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(54) **SOLAR PHOTOVOLTAIC WATER HEATING SYSTEM**

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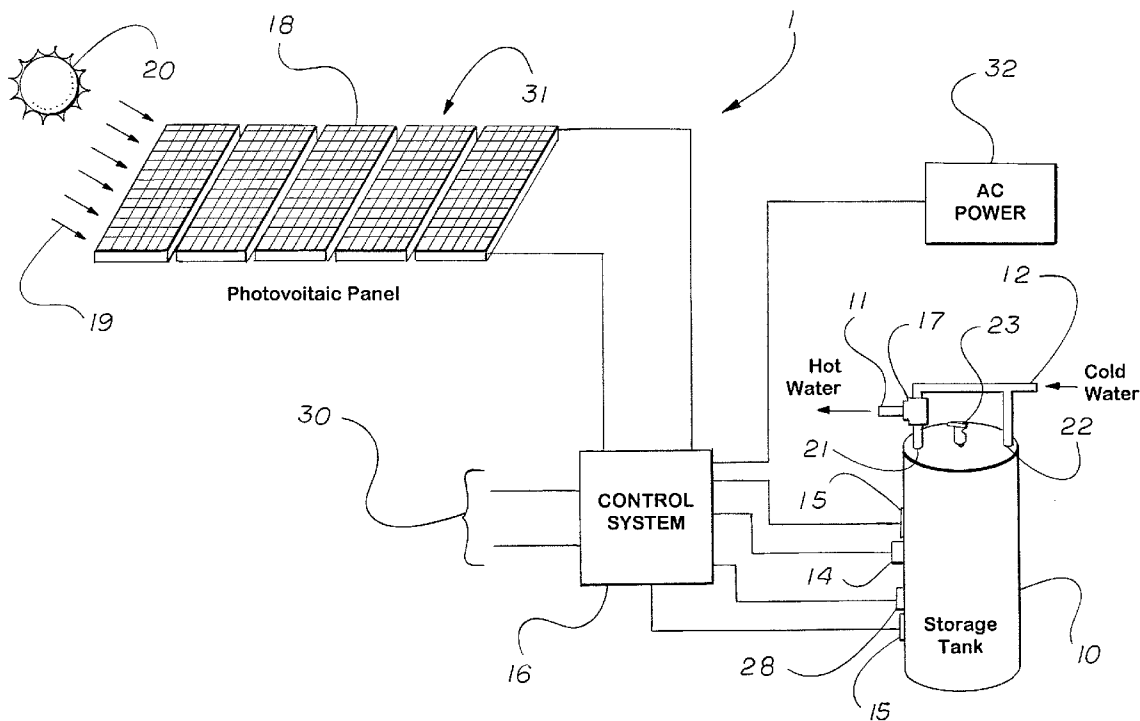
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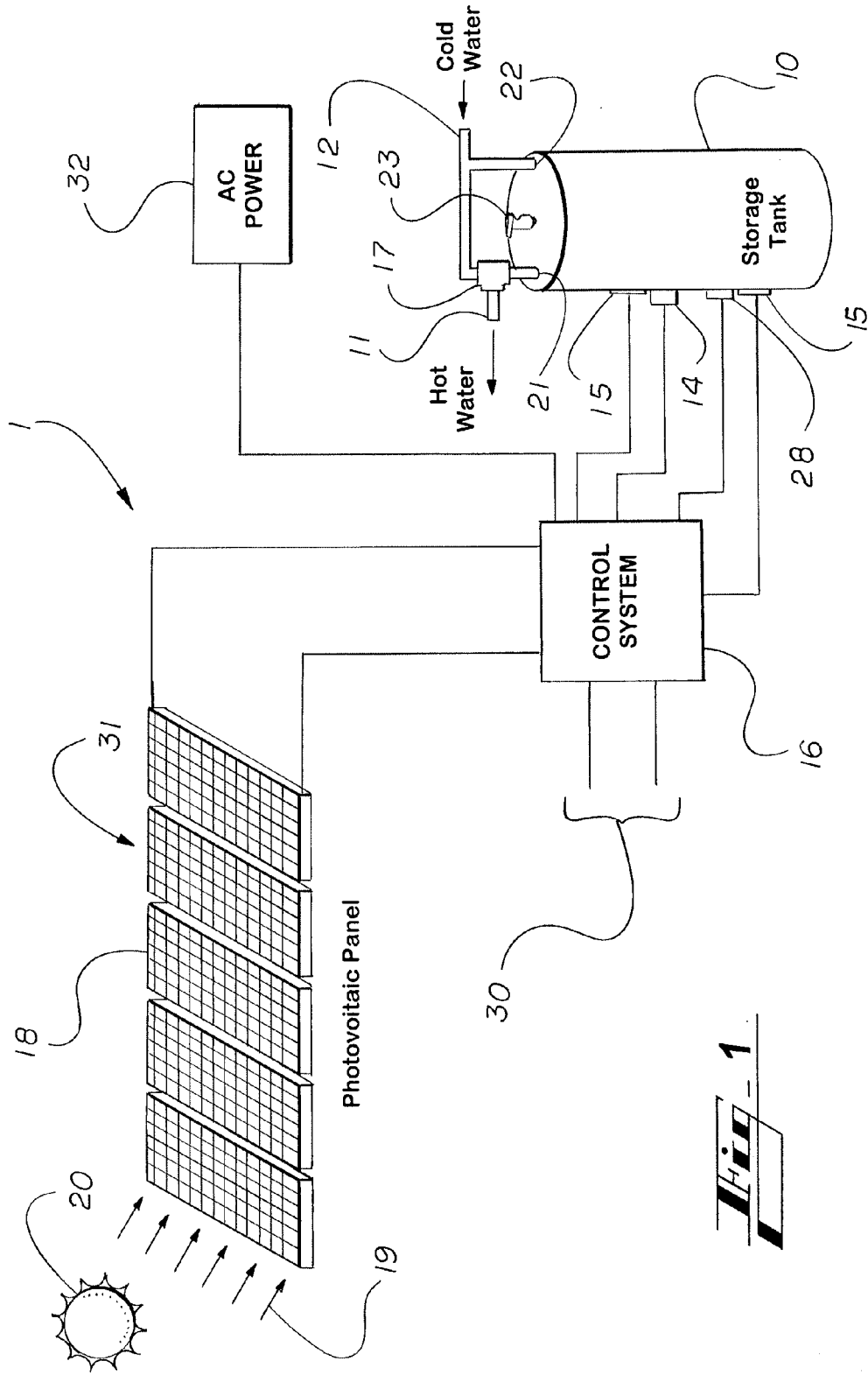
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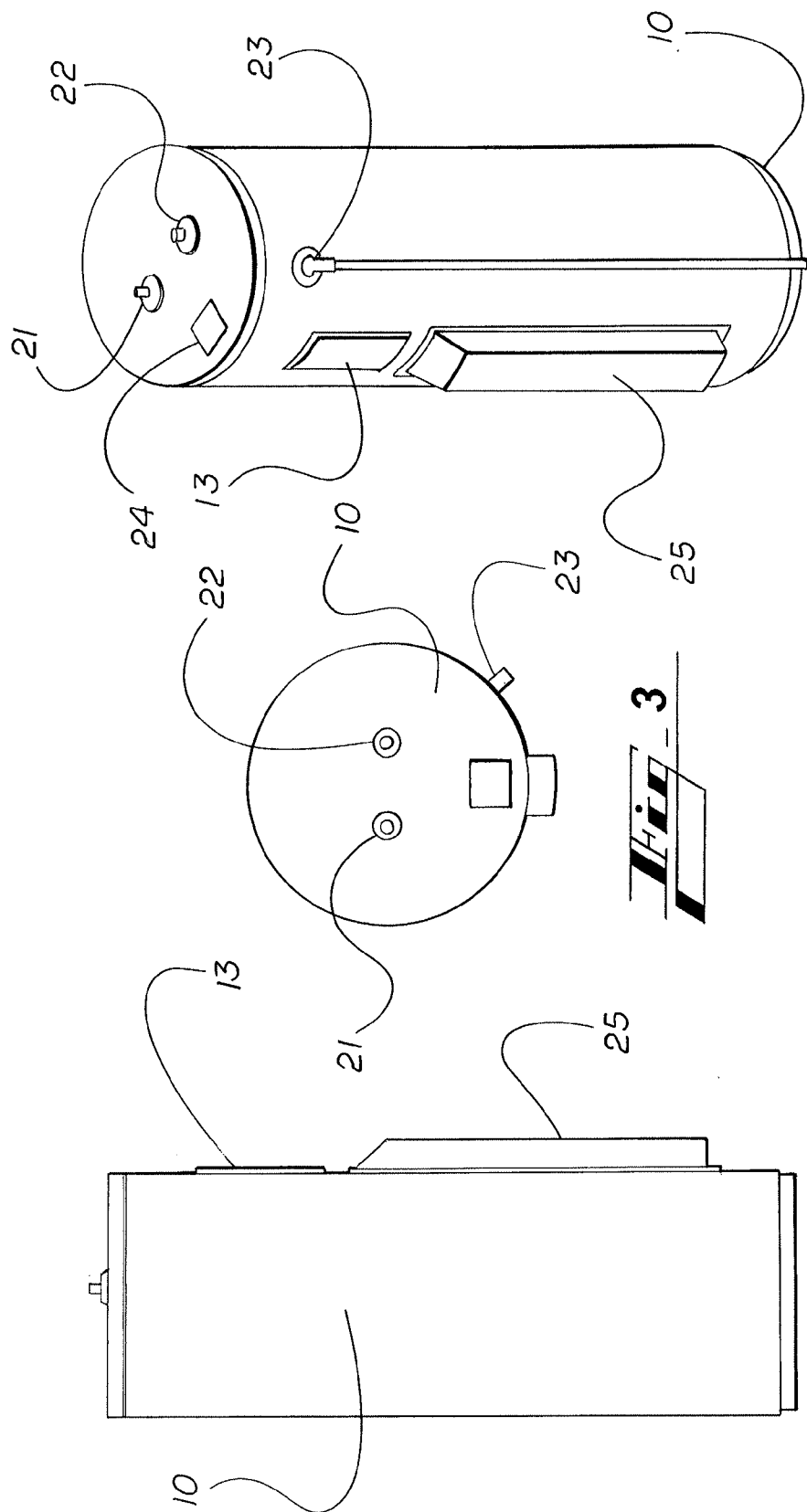
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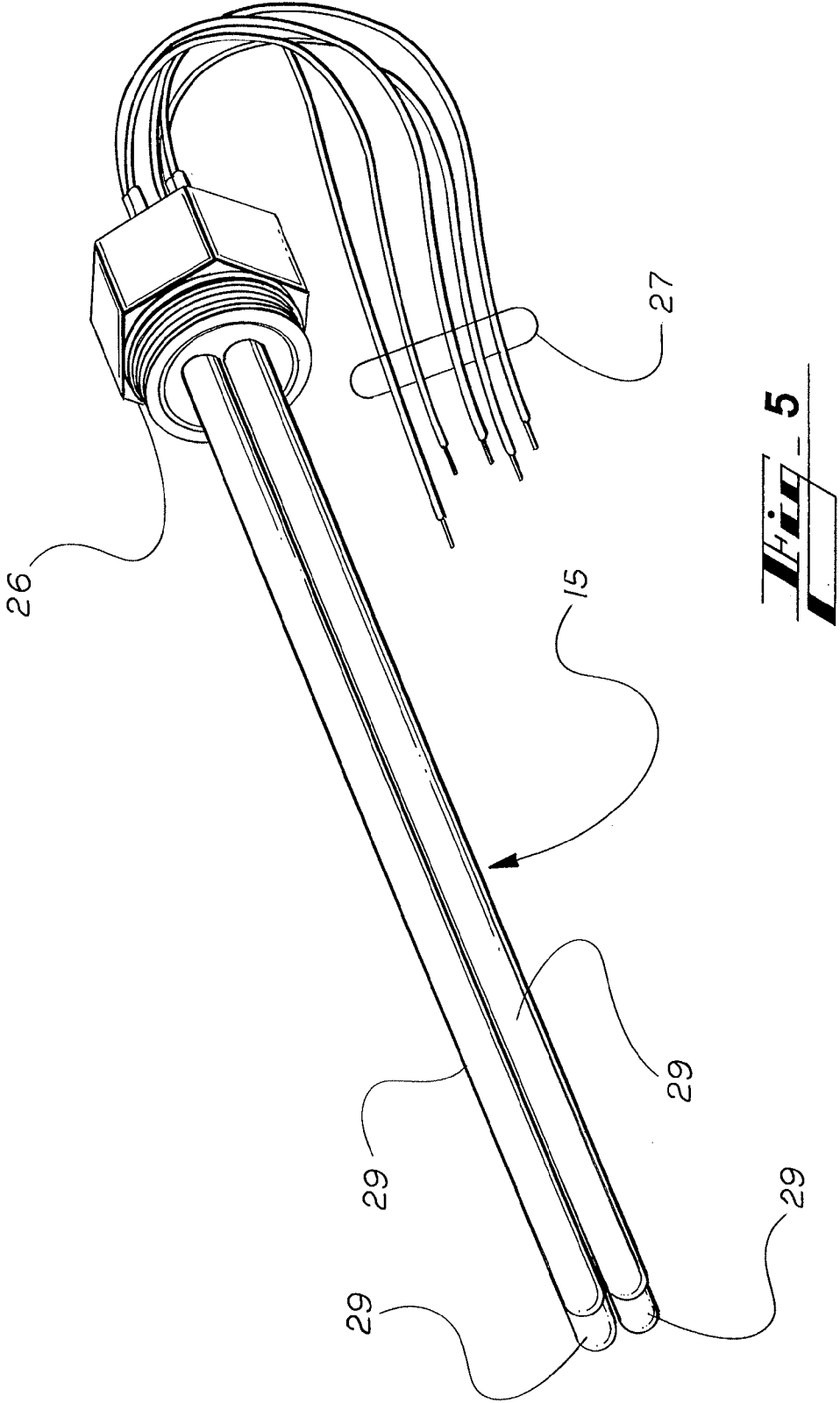
(57) **ABSTRACT**  
A solar photovoltaic water heating system is disclosed having a photovoltaic solar panel array, a storage tank containing water to be heated, a resistance heating element in the water to be heated. The water heating system matches the load resistance of the resistance heating element to the power that is available from the photovoltaic solar panel array in order to maximum energy transferred to the water in the storage tank.



