A Photovoltaic Solar Water Heating System

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A novel solar water heating system was patented in 1994. This system uses photovoltaic cells to generate electrical energy that is subsequently dissipated in multiple electric resistive heating elements. A microprocessor controller continually selects the appropriate heating elements such that the resistive load causes the photovoltaic array to operate at or near maximum power. Unlike other residential photovoltaic systems, the photovoltaic solar water heating system does not require an inverter to convert the direct current supplied by the photovoltaic array to an alternating current or a battery system for storage. It uses the direct current supplied by the photovoltaic array and the inherent storage capabilities of a residential water heater. A photovoltaic solar hot water system eliminates the components most often associated with the failures of solar thermal hot water systems. Although currently more expensive than a solar thermal hot water system, the continued decline of photovoltaic cell prices is likely to make this system competitive with solar thermal hot water systems within the next decade. This paper describes the system, discusses the advantages and disadvantages relative to solar thermal water heating systems, reviews the various control strategies which have been considered, and presents experimental results for two full-scale prototype systems.

Introduction

Energy consumed for water heating accounts for approximately 17 quads of the energy consumed by residential and commercial buildings (U.S. Congress, 1992). 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 12,000 miles per year (Divone, 1993). For over a century, attempts have been made to reduce the vast quantity of nonrenewable energy consumed for water heating through the use of solar water heaters.

The nation's first commercial solar water heater, the Climax, was patented by Clarence M. Kemp in 1891 (Butti and Perlin, 1979). 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, 1979) 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 storage tank. A freak cold spell in the winter of 1913 severely damaged systems located in the Southern California area. Bailey responded to this problem by adding a coiled tube heat exchanger within the storage tank and using 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. Water is heated within a storage tank by exposing it directly to solar radiation or by circulating a heat transfer fluid through solar collectors and delivering the captured heat to a remote storage tank. The heat transfer fluids have included water, glycol and water mixtures, and refrigerants. Fluid circulation has been accomplished through the use of utility and photovoltaic powered pumps, thermosyphon action, and differences in vapor pressure. Various materials and configurations have been used over the past 100 years in an attempt to develop a durable, cost-effective solar water heating system.

Although there are over 100 million water heaters currently in use within the U.S., durability and installation issues, as well as initial cost, have limited the use of solar water heaters to approximately one million units. 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. In many installations, the distance between the storage tank(s) and solar collectors is substantial, resulting in significant thermal losses.

This paper describes a recently patented (Fanney and Dougherty, 1994) solar photovoltaic hot water system that eliminates the durability and installation problems associated with solar thermal hot water systems. Although currently more expensive than an existing solar hot water system, photovoltaic solar water heaters offer the promise of a less expensive system within the next decade.

System Description and Operation

The major components of the system are an array of photovoltaic (PV) modules, a microprocessor controller, and a storage tank(s) which contains multiple electrical heating elements. The system may consist of two tanks, Fig. 1, or a single tank. In a two-tank configuration, water within the preheat tank is heated by the photovoltaic array. Whenever hot water is consumed, the preheated water enters the auxiliary tank. Water within the auxiliary tank is heated in a normal manner by resistive elements connected to the electric utility grid or by a fossil-fuel burner if a gas or oil water heater is used. The preheat tank supplies the majority of energy required to heat the water under favorable solar conditions. When poor weather conditions exist, the auxiliary tank ensures an adequate supply of hot water. In a single-tank configuration, the water within the lower portion of the tank is heated by resistive elements connected to the

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SOLAR PHOTOVOLTAIC HOT WATER SYSTEM

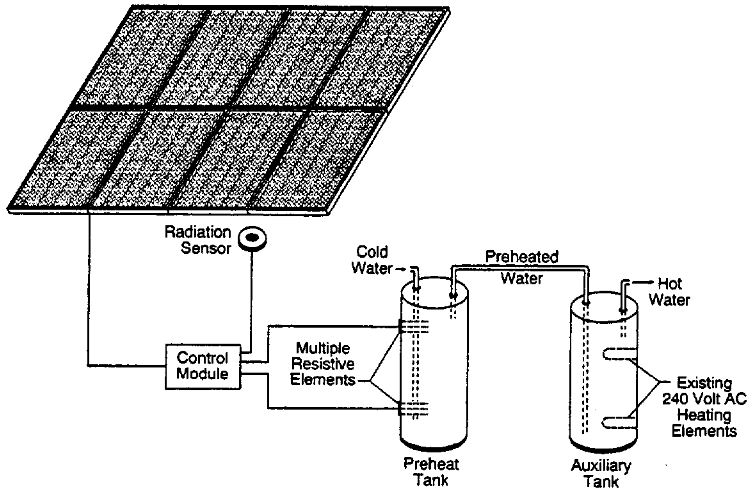

Fig. 1 Solar photovoltaic hot water system schematic

photovoltaic modules whereas the upper portion of the tank is heated by a resistive element connected to the electric utility grid.

