4%.
6 Solar radiation data were available for each day in July, August, and September 1998; daily averages equaled 14.31, 17.91, and 17.16 MJ/m^2 per day, respectively.
7 Judged to be conservative due to the exclusion of data from July 25 to September 20, 1998.

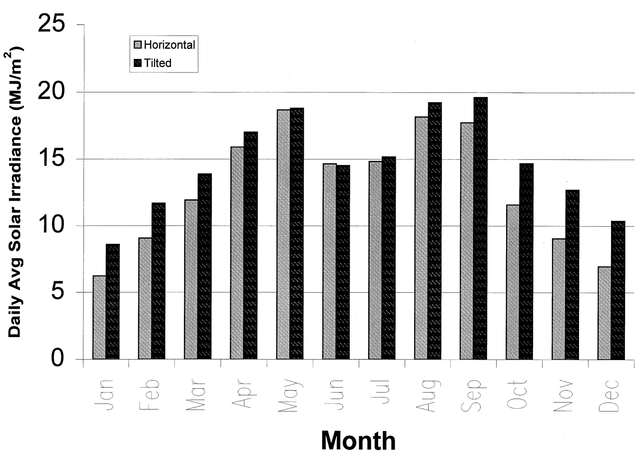

Figure 4 *Solar resources at the Great Smoky Mountains National Park.*

outage, when only one resistive element is used rather than the normally available six load options. During the “unplugged” period, the system conversion efficiency was 4.4%. This reduced efficiency is less than half the conversion efficiency achieved for the same period in 1997 and 1999. The PV system, however, continues to heat water during a power outage. If the controls were powered by the PV array, the stand-alone benefit of the system would be even further enhanced.

Insight into the water heating performance of the PVWH system and the water-conserving successes and failures among the four hot water configurations can be gained by reviewing the data summarized in Tables 3 and 4. Table 3 covers Configurations I and II, when manually operated faucets were installed. Table 4 summarizes results from the intervals when the sensor-operated faucets were installed, Configurations III and IV.

Configuration I

A total of 242,538 L (64,072 gal) were consumed during the 327 days of collected data. The average daily hot water consumption varied from 227 L (60 gal) per day during January 1997 to 1144 L (302 gal) per day for the month of July1997 (Figure 5). For the common interval of November to February, the average daily hot water draw volume was 351 L (93 gal per day—see bottom of Table 3, column 4.

The monthly electrical fractions (column 5) ranged from a low of 22.3% during the month of June to a high of 49.3% for the month of January. In this case, the 5X variation in hot water consumption played the larger role (versus the solar contribution) in affecting the monthly electrical fractions. The electrical fraction for the Configuration I monitoring interval was 30.2%. Of the total 320 days during Configuration I where the PVWH system was operating properly, there were six days (i.e., four in January and one each in February and March) when no AC auxiliary heating was needed and the daily electrical fractions were 100%. These 100% days tended to occur on days of comparatively low hot water usage.

TABLE 2
Comparisons with Other PVWH Field Sites

PVWH System	PV Array Rated Output (W)	PV System Conversion Efficiency (%)	Annual PV Energy Production (kWh)	Ratio of Annual Energy Production to Array Rated Output (kWh/W_{peak})	Average Daily Solar Irradiance (MJ/m^2)
GSMNP	2120	9.7	2245	1.06	13.42
NIST two-tank[1,2]	1590	11.0	2243	1.41	15.75
NIST single-tank[1,3]	1590	10.6	2190	1.38	15.87
FSEC two-tank[2,4]	1431	10.0	2177	1.52	18.57
FSEC single-tank[3,4]	1060	10.2	1613	1.52	18.27
Okinawa I[3,5]	1272	—[6]	1487	1.17	—[6]
Okinawa II[3,5]	1272	—[6]	1522	1.20	—[6]

[1] Refers to a PVWH system evaluated at the National Institute of Standards and Technology, Gaithersburg, Md.
[2] See Fanney et al. (1997)
[3] See Dougherty and Fanney (2001)
[4] Refers to a PVWH system evaluated at the Florida Solar Energy Center, Cocoa, Fla.
[5] Refers to a PVWH system evaluated at a U.S. military housing unit in Okinawa, Japan.
[6] Solar radiation instrumentation not installed at this field site.