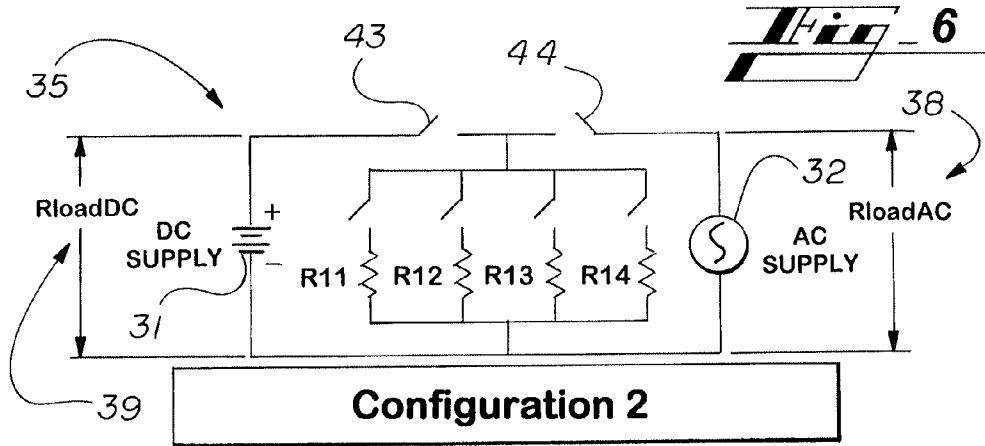
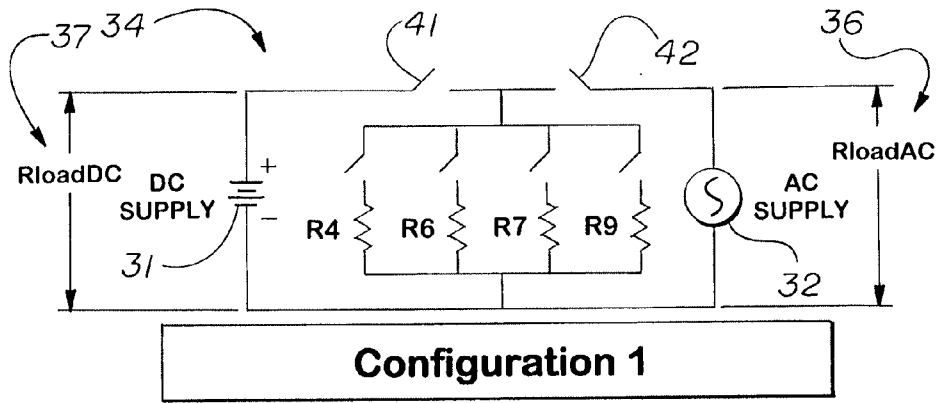