To demonstrate the operation of a solar photovoltaic water heating system, the operating characteristics of a solar photovoltaic array must be understood. Figure 2 shows the current versus voltage characteristics for a specific photovoltaic array as a function of solar irradiance at a fixed module temperature. The short circuit current, the point on the IV curve at which the voltage potential is zero, is proportional to the solar radiation. The voltage that occurs during zero current flow, the open circuit voltage, increases logarithmically with solar radiation. For the photovoltaic array represented by Fig. 2, the current is nearly constant up to an array voltage of approximately 170 volts. For a given solar radiation level and array temperature, there is a current and voltage combination that results in maximum power output, P_{max}, for any given solar radiation level. The goal is to operate the photovoltaic array at the voltage-current combination that yields maximum power, P_{max}. The conversion of electrical energy to thermal energy within the water heater storage tank is accomplished through the use of resistive elements. In Fig. 2, a load line corresponding to a 13 ohm resistance element is superimposed on the current versus voltage characteristics of a photovoltaic array subjected to a solar irradiance of 1000 W/m^2. For this solar irradiance level and module temperature, the 13 ohm resistive element passes through the maximum power point. As the irradiance varies throughout the day, however, the 13 ohm load line no longer coincides with the maximum power point. At an irradiance of 200 W/m^2, a level typical of early morning and late afternoon hours, the power output of this example photovoltaic array connected to the 13 ohm resistive load would be 100 watts. If the resistive load were 67 ohms instead of 13 ohms, the photovoltaic array would be forced to operate at its maximum power point, resulting in a power output of 445 watts, a 345 percent increase in power. Thus, in order to capture the maximum possible energy, a variable load is needed such that the photovoltaic array operates at its maximum power point as the solar irradiance changes. It has been assumed that the module temperature is constant for this illustrative example.

For a two-tank photovoltaic solar water heater system, the upper and lower heating elements in the preheat tank are both replaced with an assembly having multiple elements. A microprocessor-based controller connects these elements in a manner such that the photovoltaic array operates near its maximum power point for any given solar irradiance level. For example, in Fig. 2 an optimum controller would select a resistive load of 67 ohms when the solar irradiance level is 200 W/m^2 and a 13 ohm resistive load when a 1000 W/m^2 solar irradiance level is present. Throughout the day, the controller reconfigures the resistive load such that the photovoltaic array always operates near its maximum power point.

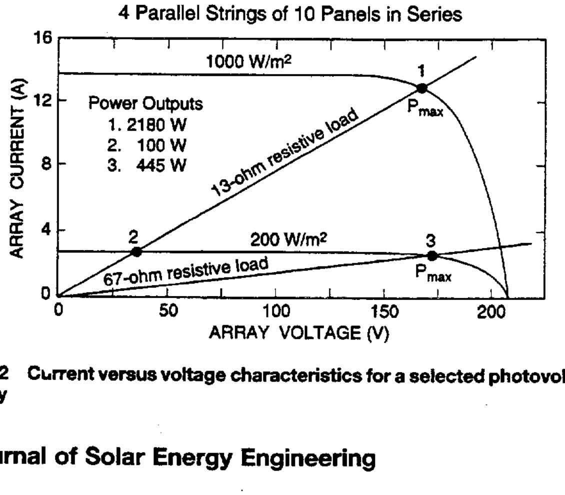

Fig. 2 Current versus voltage characteristics for a selected photovoltaic array

Prototype Systems

The first of two full-scale prototype systems installed at the National Institute of Standards and Technology (NIST) in Gaithersburg, Md became fully operational on Feb. 5, 1995. For this first system, Prototype System 1, the photovoltaic array was composed of 40 modules and covered an area of 17.1 m^2. Each module consists of 36 single crystal silicon cells connected in series. At a solar irradiance of 1000 W/m^2 and 25°C module temperature, the short circuit current and open circuit voltage for each module are, respectively, 3.4 amps and 12.7 volts. The array was configured to have four parallel strings of 10 series wired modules resulting in a rated output of 2120 watts for an irradiance of 1000 W/m^2 and a 25°C array temperature. Prototype System 1 used a 250 liter electric water heater as the preheat tank and a 190 liter electric water heater as the auxiliary tank. The auxiliary tank contained two interlocked 4500 watt heating elements. Design information for Prototype System 1 is summarized in Table 1.

For Prototype System 1, the resistive element assemblies used to replace both upper and lower heating elements in the preheat tank consisted of two 60-ohm elements and one 120-ohm element. One such three-element assembly is shown in Fig. 3. The 120-ohm element in the lower portion of the tank is always connected to the photovoltaic array. As the irradiance increases, heating elements are sequentially added in parallel as follows: the 120-ohm upper element, the first 60-ohm lower element, the second 60-ohm lower element, the first 60-ohm upper element, and finally the second 60-ohm upper element. The resistive elements are wired in parallel because it minimizes the number of power relays, helps to minimize the current flow through each relay and heating element, and simplifies the control logic. Although six, parallel-wired elements provide the opportunity for a maximum of 63 different resistive loads (if all resistors have a different resistance), Prototype System 1 was limited to six resistive loads.