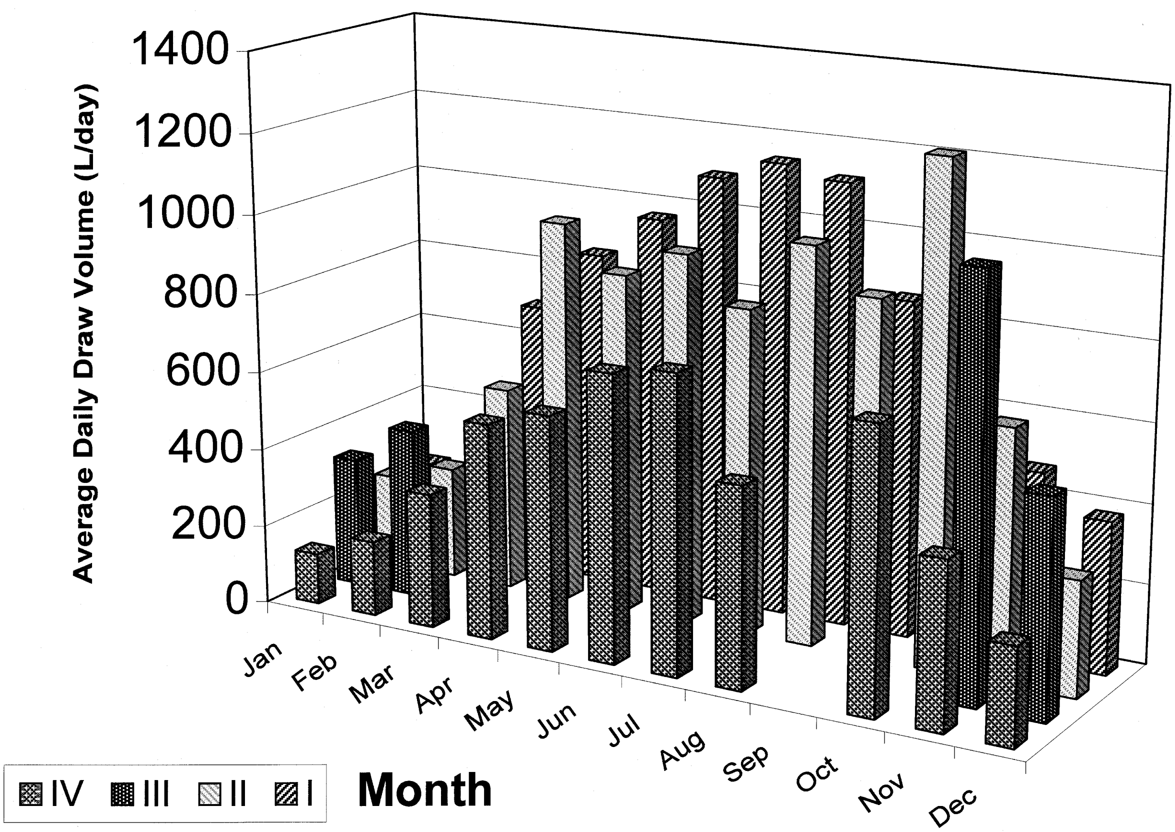

Figure 5 *Daily hot water consumption.*

TABLE 3
Overall System Performance When Using Manually Operated Faucets

Month or Partial Interval	Days of Data[1]	Hot Water Volume (L)	Daily Average Hot Water Volume (L/day)	Electrical Fraction (%)	AC Electric Energy Supplied to Auxiliary Tank (kWh)	Daily Average AC Energy Supplied to Auxiliary Tank (kWh/day)	AC Energy Input Per Hot Water Volume Withdrawn (Wh/L)
Configuration I. Manually Operated Faucets with 17 L/min rated aerators, November 1, 1996, to October 1, 1997							
Nov 1996	30	14191	473	26.1	344.0	11.47	24.2
Dec 1996	29	11042	381	28.6	296.1	10.21	26.8
Jan 1997	31	7022	227	49.3	155.0	5.00	22.1
Feb 1997	28	9221	329	40.6	206.9	7.39	22.4
Mar 1997[2,3]	31 / 24	21622	697	37.9	335.2	13.97	21.0
Apr 1997	24	20521	855	28.2	463.3	19.30	22.6
May 1997	31	29969	967	28.5	646.2	20.85	21.6
Jun 1997	30	32706	1090	22.3	671.9	22.40	20.5
Jul 1997	31	35450	1144	28.7	589.9	19.03	16.6
Aug 1997	31	34599	1116	28.7	578.5	18.66	16.7
Sep 1997	30	25389	846	31.8	443.1	14.77	17.5
Oct 1-2, 1997	1	806	—[4]	—[4]	14.0	—[4]	—[4]
Configuration II. Manually Operated Faucets with 8.3 L/min rated aerators, October 3, 1997, to October 19, 1998							
Oct 3-31, 1997	28	34845	1244	19.7	699.9	25.00	20.1
Nov 1997	30	18866	629	19.6	438.9	14.63	23.3
Dec 1997	24	6920	288	27.0	179.5	7.48	25.9