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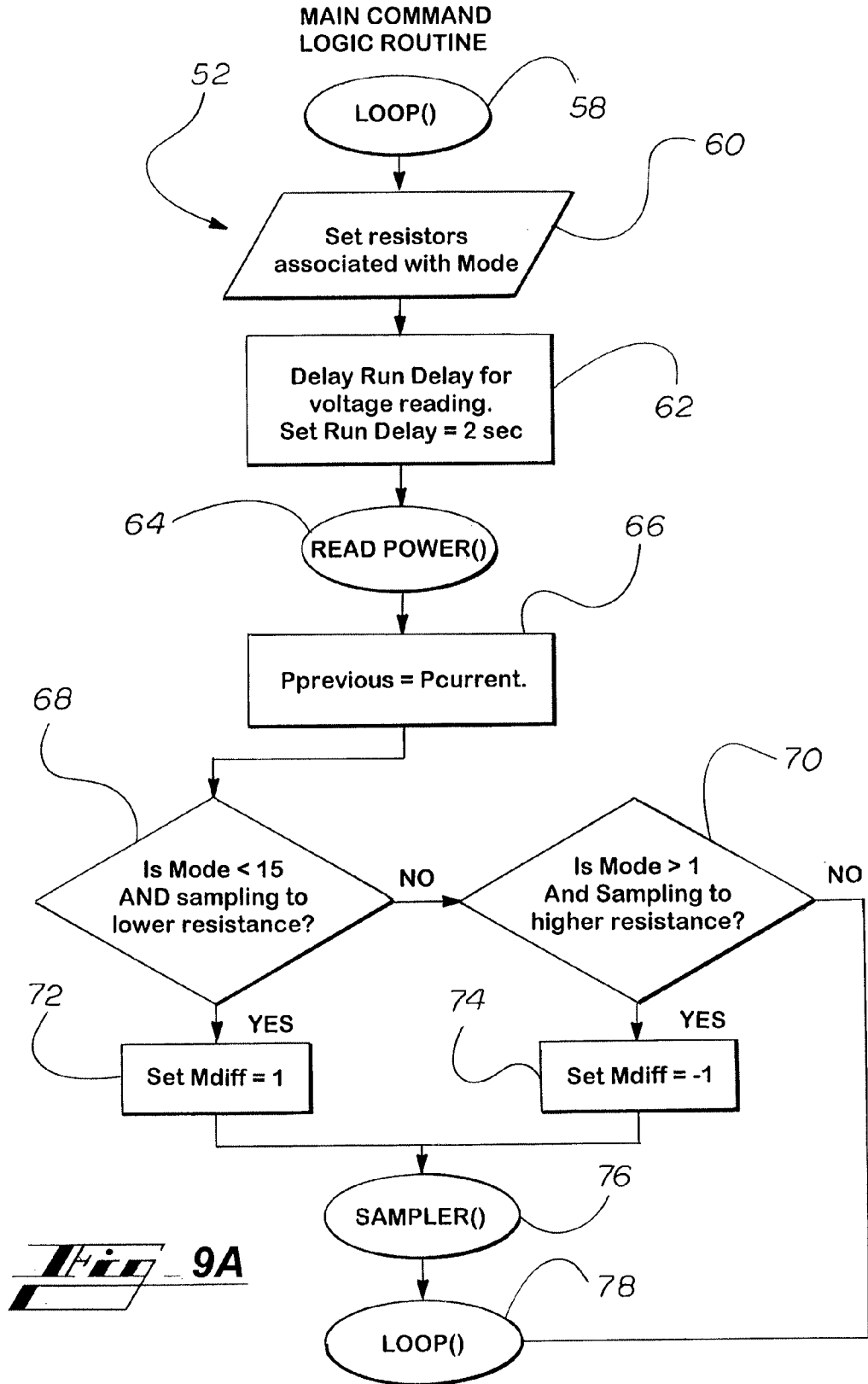