The selection of the six resistive elements, a trial and error process, was performed after the array configuration was selected. A bar chart of available solar energy, in units of kJ, was plotted against irradiance intervals (e.g., 0 to 50 W/m^2, 50 to 100 W/m^2, etc.) using hourly weather data from the closest meteorological site. Six irradiance levels were chosen such that they cover the range of 0 to 1000 W/m^2 and, based on the described plot, fall within the irradiance "bins" that yield the highest available solar energies. Using an algorithm that predicts the characteristic I-V curve of the array based on irradiance and an estimated array temperature (ASTM, 1985; Duffie and Beckman, 1991), the resistive load that corresponds to the maximum power point was identified for each of the six selected irradiances. Using these overall loads and given that the resistive elements will be wired in parallel, the resistance of each individual element was calculated. The solar irradiance range over which each resistor combination will be used is subsequently determined by finding the irradiance at which two resistor combinations (approximately) tie in yielding the highest power output among the six load options. Finally, using a computer model of the entire PV water heating system, a simulation was conducted to predict annual performance. Part or all of the process is repeated, including trying a different array size or array configuration, with the annual performance predictions being used for making the final design decisions.

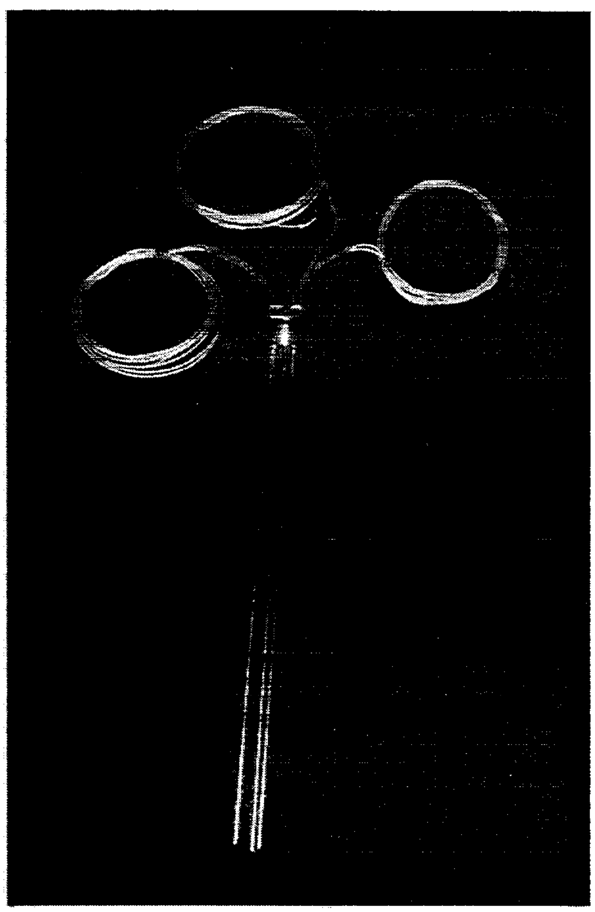

Fig. 3 Three-element heater assembly

Prototype System 1 made use of simple control logic. With the exception of the last 21 days of the monitoring period, the number of resistors connected at any time depended only on the incident solar irradiance. The irradiance levels, H_T, over which each heating element combination was used are given in Table 1. During the final 21 days, the photovoltaic module temperature was also factored into the control scheme. Solar irradiance and the photovoltaic module temperature were measured using a calibrated precision pyranometer and a calibrated, type-T, thermocouple, respectively. The pyranometer's voltage signal and the thermocouple's emf were converted to irradiance and temperature, respectively, using a data acquisition system interfaced to a personal computer. An arbitrary decision was made to have the computer select the optimal resistor combination every 20 seconds.

A second, computer-interfaced, data acquisition system was used to impose a daily draw schedule and to monitor the overall performance of the photovoltaic solar water heating system. The draw schedule consisted of 20.5 liters withdrawn at 6:00 a.m. and 6:00 p.m., 61 liters at 7:00 a.m. and 7:00 p.m., and 40.5 liters at 8:00 a.m. and 8:00 p.m. A water conditioning system maintained the temperature of the make-up water to the preheat tank at 9°C during the monitoring of Prototype System 1. The storage tanks were located within a conditioned space maintained at approximately 22°C.

Prototype System 1 supplied 66 percent of the total hot water load during the Feb. 5 through May 8 test period (Table 2). The conversion efficiency of the photovoltaic array was 11.4 percent. The percentage of energy delivered by Prototype System 1 in comparison to the energy that could have been delivered had a continuously variable resistor been used, is 96 percent, Table 2. This controller performance index was arrived at by modeling, in real-time, the performance of Prototype System 1 versus a system that used the same photovoltaic array but always operated at the maximum power point. The model, which used the algorithms within ASTM Standard E 1036-85 (ASTM, 1985) over predicted the daily energy delivered by the photovoltaic array by an average of four percent compared to measured values. Although better absolute agreement is preferred, using the model to evaluate relative changes in performance was nonetheless deemed acceptable.