Jan 1998	24	5693	237	36.9	136.9	5.70	24.0
Feb 1998	28	7995	286	38.9	183.2	6.54	22.9
Mar 1998	31	16156	521	32.0	400.4	12.92	24.8
Apr 1998	30	29129	971	22.9	689.5	22.98	23.7
May 1998	31	26729	862	29.1	553.4	17.85	20.7
Jun 1998	30	28057	935	29.8	494.4	16.48	17.6
Jul 1998[2,5]	31 / 24	25461	821	28.2	419.1	17.46	16.5
Aug 1998[2,5]	31 / 0	30938	998	—	—	—	—
Sep 1998[2,5]	30 / 10	26744	891	—[4]	136.4	—[4]	—[4]
Oct 1-18, 1998	16	20608	1288	25.0	352.0	22.00	17.1
Cumulative Totals for the Complete Monitoring Periods							
Configuration I[2,3]	327 / 320	242538	742	30.2	4744.1	14.83	
Configuration II[2,5]	364 / 306	278140	764	26.8	4683.6	15.31	
Cumulative Totals for November Through February							
Configuration I	118	41477	351	34.7	1002.0	8.49	24.2
Configuration II	106	39474	372	28.3	938.5	8.85	23.8

1 Where two entries are listed, the first entry is the number of days when the hot water volume measurements are complete; the second, underlined entry is the number of days when the PVWH controller was operating correctly.
2 Underlined entries are based on the same data set (see note 1).
3 Energy quantities are not reported for the seven days in March where a loose fuse prevented PV water heating.
4 Data interval judged insufficient to report a value for the designated category.
5 PVWH controller accidentally unplugged from July 25 to September 20, 1998.