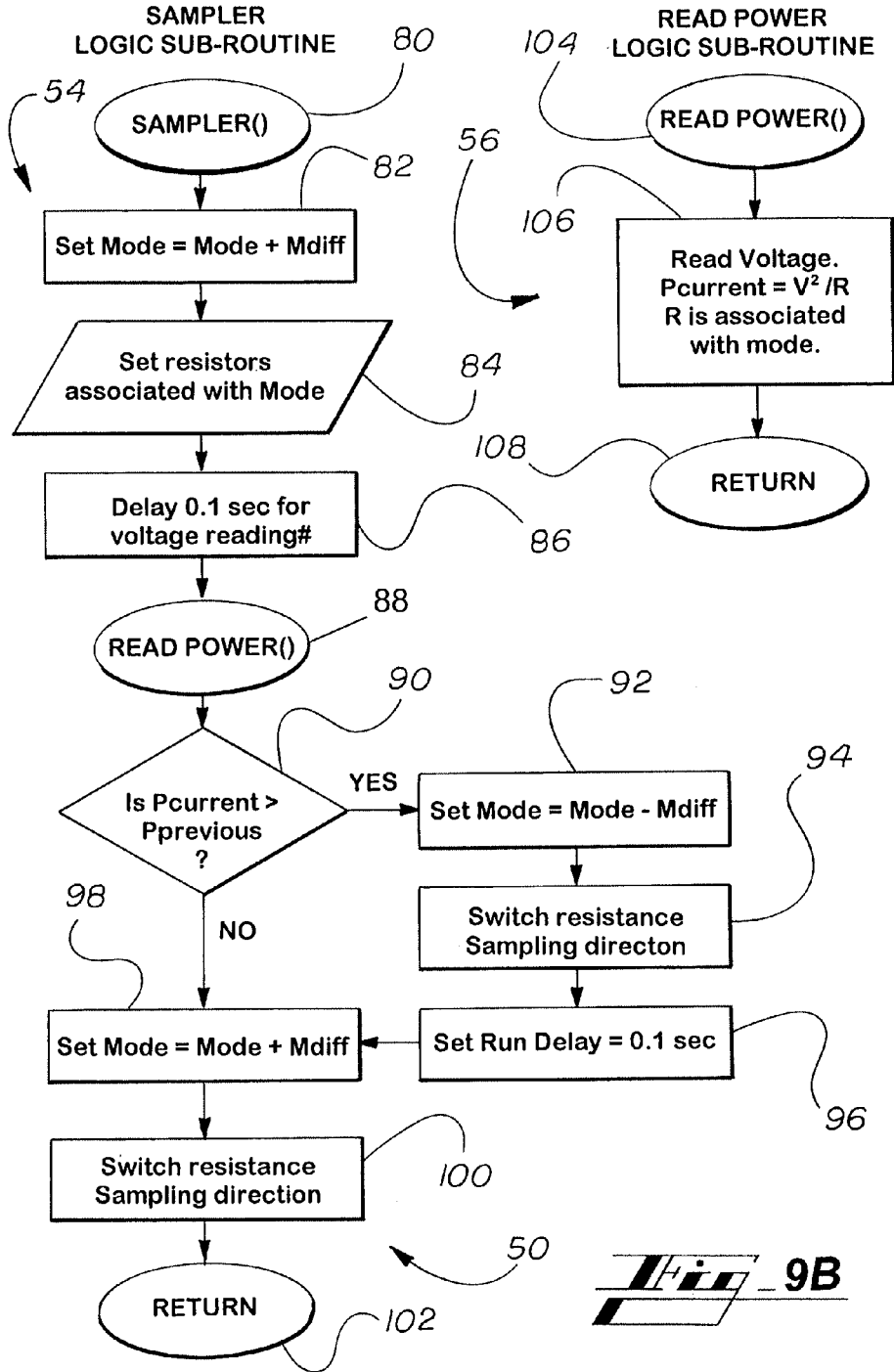
**Fig. 5**

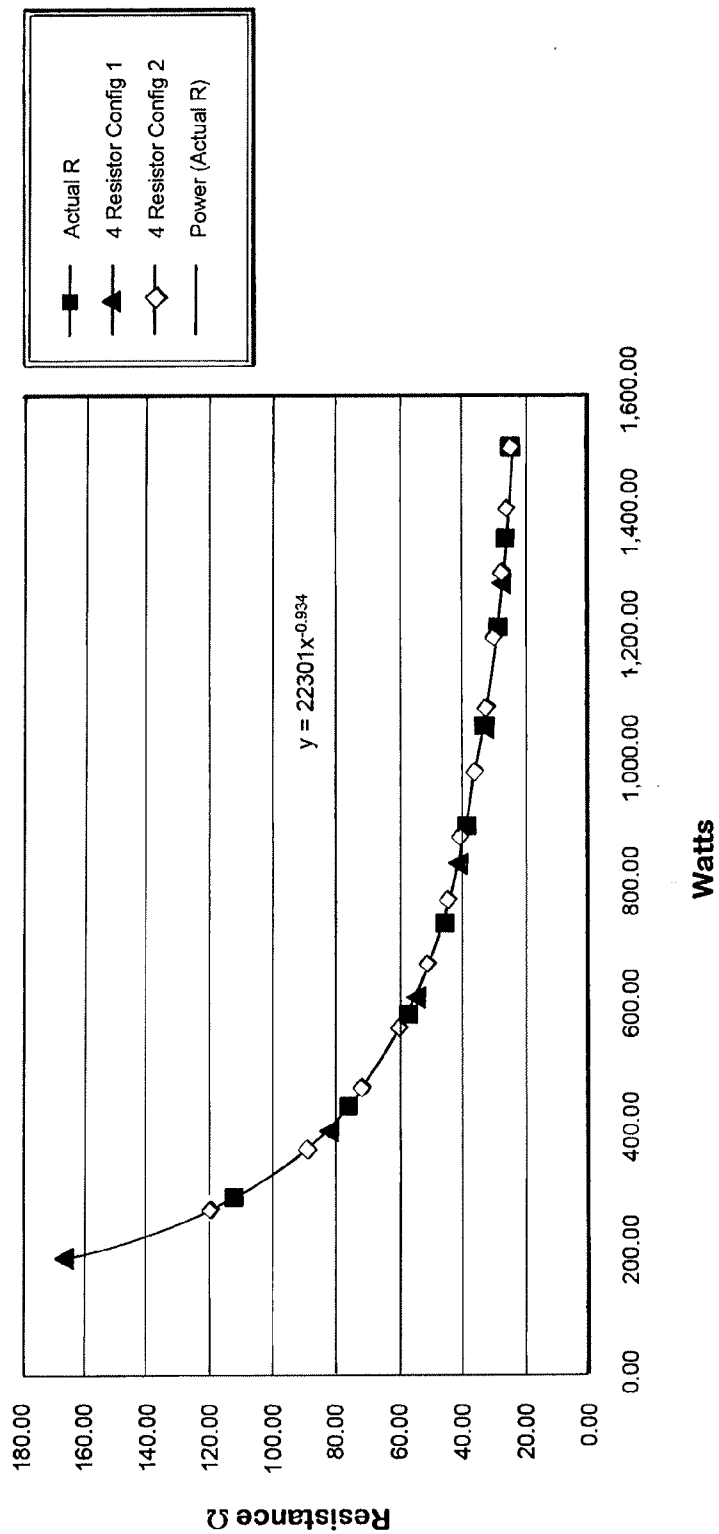


Irradiance Watts/m <sup>2</sup>	Panel Volts	Array Volts	Amps	Actual R	Actual W
1,000.00	38.01	190.05	7.98	23.82	1,516.60
900.00	38.32	191.60	7.12	26.91	1,364.19
800.00	37.80	189.00	6.43	29.39	1,215.27
700.00	37.72	188.60	5.63	33.50	1,061.82
600.00	37.19	185.95	4.79	38.82	890.70
500.00	37.01	185.05	3.99	46.38	738.35
400.00	36.83	184.15	3.19	57.73	587.44
300.00	36.64	183.20	2.39	76.65	437.85
200.00	36.16	180.80	1.60	113.00	289.28