The percentage of the water heating provided by the PV system exceeded 90 percent on 16 of the 81 test days, revealing that the photovoltaic array was oversized. In addition, the preheat tank storage temperature often exceeded 70°C compared to the auxiliary tank's thermostat set point of 57°C. The thermal losses from the storage tanks were also found to be significant, equal to 19 percent of the energy supplied by the photovoltaic array. As a result of these findings, a second prototype system was designed and installed.

Design goals of the Prototype System 2 included having a correctly sized photovoltaic array, reducing the standby losses from the storage tanks, and using a microprocessor controller in lieu of a personal computer and data acquisition system to select the appropriate heating elements. The photovoltaic array size was reduced by 25 percent, to three parallel strings of 10 series wired modules having a total array area of 12.8 m^2. A 303 l tank replaced the 250 l preheat tank. In an effort to reduce storage tank thermal losses, both tanks were placed on a 51 mm thick piece of extruded polystyrene insulation, the quantity of

Table 1 System specifications photovoltaic solar hot water systems

	Prototype System 1	Prototype System 2
Photovoltaic Array Size (m^2)	17.1	12.8
Number of Modules in Series	10	10
Number of Module Strings in Parallel	4	3
Nominal / Actual Preheat Tank Volume (ℓ)	250 / 220.3	303 / 272.4
Nominal / Actual Auxiliary Heating Tank Volume (ℓ)	190 / 170.4	190 / 170.4
Auxiliary Heating Tank Thermostat Set Point (°C)	57	57
Preheat Storage Tank Heat Loss Coefficient (W/°C)	2.09	1.92
Auxiliary Heating Tank Heat Loss Coefficient (W/°C)	1.67	1.21
Preheat Tank Upper Heating Elements: Nominal Resistance(Ω) – Operating Sequence	120 – 2 60 – 5 60 – 6	180 – 1 120 – 5 75 – 6
Preheat Tank Lower Heating Elements: Nominal Resistance (Ω) – Operating Sequence	120 – 1 60 – 3 60 – 4	180 – 2 110 – 3 75 – 4
Solar Irradiance Range, H_T, (W/m^2) for Each Nominal Resistive Load	120: $5 < H_T < 157$ 60: $157 \leq H_T < 320$ 30: $320 \leq H_T < 545$ 20: $545 \leq H_T < 767$ 15: $767 \leq H_T < 988$ 12: $988 \leq H_T$	180: $5 < H_T \leq 138$ 90: $138 < H_T \leq 273$ 50: $273 < H_T \leq 483$ 30: $483 < H_T \leq 687$ 24: $687 < H_T \leq 882$ 18: $882 < H_T$

insulation on all piping associated with the system was increased, a 76-mm thick glass-fiber insulation blanket was added to the auxiliary tank, and the all-metal water meter was relocated to minimize its tendency to act as a heat sink. The resulting heat transfer rate was reduced by 8.1 percent for the preheat tank, even though the tank's volume was 20 percent greater. The auxiliary tank's heat transfer rate was reduced by 27.5 percent.

Prototype System 2, Fig. 4, incorporates a microprocessor controller to select and connect the appropriate heating elements. The controller contains multiple analog input and digital output channels. A photovoltaic reference cell, which is

Table 2 Performance summary—photovoltaic solar hot water systems

	Prototype System 1	Prototype System 2
Test Intervals	Feb. 5 to May 8, 1995	Jul. 1 to Aug. 31, 1995
Number of Test Days (-)	81[1]	62[2]
Hot Water Load - System (kJ)[3]	3,938,187	2,749,862
Hot Water Load - Preheat Tank (kJ)	2,599,055	1,669,811
Hot Water Load - Auxiliary heating tank (kJ)	1,381,369	1,111,864
Electrical Energy Supplied by PV Array (kJ)	2,712,645	1,715,233
Electrical Energy Consumed by Auxiliary Tank Heating Elements (kJ)	1,806,804	1,327,631
Preheat Tank Jacket Heat Loss (kJ)	110,061	64,336
Auxiliary heating tank Jacket Heat Loss (kJ)	400,418	210,355
Change in Stored Energy - Preheat Tank (kJ)	22141	1045
Change in Stored Energy - Auxiliary heating tank (kJ)	11053	2404
Total Incident Solar Radiation (kJ/m^2)	1,397,815	1,287,501
Average Incident Solar Radiation (kJ/m^2·day)	17,257	20,766
Percent of Load Supplied by Solar (%)	66	61
Percent of Total Electrical Energy Supplied by PV Array (%)	60	56
Controller Performance Index (%)	96	96
Photovoltaic Array Efficiency	11.4	10.4