TABLE 4
Overall System Performance When Using Sensor-Actuated Faucets

Month or Partial Interval	Days of Data[1]	Hot Water Volume (L)	Daily Average Hot Water Volume (L/day)	Electrical Fraction (%)	AC Electric Energy Supplied to Auxiliary Tank (kWh)	Daily Average AC Energy Supplied to Auxiliary Tank (kWh/day)	AC Energy Input Per Hot Water Volume Withdrawn (Wh/L)
Configuration III. IR-Actuated Faucets with 8.3 L/min rated aerators, October 27, 1998, to March 8, 1999							
Oct 27-31, 1998	4	8460	—[2]	—[2]	150.8	—[2]	—[2]
Nov 1998	30	31275	1042	16.1	699.8	23.33	22.4
Dec 1998	31	16720	539	20.0	397.1	12.81	23.7
Jan 1999	31	10213	329	38.3	208.5	6.73	20.4
Feb 1999	28	12091	432	40.1	236.8	8.46	19.6
Mar 1-8, 1999	8	3717	—[2]	—[2]	73.4	—[2]	—[2]
Configuration IV. IR-Actuated Faucets with 1.9 L/min rated aerators, March 10, 1999, to February 29, 2000							
Mar 10-31, 1999	22	7499	341	68.7	65.0	2.95	8.7
Apr 1999	28	15270	545	56.3	166.5	5.95	10.9
May 1999	31	18382	593	59.7	177.9	5.74	9.7
Jun 1999	30	21626	721	42.0	274.2	9.14	12.7
Jul 1999	27	20161	747	47.7	201.0	7.44	10.0
Aug 1999	30	15066	502	91.9	21.8	0.73	1.4
Sep 1999	12	4913	—[2]	—[2]	6.8	—[2]	—[2]
Oct 1999	31	21781	703	46.3	239.6	7.73	11.0
Nov 1999	29	11985	413	61.5	107.3	3.70	9.0
Dec 1999	31	7491	242	78.5	42.2	1.36	5.6
Jan 2000[3,4]	29 / 11	3766	130	—[2]	9.8	—[2]	—[2]
Feb 2000[3,5]	29 / 0	5512	190	—	—	—	—
Cumulative Totals for the Complete Monitoring Periods							
Configuration III	132	82476	625	25.5	1766.4	13.38	
Configuration IV[3,4,5]	329 / 282	153453	466	59.7	1312.1	4.65	
Cumulative Totals for November Through February							
Configuration III	120	70299	586	25.2	1542	12.85	21.9
Configuration IV[3,5]	118 / 71	28754	244	—[2]	—[2]	—[2]	—[2]

[1] Where two entries are listed, the first entry is the number of days when the hot water volume measurements are complete; the second, underlined entry is the number of days when the PVWH controller was operating correctly.
[2] Data interval judged insufficient to report a value for the designated category.
[3] Water heater high-temperature safety limit thermostat tripped on January 12, 2000; manually reset on February 17, 2000; no PV water permitted during this interval.
[4] Underlined entries are based on the same data set (see note 1).
[5] An electrical connection within one of the PV module failed in mid-February, thus causing a one-quarter reduction in PV energy generation.

Configuration II

As noted in Table 3, hot water consumption hovered around 35,000 L (9200 gal) per month during July and August 1997. Based upon this high hot water consumption, park personnel supported actions to reduce the quantity of hot water consumed.

The first attempt at reducing hot water consumption—replacing the existing 17.0 L/min (4.5 gpm) faucet aerators within the restroom facilities with 8.3 L/min (2.2 gpm) units—was found to have little impact. Hot water consumption actually increased 3.0% (742 to 764 L/day) when considering the full Configuration I and II intervals and 6.0% (351 to 372 L/day) when considering the common interval of November through February. The other indicators of performance changes, electrical fraction and daily AC energy to the auxiliary tank, also yielded poorer numbers for Configuration II than for Configuration I. These energy descriptor changes, however, were partly due to comparatively lower PVWH contribution, 4.51 kWh/day for Configuration I versus 3.49 kWh/day for Configuration II. During the 306 days reported for Configuration II, none recorded an electrical fraction of 100%; some level of auxiliary heating was always required.

A direct measurement of the number of individual sink draws within the visitor center restroom facilities was never pursued. To provide insight as to whether the increase in hot water usage was due to more people using the restroom facilities, the authors used the monthly attendance logs that are maintained by the National Park Service. Attendance numbers for the Gatlinburg park entrance, which is where the main visitors center is located, were used. The average daily entries increased from 9356 people per day for Configuration I to 10,289 people per day for Configuration II, a 10.0% increase. Whereas this result suggests that the new aerators may have marginally helped, a comparison of the entry numbers for the common months of November to February were virtually identical. The general conclusions of those involved with the project were that the replacement aerators had little impact and that another alternative water conservation measure should be pursued.