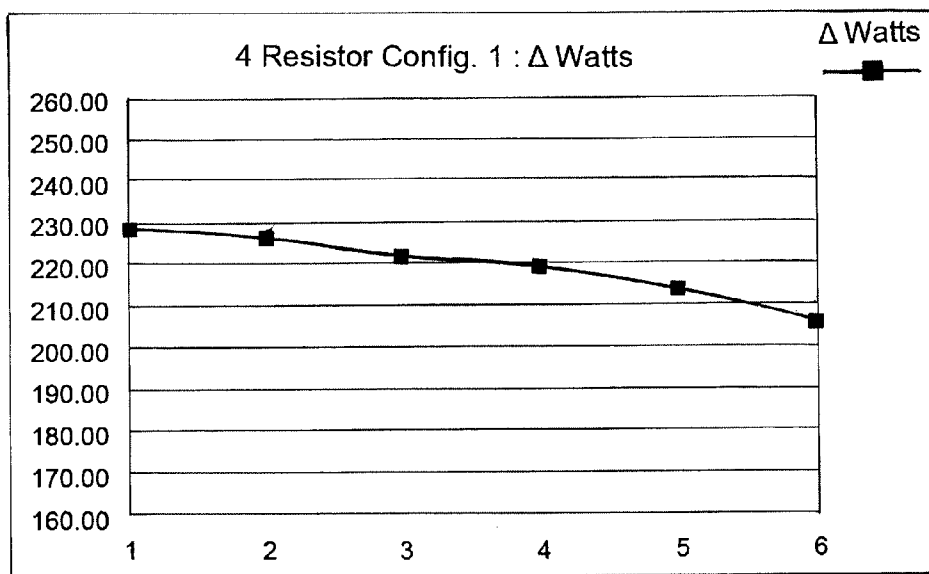




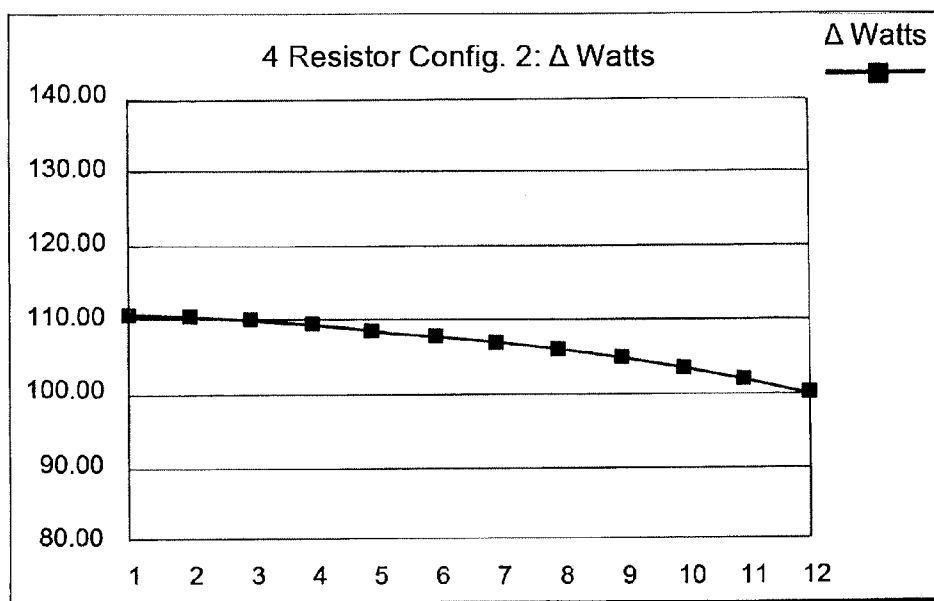


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**Fig. 11A**



**Fig. 11B**

4 Resistor Config 1	Resistance	Watts	Δ Watts	Volts	Amps	Switch Rs
R1	23.82	1,518.57		190.17	7.99	1110
R2	27.79	1,287.53	231.04	189.14	6.81	1100
R3	33.34	1,059.20	228.32	187.93	5.64	1010
R4	41.68	834.11	225.10	186.45	4.47	1000
R5	55.57	612.99	221.12	184.56	3.32	0110
R6	83.36	397.12	215.87	181.94	2.18	0100
R7	166.71	189.07	208.05	177.54	1.06	0010
R8 (AC)	16.46	3,500.00		240.00	14.58	1111
					All off	0000

All On



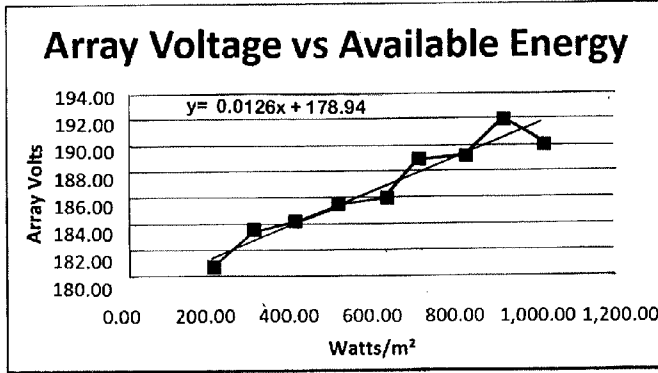
Fixed R Values	R	Ratios of R4
R4	41.68	1.00
R6	83.36	2.00
R7	166.71	4.00
R9	53.26	(method determined value)

4 Resistor config 2	Resistance	Watts	Δ Watts	Volts	Amps	Switch Rs
R1	23.82	1,518.57		190.17	7.99	1110
R2	25.52	1,410.44	108.13	189.71	7.43	1101
R3	27.48	1,302.85	107.59	189.21	6.89	1011
R4	29.77	1,195.85	107.00	188.68	6.34	0111
R5	32.48	1,089.47	106.37	188.10	5.79	1100
R6	35.72	983.78	105.69	187.47	5.25	1010
R7	39.69	878.84	104.95	186.77	4.71	1001
R8	39.69	878.84	0.00	186.77	4.71	0110
R9	44.65	774.71	104.12	186.00	4.17	0101
R10	51.03	671.51	103.21	185.12	3.63	0011
R11	59.54	569.34	102.17	184.12	3.09	1000
R12	71.45	468.38	100.66	182.93	2.56	0100
R13	89.31	368.84	99.54	181.50	2.03	0010
R14	119.08	271.06	97.78	179.66	1.51	0001
R15 (AC)	19.85	2,902.28		240.00	12.09	1111
					All off	0000

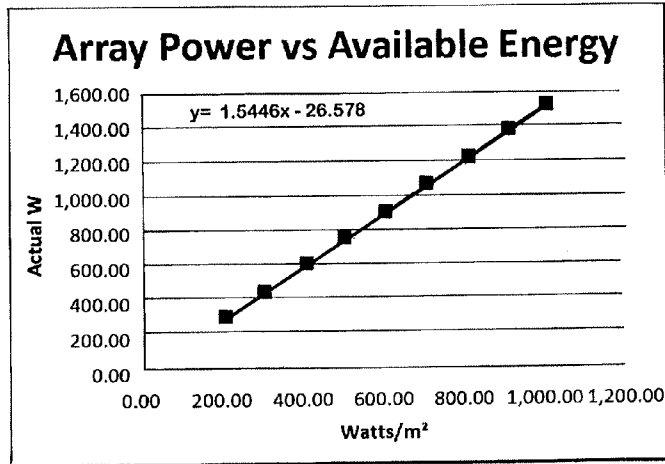
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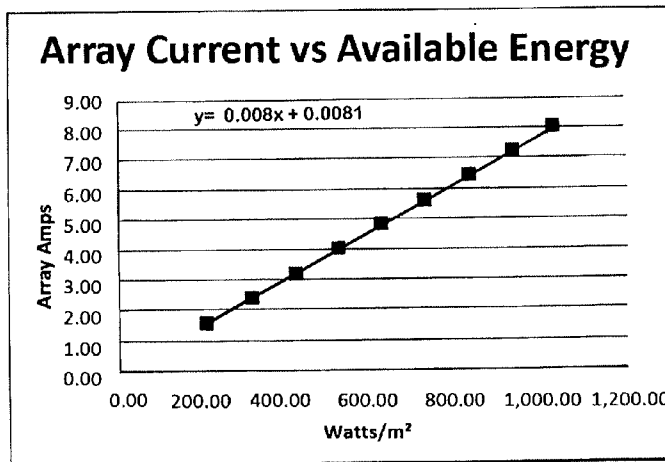
Fixed R Values	R	Ratios of R11
R11	59.54	1.00
R12	71.45	1.20
R13	89.31	1.50
R14	119.08	2.00



**Fig. 13A**



**Fig. 13B**



**Fig. 13C**

## SOLAR PHOTOVOLTAIC WATER HEATING SYSTEM

### CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims priority to U.S. Provisional Patent Application Ser. No. 61/733,595, filed Dec. 5, 2012, which is incorporated herein by reference.

### FIELD OF THE INVENTION

**[0002]** The invention relates to a direct current (DC), photovoltaic (PV) water heating system. In particular, the invention is a photovoltaic water heating system that controls the electrical energy used to heat the water.