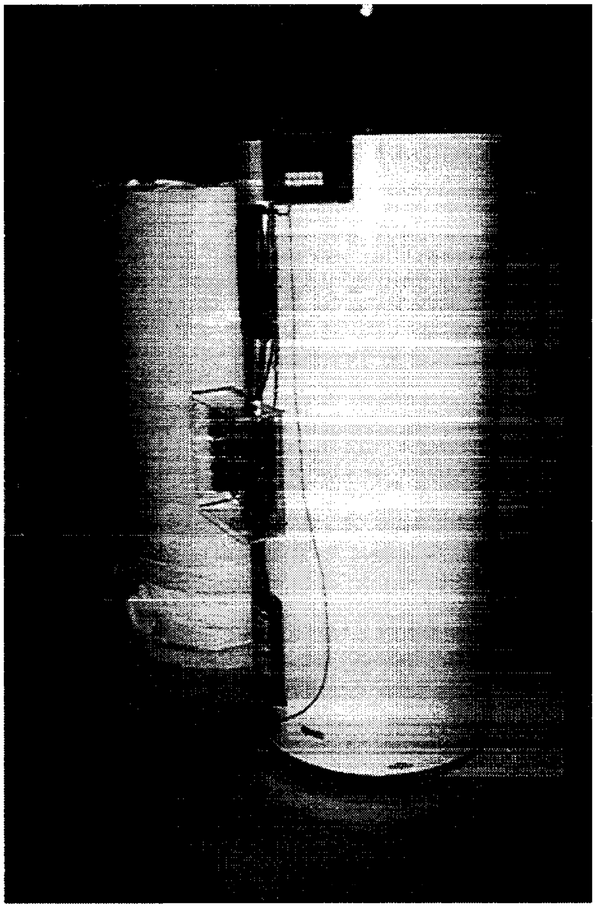

Fig. 4 Prototype system 2 preheat and auxiliary storage tanks

mounted adjacent to the photovoltaic array, is used to measure solar irradiance. The controller's digital output channels are used to drive DC switching relays. The microprocessor controller, programmed using C language, executes the controller logic of selecting the appropriate heating element combination based upon the measured irradiance. The resulting program is "burned" into an on-board erasable programmable read-only memory chip. The controller measures irradiance and selects the appropriate relay settings every 20 seconds. The six preheat tank heating elements, which are different from those used in Prototype System 1 (see Table 1), were selected to optimize the performance of the downsized photovoltaic array.

Prototype System 2 became operational on June 22. The hot water load was identical to that used during the evaluation of the first prototype system with the exception of the inlet water temperature. The inlet water temperature for Prototype System 2 was changed on a monthly basis to reflect the variations in inlet water temperature for the Gaithersburg, MD test location. For the months of July and August the inlet water temperature was maintained at 12.7°C and 12.6°C, respectively.

The experimental results for Prototype System 2 for the months of July and August are summarized in Table 2. The photovoltaic solar hot water system supplied 61 percent of the total hot water load during July and August. The photovoltaic array conversion efficiency for the two-month period was 10.4 percent. With the exception of days where no morning draws occurred (July 17 and 19), the highest temperature obtained within the preheat tank was 61.4°C. This temperature is 21.4°C lower than the high temperature recorded for Prototype System 1. With the exception of July 17 and 19, the daily fraction of the total hot water load supplied by the photovoltaic solar water heating system did not exceed 70 percent. Figures 5 and 6 show the daily solar fractions for July and August, respectively.

Controller Algorithm Comparisons

Prototype System 1 used two control algorithms. Initially the resistor combinations were selected based on the irradiance as measured by the precision pyranometer. During the final 21 days of the monitoring period, both array temperature and irradiance were used within the control logic. The solar radiation was measured using a precision pyranometer. Performance differences from using these two control algorithms could not be ascertained due to changing weather conditions. Thus, while evaluating the performance of Prototype System 2, alternative control strategies and resistive element combinations were evaluated using computer simulations. These simulations accounted for the photovoltaic array, the controller, and the resistive element combinations. The operation of the preheat and auxiliary tanks were not modeled. Several theoretical control strategies were evaluated, including Prototype System 2 and an optimal system where the photovoltaic array always delivered its maximum power output. The latter was used when calculating the controller performance indexes: the maximum possible energy that could be captured by the respective nonoptimal systems.

The photovoltaic array was modeled using a single-diode four-parameter model (Duffie and Beckman, 1991). For all of the simulated systems, the photovoltaic array was the same as used for Prototype System 2. Although the majority of theoretical systems were limited to the same six resistor combinations as used by Prototype System 2, a few cases were investigated where other combinations were used. Different options for measuring solar irradiance were evaluated. The effect of having the irradiance range for each resistor combination fixed versus varying with array temperature was also investigated. Table 3 contains a brief description of each system and the controller performance index predicted by the real-time simulations. A description of each system and the results are as follows:

Prototype System 2. This modeled system is identical in components and control logic to the Prototype System 2 constructed at NIST. For the months of July and August, the model over predicted the measured controller performance index by 0.5 percent. The measured and predicted daily values for the energy delivered by the photovoltaic array during August are compared in Figure 7. Based on this result the model was judged adequate for comparing the predicted controller index for the various theoretical systems.