Configuration III

Questioning whether users tend to run the water more than is needed, the project leaders decided to try automatic faucets. The aerators on the new faucets had the same nominal flow rating, 8.3 L/min (2.2 gpm), as the aerators used for Configuration II. Automatic faucets offer the trade-off of potentially shorter draw times versus always operating at maximum flow. No throttling is provided as with a manual faucet.

The water volume and energy usage results for Configuration III were poorer than for the two previous hot water configurations. Using the common interval of November to February as the basis for comparison, the average daily hot water volume increased 58% (372 L/day to 586 L/day). The average daily AC energy requirement increased to 12.85 kWh/day, as compared to 8.49 and 8.85 kWh/day for Configuration I and II, respectively. Electrical fraction dipped to 25.2%. This value is compared with the 34.7% value for Configuration I where the PVWH contribution (4.51 kWh/day) was close to the Configuration III PVWH input (4.34 kWh/day).

The changes in the Configuration III energy performance descriptors could potentially have been worse. The ratio of the AC energy input per volume withdrawn (column 8 in Tables 3 and 4) actually decreased: 21.9 Wh/L for Configuration III versus 24.2 Wh/L for Configuration I and 23.8 Wh/L for Configuration II. With the PVWH contribution being diluted by the larger draw volumes, this ratio was expected to increase. A possible explanation for the reversal is the earlier noted difference between the hot water delivery temperatures measured during the first year versus those measured after the close of the monitoring project. If the auxiliary tank thermostat setting was reduced when the automatic faucets were installed, then the amount of auxiliary energy would be lessened, thus driving the per volume ratio down and reducing the negative impact on electrical fraction and daily average AC energy consumption.

Part of the changes noted with Configuration III appears to be a result of more people using the restroom facilities. The November to February attendances for Configurations I and II were nearly identical, as were the attendance numbers for Configurations III and IV. However, the III and IV attendance numbers are approximately 22% higher than the I and II numbers. The significant jump between the Configuration II November to February interval and the Configuration III interval helps to explain some, but certainly not all, of the volume and energy usage changes.

These results suggest that the “always maximum flow” feature of the automatic faucets had a greater impact than the “potential” decrease in the total draw time, which may or may not have been realized. Although intended to be an improvement, hot water Configuration III had quite the opposite effect. Thus, within a few months of operating with the sensor-actuated faucets, a decision was made to install the alternative, lower flow aerators that were specifically made for the installed model of faucet.

Configuration IV

Whereas going from a 17 L/min-rated aerator (Configuration I) to an 8.3 L/min-rated aerator (Configuration II) had virtually no impact, the change to 1.9 L/min-rated aerators had a significant impact. Referring to Figure 5, the aerators yielded significantly lower monthly hot water consumptions. This result occurred even though average daily attendance at the park was slightly higher for the Configuration IV overall monitoring period than for the Configurations I and II overall intervals. When compared over the common November to February interval, the average daily usage for Configuration IV was 58% lower than the usage for Configuration III (244 L/day versus 586 L/day). Despite the approximately 22% greater attendance, the Configuration IV November to February usage of 244 L/day was well below the Configuration I and II values of 351 and 372 L/day, respectively.

The Configuration IV monthly electrical fractions soared (Table 4). The monthly low was 42.0% for June while the monthly high was August with 91.9%. The electrical fraction for the overall Configuration IV interval was 59.7%. Finally, of the 282 days reported, electrical fractions of 100% were recorded on 55 days. The reduction in the hot water load was so great that the PV array could now be qualified as borderline oversized.

SUMMARY

A solar photovoltaic water heating system was installed at the Great Smoky Mountains National Park in September 1996 and then monitored until early in 2000. The photovoltaic system eliminates the durability and reliability issues associated with solar thermal hot water systems without requiring an inverter or battery storage system. The main component of the system, the photovoltaic module, is currently being offered by several manufacturers with 25-year performance warranties.

The system provided hot water to the restroom facilities and a janitorial closet at the park's main visitors center. During the first 11-month monitoring interval (Configuration I), the system provided 30% of the energy required for water heating. Alarmed at the amount of hot water being consumed within the restroom facilities, park personnel implemented a number of hot water conservation efforts. These efforts produced mixed results until the third change, the installation of 1.9 L/min (0.5 gpm) rated aerators, caused a significant reduction in hot water and auxiliary energy usage. This final change, Configuration IV, not only saved water and associated sewage disposal costs, but also resulted in the solar system providing 60% of the energy consumed for water heating.