### BACKGROUND OF THE INVENTION

**[0003]** Solar water heaters are known in the prior art. Kemp U.S. Pat. No. 451,384, entitled, "Apparatus for Utilizing the Sun's Rays for Heating Water," discloses a solar water heating system that comprises a series of large diameter pipes connected in series in a wooden box, insulated with sand, and covered with green house glass panes. The pipes contained a volume of water that was directly heated by solar irradiance during the day for use in the evening. Subsequent to the Kemp patent, an improved solar water heating system comprised a separate solar collector and a storage tank. The solar collector used the decrease in the density of the water when heated to move water into the tank. This arrangement created a thermosiphonic flow. Solar water heating systems have been evolving along those same technological lines ever since. Essentially, there is a tank, a collector, and a means to move heat energy from the collector to the tank.

**[0004]** Fanney et al. U.S. Pat. No. 5,293,447, titled "Photovoltaic Solar Water Heating System", issued in 1994, discloses a solar water heating system that uses solar generated electricity from photovoltaic panels to power specialized electric resistance heating elements that are fully immersed in the water heater tank. The resistance heating elements are connected in various parallel combinations, directly to the DC output of the photovoltaic solar panels. A computer control system selects the configuration of resistance elements to match the electric power output characteristics of the photovoltaic panels. The computer control system measures the power characteristics of the photovoltaic panels and operates electrical/mechanical relays that provide the direct connection of the DC power from the photovoltaic array to the resistance heating element combinations. The heating element combinations are determined to extract the optimum amount of power from the photovoltaic array. The solar water heating system of the Fanney et al. patent is, however, limited to a maximum of 7 combinations of resistance and those combinations are not mathematically optimized to achieve even step changes in power delivery from the PV panel array.

**[0005]** Ashkenazy United States Patent Application Publication No. 20120187106, entitled "Photovoltaic Heater", filed on Mar. 29, 2012, discloses a photovoltaic heating system that relies on an inverter device for the conversion of direct current from a photovoltaic solar array to alternating current (AC) to power a conventional resistance heating element. DC to AC inverters have been used in PV systems for homes for many years to provide AC power for the various loads and appliances including resistance water heaters. The Ashkenazy Application further discloses a switching circuit

that disconnects the inverter's AC power from the resistance heating elements and connects the AC power from the electrical grid to the resistance heating elements. Consequently, the resistance heating elements are switched between one AC power source of a variable level (solar) to another AC power source of a known and constant level (electrical grid).

**[0006]** Yet another patent Thomasson United States Patent Application Publication No. 2009/0188486, entitled "PV Water Heater with Adaptive Control", filed Jan. 24, 2008, discloses a method to detect hot water usage, and interact with the PV that limits the energy delivery to the water heater as a function of hot water usage.

### SUMMARY OF THE INVENTION

**[0007]** The solar photovoltaic water heating system of the present invention comprises a solar PV array consisting of PV panels, a water storage tank for storing heated water, resistance heating elements in the water tank for heating the water, and a programmable control system for delivering DC power from the PV panels to the resistance heating elements.

**[0008]** In overcoming the deficiencies of the prior art solar heating systems, the solar photovoltaic water heating system of the present invention assures safety for the users of the hot water and assures safety in connection with the use of direct electric current. The solar photovoltaic water heating system is an advancement over other DC power powered direct PV heating systems in that the present invention employs formulae and methods for more accurately determining power output from the PV panels of the PV array in order to optimize energy deliver over a wider range of operating conditions.

**[0009]** A feature of the present invention is the programmable control system that switches or redirects power available from the PV panels of the PV array when the hot water load demand has been met.

**[0010]** A further feature of the present invention is a method implemented by the control system that causes the photovoltaic water heating system to store higher temperature water in the storage tank but then safely delivers water at a lower temperature to the users of the hot water, thus allowing more energy to be stored in the tank during periods of high solar irradiance.

**[0011]** Another feature of the present invention, the programmable control system which includes a high temperature limit switch to insure water temperatures do not exceed the practical operating limit of the particular storage tank being used, thereby prolonging the life of the storage tank and reducing warranty claims and issues.

**[0012]** An additional feature of the present invention is a method implemented by the control system for determining the best resistance values for multiple resistance heating elements that are used in varied connection arrangements to maximize electrical energy delivery from the PV array. The method includes formulae to determine resistance values for the resistance heating elements that create more even steps in the power point tracking of the energy delivered from the PV array to the resistance heating elements.

**[0013]** A further feature of the present invention is a method of accumulating and storing data related to the energy delivered by the PV array to the resistance heating elements and to report that data to a remote data acquisition system.

**[0014]** According to yet a further feature of the present invention is a method to remotely access the control system for programming and data downloads of stored information that users may determine is needed for other purposes.

[0015] Another feature of the present invention is a multiple resistance heating element having four individual and discrete heating elements in a single assembly. The four prong resistance heating element is adaptable for use with either AC or DC electrical power.

[0016] An additional feature of the present invention is a structure for the four pronged resistance heating element that can be used for either AC or DC electrical power.

[0017] Further objects, features and advantages will become apparent upon consideration of the following detailed description of the invention when taken in conjunction with the drawings and the appended claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. 1 is a schematic diagram of a solar photovoltaic water heating system in accordance with the present invention.

[0019] FIG. 2 is a perspective view of a storage tank in accordance with the present invention.

[0020] FIG. 3 is a top plan view of the storage tank in accordance with the present invention.

[0021] FIG. 4 is a side elevation view of the storage tank in accordance with the present invention.

[0022] FIG. 5 is a perspective view of a four pronged electrical resistance heating element in accordance with the present invention.

[0023] FIG. 6 is a schematic diagram of a resistance value switching circuit in accordance with the present invention.

[0024] FIG. 7 is a schematic diagram of another resistance value switching circuit in accordance with the present invention.

[0025] FIG. 8 is a data table showing irradiance performance of a typical photovoltaic panel.

[0026] FIGS. 9A and 9B is a flowchart of the control logic that is used in the photovoltaic water heating system to control energy delivery from a solar panel array to the four pronged electrical resistance heating element.

[0027] FIG. 10 is a graph illustrating of a theoretical ideal power curve for an infinitely variable resistance load for a variable direct current power source and illustrating the power curve for the four pronged resistance heating element, connected in various combinations to provide a variable resistance load.

[0028] FIGS. 11A and 11B are graphs illustrating two power point matching curves that illustrate step changes in power (wattage) as a function of changes in solar irradiance.

[0029] FIGS. 12A and 12B are data tables used in developing resistance values for optimum operation of the photovoltaic water heating system in accordance with the present invention.

[0030] FIGS. 13A-13C are data tables used in developing system resistance values for optimum operation of the photovoltaic water heating system in accordance with the present invention.

#### DETAILED DESCRIPTION OF THE INVENTION

[0031] Turning to FIG. 1, a solar photovoltaic water heating system 1 is shown. The solar photovoltaic water heating system 1 includes a photovoltaic panel array 31 consisting of individual solar photovoltaic panels 18, a water storage tank 10 with resistance heating elements 15, a programmable control system 16, and an alternating current power source 32. The control system 16 is connected between the storage tank

10 and the photovoltaic panel array 31 and the alternating current power source 32 in order to control the delivery of power from either the photovoltaic panel array 31 or the alternating current power source 32 to the resistance heating elements 15. One of the heating elements 15 may be a standard alternating current resistance heating element that is only connected to the alternating current power source 32. Alternatively, both heating elements 15 may be alternating current and direct current compatible, resistance heating elements such as the resistance heating element 15 shown in FIG. 5 and described below.