Theoretical System 1. This system computed the incident solar irradiance by using the reference cell's short circuit current, temperature and an equation supplied by the reference

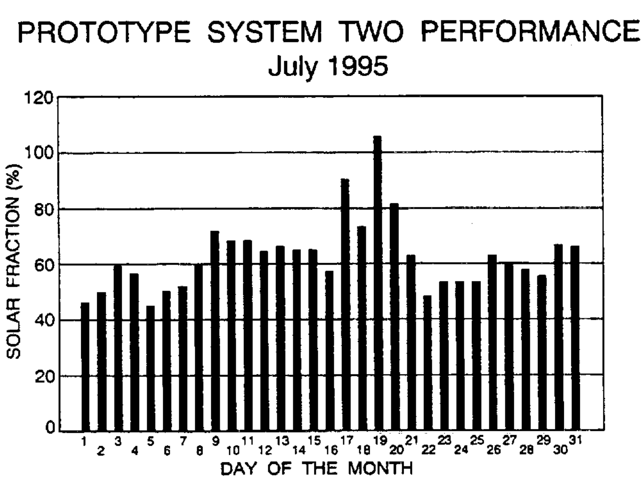

Fig. 5 Prototype system 2 daily solar fraction—July

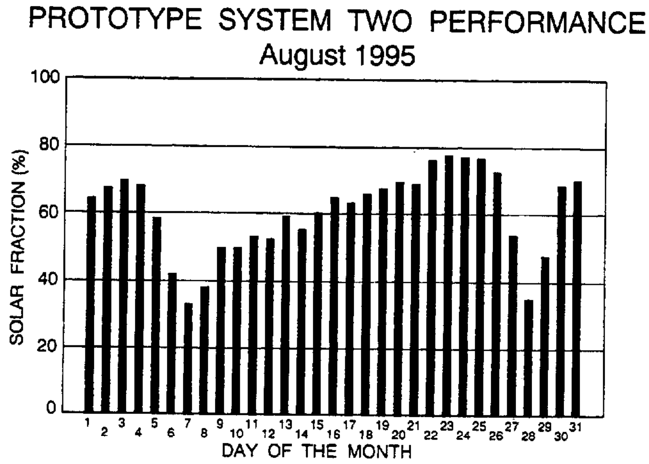

Fig. 6 Prototype system 2 daily solar fraction—August

cell's manufacturer. This system produced the unexpected finding that the controller performance index was slightly less, 0.2 lower, than the value predicted for Prototype System 2 in which the reference cell temperature was ignored. This result is attributed to the fact that calibration of the reference cell took place during weather conditions similar to those encountered during the July-August test interval.

Theoretical System 2. The control logic within this system takes into account the influence of array temperature on the photovoltaic array's I-V relationship. This effect is captured by having the irradiance range for operating each resistor combination change with array temperature. The controller logic within the other systems ignores this temperature effect. The inclusion of the temperature effect increased the performance index from 96.6 to 96.9.

Theoretical System 3. This system uses adaptive control logic to select the combination of electric resistive elements which results in maximum power delivery. Initially, the controller logic selects the combination of heating elements based upon the solar irradiance. Each time the controller selects a new combination of resistive elements it measures the power output of the photovoltaic array prior to and after the selection. If the resulting power is less than the power output measured immediately before the change, the control logic adjusts the switch point. The resulting controller performance index was only 0.1 greater than that obtained using fixed irradiance levels for the switch points.

Theoretical System 4. Six heating elements are connected in various parallel combinations resulting in 17 discrete levels of load resistance versus six used in the other theoretical systems. This system used both the reference cell's short circuit current and temperature to compute solar irradiance and thus should be compared to Theoretical System 1. The results show that increasing the number of discrete resistive loads from 6 to 17 resulted in only a modest improvement, 96.4 to 97.5, in the controller index.

Theoretical System 5. This system employed only three heating elements and connected them in various configurations that resulted in seven discrete levels of load resistance. The solar irradiance was measured in a manner identical to Theoretical Systems 1 and 4. The resulting controller index, 96.4, is 0.1 less than that observed for the systems which employed six discrete levels of load resistance, Theoretical System 1, and 1.1 lower than that observed when 17 discrete levels of load resistance are used, Theoretical System 4.

As shown in Table 3, the various controller and resistive load options explored within this study did not have a significant effect on the controller performance index. The increased complexity of incorporating photovoltaic array and/or reference cell temperature within the control logic is not warranted. Finally,

Table 3 An evaluation of various controller and resistive load options

System	Solar Irradiance Measurement	Resistive Load Options	Other Distinguishing Features	Controller Performance Index
Prototype 2 (Measured)	Reference cell: short circuit current	6 resistors 6 wiring configurations	Irradiance range for each resistor combination fixed	96.1
Prototype 2 (Predicted)	Reference cell: short circuit current and cell temperature	6 resistors 6 wiring configurations	Irradiance range for each resistor combination fixed	96.6
Theoretical 1	Reference cell: short circuit current	6 resistors 6 wiring configurations	Irradiance range for each resistor combination fixed	96.4
Theoretical 2	Reference cell: short circuit current	6 resistors 6 wiring configurations	Irradiance range for each resistor combination dependent on array temperature	96.9
Theoretical 3	Reference cell: short circuit current	6 resistors 6 wiring configurations	An adaptive controller. Irradiance range for each resistor combination adjusted	96.7
Theoretical 4	Reference cell: short circuit current and cell temperature	6 resistors 17 wiring configurations	Irradiance range for each resistor combination fixed	97.5
Theoretical 5	Reference cell: short circuit current and cell temperature	3 resistors 7 wiring configurations	Irradiance range for each resistor combination fixed	96.4