Photovoltaic solar water heating systems are currently more expensive than solar thermal systems. At a photovoltaic module price of \$5.00/W_{peak}, the total system cost (including the microprocessor controller, resistive heating element assemblies, and solar radiation sensor) is more than twice the cost of a solar thermal system. For a typical residential-sized system, a photovoltaic module cost of \$1.90/W_{peak} would be needed to make the initial expense equivalent to a thermal system (Fanney and Dougherty 1997). Profitable module costs are projected to fall to \$2.00/W_{peak} by 2005 and \$1.50/W_{peak} by 2010 (Maycock 2000). Once these prices are achieved, the authors believe that solar photovoltaic hot water systems will capture the majority of the renewable water heating market.

ACKNOWLEDGMENTS

Great Smoky Mountains National Park personnel assisted in numerous ways during the project. The authors are especially thankful to the following: Superintendent Karen Wade for granting approval to install the system and for supporting the extension of the project to pursue improved water conservation; Tom Vance for his on-site technical troubleshooting and overall stellar assistance; Rose Ownby for forwarding experimental data; and Nancy Gray for coordinating the public relations effort. NIST personnel who played a significant role in this project included Don Ebberts, who assisted in the installation and instrumentation of the solar photovoltaic hot water system; Stanley Morehouse for reducing the experimental data; and Paula Svincek for preparing this manuscript and a web page devoted to the system (http://www.bfrl.nist.gov/863/pvsolar/flyer.html).

REFERENCES

Butti, K., and J. Perlin. 1979a. Early solar water heaters. *A Golden Thread*. New York: Van Nostrand Reinhold, pp. 117-127.

Butti, K., and J. Perlin. 1979b. Hot water-day and night. *A Golden Thread*. New York: Van Nostrand Reinhold, pp. 129-141.

Divone, L.V. 1993. Presentation entitled "Overview of the U.S. Department of Energy's Office of Building Technologies."

Dougherty, B.P., and A.H. Fanney. 2001. Experiences with using solar photovoltaics to heat domestic water. *Proceedings of Forum 2001, Solar Energy: The Power to Choose*, April 21-25, Washington, D.C.

Fanney, A.H., and B.P. Dougherty. 1997. A Photovoltaic solar water heating system. *Journal of Solar Energy Engineering-Transactions of the ASME* 119: 126-133.

Fanney, A.H., B.P. Dougherty, and K.P. Kramp. 1997. Field performance of photovoltaic solar water heating systems. *Journal of Solar Energy Engineering-Transactions of the ASME* 119: 265-272.

Fanney, A.H., and B.P. Dougherty. 1994. *Photovoltaic Solar Water Heating System*. United States Patent Number 5,293,447, Mar.

Great Smoky Mountains National Park (National Park Service). 1 Sep 2000. < http://www.nps.gov/grsm/>.

Maycock, P.D. The world PV Market 2000: Shifting from subsidy to "fully economic"? *Renewable Energy World, Review Issue 2000-2001,* 3(4): 58-74.

U.S. Department of Energy. 1999. Energy Information Administration. *A Look at Residential Energy Consumption in 1997*.

U.S. Department of Energy. 1997. Energy Information Administration, The Commercial Buildings Energy Consumption Survey (CBECS). *Commercial Buildings Energy Consumption and Expenditures 1995*.

Williams, P.M. 1996. Development and analysis tool for photovoltaic-powered solar water heating systems. Master's thesis, Mechanical Engineering, University of Wisconsin-Madison, Madison, Wisc.

Zogg, R.A., and R.A. Barbour. 1996. Joint Industry/ Department of Energy Program to Promote High-Efficiency Water-Heating Technologies. Program Proposal, 31186, prepared for the Edison Electric Institute and the Department of Energy, Nov.