[0032] The photovoltaic panels 18 are conventional and produce direct current power when exposed to irradiance 19 from the Sun 20. The amount of direct current power produced by each photovoltaic panel 18 depends on the level of irradiance 19 impinging on the photovoltaic panels 18. Consequently, because the level of irradiance 19 varies based on the time of day and atmospheric conditions, the level of direct current power produced by each photovoltaic panel 18 varies accordingly. FIGS. 13A-13C are graphs that show the typical energy available from the photovoltaic array 31 for different voltages, power levels, and averages.

[0033] The water storage tank 10 is generally conventional and is shown in FIGS. 2-4. The water storage tank 10 includes a cold water inlet 22 extending to near the bottom of the storage tank 10 for the introduction of cold water 12 into the storage tank 10. The storage tank 10 further includes a hot water outlet 21 extending into the upper part of the storage tank 10. A mixing valve 17 is connected to the hot water outlet 21 and to a cold water shunt 33 in order to provide a mixture of hot and cold water to the hot water outlet 11, which in turn is connected to a consumer water system (not shown). The mixing valve 17 is thermostatically controlled to ensure that the hot water 11 is not too hot for a consumer water system such as residential hot water system. The operation of the mixing valve 17 allows the water in the storage tank 10 to be raised substantially higher than a normal residential consumer water system thereby allowing the solar photovoltaic water heating system 1 to store more energy in the storage tank 10. The water storage tank 10 further includes a cover 25 for housing and protecting the control systems 16 and associated wiring. A pressure relief safety valve 23 is also connected to and in communication with the interior of the water storage tank 10. If the pressure inside the water storage tank 10 exceeds a preselected level for the relief safety valve 23, the relief safety valve 23 opens so that the pressure inside the water storage tank 10 can be relieved.

[0034] The resistance heating elements 15 are located in the water storage tank 10 at one or more levels to ensure consistency of the water temperature in the water storage tank 10. As shown in FIG. 5, the resistance heating element 15 comprises, for example, four individual resistance heating rods 29 connected through a stainless steel fitting 26. The resistance heating rods 29 may be formed of stainless steel, inconel, carbon steel, or copper. The stainless steel fitting 26 is threaded into the side of the water storage tank 10 to form a water and pressure tight seal. Each individual resistance heating rod 29 has a pair of connecting wires 27 that allow each resistance heating rod 29 to be individually connected to either the photovoltaic array 31 or the direct current power source 32 through a switching circuit, such as one of switching circuits 34 (FIG. 6) and 35 (FIG. 7).

[0035] The switching circuits 34 and 35 are controlled by the control system 16 in order to select the optimum load

resistance, such as direct current load resistance RloadDC 37 or RloadDC 39 for the direct current power source 31 (photovoltaic array 31) or alternating current load resistance RloadAC 36 or RloadAC 38 for the alternating current power source 32 (public power grid). The switching circuit 34 illustrates a first configuration and is configured to provide seven resistance values for the direct current load resistance RloadDC 37 and one resistance value for the alternating current load resistance RloadAC 36. The switching circuit 34 comprises a DC switch 41, an AC switch 42, and a resistance array including fixed value resistors R4, R6, R7, and R9 with their associated switches. The resistors R4, R6, R7, and R9 represent each of the four individual heating rods 29 in the resistance heating element 15. The control system 16 opens and closes the DC switch 41, the AC switch 42, and the switches associated with each of the resistors R4, R6, R7, and R9 in order to select the optimum direct current load resistance RloadDC 37 for the direct current power source 31 or the optimum alternating current load resistance RloadAC 36 for the alternating current power source 32. Selection of the optimum load resistance RloadDC 37 or RloadAC 36 maximizes the energy delivered to the water in the water storage tank 10 by either the direct current power source 31 or the alternating current power source 32.

[0036] Likewise the switching circuit 35 illustrates a second configuration and is configured to provide 14 resistance values for the direct current load resistance RloadDC 39 and one resistance value for the alternating current load resistance RloadAC 38. The switching circuit 35 comprises a DC switch 43, an AC switch 44, and a resistance array including fixed value resistors R11, R12, R13, and R14 with their associated switches. The resistors R11, R12, R13, and R14 represent each of the four individual heating rods 29 in the resistance heating element 15. The control system 16 opens and closes the DC switch 43, the AC switch 44, and the switches associated with each of the resistors R11, R12, R13, and R14 in order to select the optimum direct current load resistance RloadDC 39 for the direct current power source 31 or the optimum alternating current load resistance RloadAC 38 for the alternating current power source 32. Selection of the optimum load resistance RloadDC 39 or RloadAC 38 maximizes the energy delivered to the water in the water storage tank 10 by either the direct current power source 31 or the alternating current power source 32.

[0037] With respect to configuration 1, illustrated by switching circuit 34 and by the table shown in FIG. 12A, the formula set forth below establishes the values for the fixed resistors R4, R6, R7, and R9 (the resistance heating rods 29 of the resistance heating element 15). Once the values for the resistors R4, R6, R7, and R9 have been established, the control system 16 runs an algorithm to open and close the switches in the switching circuit 34 to produce the optimum load resistance for the power source that is available. In order to determine the values for the resistors R4, R6, R7, and R9, the formula first solves for the single resistor R4 (one of the four heating rods 29 of the heating element 15). The value for the resistor R4 is then used in a ratio determination method, described in greater detail below, to determine the three other fixed resistance values for resistors R6, R7, and R9 (the other three of the four heating rods 29 of the heating element 15). The fixed resistance values of resistors R4, R6, R7, and R9 are used by the control system 16 in various single and parallel connection arrangements to create up to seven different direct current load resistance values R1, R2, R3, R4, R5, R6, and

R7, and one alternating current load resistance value R8 (see table, FIG. 12A). The resistance values R1-R7 are used in connection with the direct current power source 31, and the resistance value R8 is used in connection with the alternating current power source 32. The resistance value R8 is the optimum value for the alternating current power source 32, and the resistance value R8 is the lowest available resistance and results from the parallel connection of all four fixed resistors R4, R6, R7, and R9 (resistance heating rods 29 of the resistance heating element 15). R1 is the optimum resistance value for the direct current power source 31 where the direct current power source is delivering maximum energy at 1000 watts per square meter of solar irradiance 19. See FIG. 8, first line (resistance=23.82 ohms) and FIG. 12A (R1=23.82 ohms).

[0038] The formula for determining the value of the fixed resistor R4 for configuration 1 (FIG. 12A) is as follows:

[0039]  $P_{w} = \text{Array Power in watts at solar irradiance level (w)}$

[0040] MPP=Maximum Power Point (MPP—the optimum transfer of energy from the power source to the resistance load)

[0041] R=Load Resistance

[0042] W=Watts delivered to the load

[0043]  $W/m^2 = \text{Watts per square meter of solar irradiance}$

[0044]  $V_{K} = \text{Photovoltaic array operating MPP voltage (volts) @ 1000 W/m}^2$

[0045] Photovoltaic array operating MPP source (amps) @ 1000  $W/m^2$

[0046]  $V_{w} = \text{Photovoltaic array MPP voltage at a stated level of solar irradiance (w)}$

[0047]  $I_{w} = \text{Photovoltaic array MPP current at a stated level of solar irradiance (w)}$

[0048]  $M_v = \text{Slope of linear equation for calculating Voltage } (\approx 0)$

[0049]  $B_v = \text{y-intercept of linear equation for calculating Voltage } (\approx V_{w})$

$$P_w = V_w I_w \quad \text{Standard Power formula:}$$

[0050] The majority of mono-crystalline photovoltaic panels follow the approximation for input energy between 200 and 1000  $W/m^2$ .

$$V_w \approx M_v W + B_v$$

$$I_w(W/1000)I_K$$

[0051] Formula for determination of optimal value of  $R_4$  is as follows:

$$R_1 = 1 / ((1/R_4) + (1/R_6) + (1/R_7)) = V_K / I_K$$

$$I_K / V_K = (1/R_4) + (1/2R_6) + (1/4R_7) \rightarrow I_K / V_K = 1.75 / R_4 \rightarrow R_4 = 1.75 (V_K / I_K)$$

[0052] Once the value of R4 for configuration 1 (FIG. 12A) is determined, the ratio formula is used to select the optimal resistance values of fixed resistors R6, R7, and R9:

[0053]  $R_4$  is used to determine  $R_6$ , and  $R_7$  wherein

[0054]  $R_6$  is a multiple of two (2) times the value of  $R_4$

[0055]  $R_7$  is a multiple of four (4) times the value of the value of  $R_4$ .