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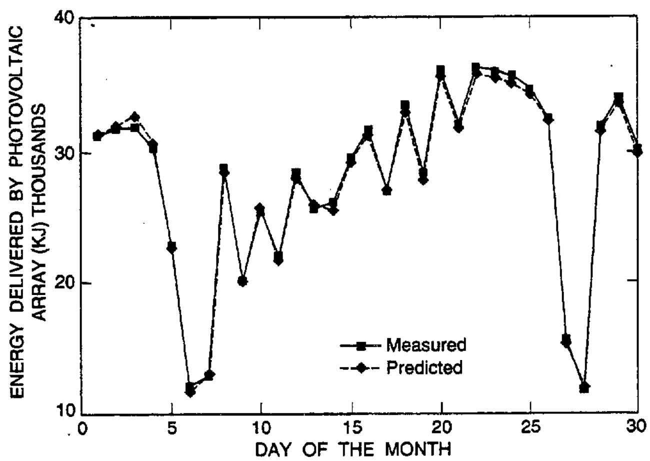

Fig. 7 Predicted versus measured photovoltaic energy—August

the use of an adaptive control strategy only marginally improved the controller performance index.

Costs

The installed cost of a solar thermal hot water system sized for a typical family of four in Florida and Southern California is approximately $3000 (Dean, 1995; Murley and Osborn, 1995). For the upper Pacific Northwest, system costs are estimated at approximately $4000 (Murley, 1995). The installed price of a photovoltaic system, sized to provide approximately 60 percent of the energy requirements for a family of four in the Mid-Atlantic City of Gaithersburg, Maryland is $8900. Figure 8 shows the price of the photovoltaic solar water heating system as a function of photovoltaic module cost per peak watt. A photovoltaic cell cost of $1.90 per peak watt will result in an installed cost of $4000 for a photovoltaic solar hot water system.

Based upon history and recent statements by the photovoltaic industry, the potential for less expensive photovoltaic modules is excellent. According to the U.S. Department of Energy (DOE, 1988), the average price per square meter of photovoltaic modules was over $11.00 per peak watt in 1982. Due to dramatically improved processing techniques, current prices are under $5.00 per peak watt. Several key manufacturers at the First World Conference on Photovoltaic Energy Conversion (TechLink, 1995) stated that photovoltaic manufacturers are quite confident of bringing down prices to $2.00 per peak watt by 1997 and suggested that costs of $1.00 per peak watt were a near-term possibility. At a price of $1.00 per peak watt the installed cost of a photovoltaic solar water heating system would be $2900.

Maintenance costs associated with the photovoltaic solar water heating system should prove to be extremely low. The only moving parts within the photovoltaic solar water heating system are switching relays. There are no fluids to freeze or leak from the system, no pumps, and no need for freeze prevention mechanisms. These components add to the cost of owning a solar thermal water heating system. A recent study by the Wisconsin Public Service Corporation (DeLaune et al., 1995) found that 41 percent of the solar thermal hot water systems within their service territory were not working. Most of the failures associated with these systems were due to the circulating pumps, controllers, and the loss of fluid. The average repair cost was $550 per system.

Comparison to Solar Thermal Systems

The photovoltaic solar water heating system is compared to two thermal hot water systems previously evaluated at the NIST site (Fanney and Klein, 1983). Both of the solar thermal systems utilized two tanks, a nominal 303-liter preheat tank and a 151-liter auxiliary tank. One of the two systems was a double-tank direct system which circulated potable water directly through the solar thermal collectors. Freeze protection was provided by an automatic system which drained the solar collectors and associated piping. The second solar thermal system utilized a wrap-around heat exchanger and a water-ethylene glycol mixture to provide freeze protection. Both systems used three single-glass flat-plate solar collectors with a total area of 4.2 m^2. Energy was transported from the solar thermal collectors by means of copper tubing insulated with a closed cell insulation material. A 85-watt pump circulated the heat transfer fluid through the collector arrays whenever the absorber plate temperature was 8.9°C greater than the water temperature within the preheat tanks. During the monitoring period, the freeze protection valve on the double-tank direct system failed. This failure resulted in burst manifold pipes within two of the three solar thermal collectors.

The efficiency of the solar thermal collectors ranged from 40 to 80 percent depending upon the ambient temperature, the temperature and flow rate of the fluid entering the solar collectors, and the solar irradiance level. During the one-year monitoring period the double-tank direct system provided 49.6 percent of the energy required for water heating whereas the double-tank indirect system provided 41.4 percent of the required. During the months of July and August, the period for which photovoltaic system performance is available, the solar fraction of the double-tank direct system was 65.8 and 60.9 percent for July and August, respectively. The monthly solar fraction for the double-tank indirect system was 48.4 and 46.0, respectively, for the months of July and August. Parasitic energy had a significant impact on the solar fraction of both systems. For example, during the month of August the circulating pump and associated controller reduced the solar fraction of the double-tank direct system from 70.5 to 60.9 percent.

The solar photovoltaic hot water system currently being evaluated at NIST uses a 303-liter preheat tank and a 190-liter auxiliary tank. The photovoltaic array area is three times larger than the solar collector area of the thermal systems. The photovoltaic solar water heating system eliminates the need for piping and associated roof penetrations to and from the solar collectors, the circulator pump, and a freeze protection mechanism. Unlike solar thermal systems, the solar photovoltaic water heating system delivers energy to the storage tank whenever solar radiation is present.

The conversion efficiency of the photovoltaic array has ranged from 9 to 14 percent dependent upon photovoltaic module temperature and incident irradiance. Unlike solar thermal collectors, in which the efficiency decreases with decreased

PHOTOVOLTAIC HOT WATER SYSTEM COST VERSUS CELL COST

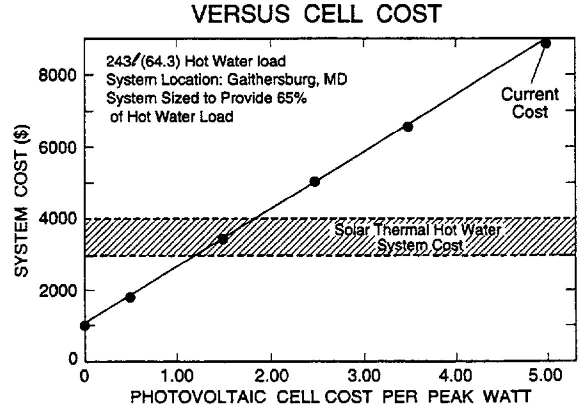

Fig. 8 Photovoltaic solar hot water system cost versus cell cost

ambient temperature, the photovoltaic module conversion efficiency improves with reduced ambient temperatures. The photovoltaic solar water heating system provided 61 percent of the hot water load during both July and August. The effect of parasitic energy on the performance of the photovoltaic solar water heating system is negligible. For example, during the month of July the controller and associated relays consumed 1.5 kWh of electricity compared to the 237 kWh of energy delivered to the system by the photovoltaic array.

Summary and Future Activities

A photovoltaic solar hot water system offers significant improvements over solar thermal hot water systems. Unlike solar thermal water heating systems, the photovoltaic solar hot water system does not require a fluid and associated piping to transport the energy produced by the solar collectors to the storage tanks. Unlike other residential photovoltaic systems, the photovoltaic solar water heating system does not require an inverter to convert the direct current supplied by the photovoltaic array to alternating current or a battery system for storage.

The cost of a photovoltaic solar water heating system is more than twice the cost of a solar thermal water heating system at the current photovoltaic cell costs of $5.00 per peak watt. A photovoltaic cell cost of $1.90 would result in the cost of the system being equivalent to a $4,000 solar thermal hot water systems.

Two prototype systems have been constructed at the NIST site in Gaithersburg, MD. The second prototype system has provided 61 percent of the hot water load during its first two months of operation. The microprocessor controller on the present system selects the optimum combination of elements which forces the photovoltaic array to operate near its maximum power point as the irradiance varies. Use of this control strategy has resulted in 96 percent of the maximum possible energy being collected. The use of various control strategies did not have a significant impact on the controller performance index. The experimental data supports using irradiance as the lone controller input parameter. Finally, in looking ahead to the possibility of a single-tank application, a single assembly consisting of three resistive elements is predicted to closely approach the performance obtained from using six resistors.

Future activities include field monitoring of at least four additional systems, the development of computer simulation tools to analyze and design photovoltaic solar domestic water heating systems, and an attempt to develop a single-tank, photovoltaic solar water heating system. An extensively instrumented system was installed at the Florida Solar Energy Center (FSEC) in November 1995. Two photovoltaic solar water heating systems will be installed at the Kadena Air Force Base in Okinawa, Japan during 1997. A fourth system, sponsored by Tennessee Valley Authority, was installed at the main visitor's center at the Great Smoky Mountains National Park in Oct. 1996.

The second activity is the development of computer simulation capability for photovoltaic solar hot water systems. A grant has been awarded to the University of Wisconsin to develop simulation tools to optimize system components and provide estimates of the displaced conventional electrical energy on daily, weekly, monthly, and yearly time scales. Predictions of electrical demand reductions and the impact on the environment through widespread use of the photovoltaic solar water heating systems will also be possible.

The third activity is to develop a single-tank photovoltaic solar water heating system. A major design goal of the single-tank system is to ensure that an adequate supply of hot water is available during extended periods of poor weather conditions.

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