[0056]  $R_9$  is determined by inserting the derived value for optimal AC operation as follows:

[0057]  $W_{AC} = \text{desired power output for alternating current power source}$

- [0058]  $V_{AC}$ =voltage for the alternating current power source
- [0059]  $I_{AC}=W_{AC}/V_{AC}$
- [0060]  $R_{AC}=V_{AC}/I_{AC}$  Example:  $W_{AC}=3500$  watts  
 $V_{AC}=240$  volts
- [0061] The calculation then proceeds as follows:  $I_{AC}$  (current)= $3500/240=14.58$  mps  
 $R_{AC}=240/14.58=16.46$   
 $R_9=1/((1/R_{AC})-(1/R_4)-(1/R_6)-(1/R_7))^*=1/((1/R_{AC})-(1.75/R_4))$   
 $R_8=1/((1/R_4)+(1/R_6)+(1/R_7)+(1/R_9))=R_{AC}^{**}$   
 $R_7=4 R_4^*$   
 $R_6=2R_4^*$   
 $R_5=1/((1/R_7)+(1/R_6))$   
 $R_4$ =Value of resistance to be determined using proprietary formula\*  
 $R_3=1/((1/R_4)+(1/R_7))$   
 $R_2=1/((1/R_4)+(1/R_6))$   
 $R_1=1/((1/R_4)+(1/R_6)+(1/R_7))$   
 $R_0=\infty$  (all off)

- [0062] \* (these are the fixed values of resistance for the four (4) pronged heating element 15)
- [0063] \*\* (the  $R_8$  value being the optimum resistance for operation on grid alternating current power)
- [0064] With reference to FIGS. 6 and 12A, the direct current load resistance RloadDC 37 and the alternating current load resistance RloadAC 36 for the switching circuit 34 are selected by the switch configurations defined by the binary bits, in the column "Switch RS." Each of the binary bits indicates the status of the associated switches for the fixed resistors R4, R6, R7 and R9. For example, for the direct current power source 31, the control system 16, based on the output from direct current power source 31, closes the DC switch 41, opens the AC switch 42, and sets the binary code to 1110. With the binary code set to 1110, the associated switches for fixed resistors R4, R6, and R7 are closed, and the direct current load resistance RloadDC 37 equals the parallel combination of fixed resistors R4, R6, and R7, equals resistance R1, and equals 23.82 ohms (FIG. 12A, line R1). As a further example, for the alternating current power source 32, the control system 16 closes the AC switch 42, opens the DC switch 41, and sets the binary code to 1111. With the binary code set to 1111, the associated switches for fixed resistors R4, R6, R7, and R9 are closed, and the alternating current load resistance RloadAC 36 equals the parallel combination of fixed resistors R4, R6, R7 and R9, equals resistance R8, and equals 16.46 ohms (FIG. 12A, line R8).
- [0065] With respect to configuration 2, illustrated by switching circuit 35 (FIG. 7) and by the table shown in FIG. 12B, the formula set forth below establishes the values for fixed resistors R11, R12, R13, and R14 (the four resistance heating rods 29 of the resistance heating element 15). Once the values for the resistors R11, R12, R13, and R14 have been established, the control system 16 runs an algorithm to open and close the switches in the switching circuit 35 to produce

the optimum load resistance for power source that is available. In order to determine the values for the resistors R11, R12, R13, and R14, the formula first solves for the single resistor R11 (one of the four heating rods 29 of the heating element 15). The value for the resistor R11 is then used in a ratio determination method, described in greater detail below, to determine the three other fixed resistance values for resistors R12, R13, and R14 (the other three of the four heating rods 29 of the heating element 15). The fixed resistance values of resistors R11, R12, R13, and R14 are used by the control system 16 in various single and parallel connection arrangements to create up to 14 different direct current load resistance values R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R12, R13, and R14 and one alternating current load resistance value R15 (see table, FIG. 12B). The resistance values R1-R14 are used in connection with the direct current power source 31, and the resistance value R15 is used in connection with the alternating current power source 32. The resistance value R15 is the optimum value for the alternating current power source 32, and the resistance value R15 is the lowest value and results from the parallel connection of all four fixed resistors R11, R12, R13, and R14 (resistance heating rods 29 of the resistance heating element 15). R1 is the optimum resistance value for the direct current power source 31 where the direct current power source is delivering maximum energy at 1000 watts per square meter of solar irradiance 19. See FIG. 8, first line (resistance=23.82 ohms) and FIG. 12B (R1=23.82 ohms).

- [0066] The formula for determining the value of the fixed resistor R11 for configuration 2 (FIG. 12B) is as follows:
- [0067]  $P_{W}$ =Array Power in watts at solar irradiance level (w)
- [0068] MPP=Maximum Power Point (MPP-the optimum transfer of energy from the power source to the resistance load)
- [0069] R=Load Resistance
- [0070] W=Watts
- [0071]  $W/m^2$ =Watts per square meter of solar irradiance
- [0072]  $V_K$ =Photovoltaic array operating MPP voltage (volts) @ 1000 W/m<sup>2</sup>
- [0073]  $I_K$ =Photovoltaic array operating MPP current (amps) @ 1000 W/m<sup>2</sup>
- [0074]  $V_{W}$ =Photovoltaic array MPP voltage at a stated level of solar irradiance (w)
- [0075]  $I_{W}$ =Photovoltaic array MPP current at a stated level of solar irradiance (w)
- [0076]  $M_v$ =Slope of linear equation for calculating Voltage ( $\approx 0$ )
- [0077]  $B_y$ =y-intercept of linear equation for calculating Voltage ( $\approx V_{W}$ )

$P_{W}=V_{W}I_{W}$  Standard Power formula:

[0078] The majority of mono-crystalline PV panels follow the approximation for input energy between 200 and 1000 W/m<sup>2</sup>.

$V_{W}\approx M_v W+B_y$   
 $I_{W}\approx (W/1000)I_K$

$R_K$ =Optimum resistance for Maximum Power delivery at 1000 W/m<sup>2</sup>



[0079] Formula for determination of optimal value of  $R_{11}$  is as follows:

$$R_1 = R_K = V_K / I_K = 1 / ((1/R_{11}) + (1/1.2R_{61}) + (1.5/R_{11}))$$

$$I_K / V_K = (1/R_{11}) + (0.8333/R_{11}) + (0.6666/R_{11}) \rightarrow I_K / V_K = 2.5 / R_{11} \rightarrow R_{11} = 2.5 (V_K / I_K)$$

[0080] Once the value of R11 for configuration 2 (FIG. 12B) is determined, the ratio formula is used to select the optimal resistance values of fixed resistors R12, R13, and R14:

[0081]  $R_{12}$  is a 1.20 ratio of  $R_{11}$ .

[0082]  $R_{13}$  is a 1.50 ratio of  $R_{11}$ .

[0083]  $R_{14}$  is a 2.00 ratio of  $R_{11}$ .

[0084] Thus creating the resistance values:

$$R_0 = \infty \text{ (all off)}$$

$$R1 = 1 / ((1/R11) + (1/R12) + (1/R13))$$

$$R2 = 1 / ((1/R11) + (1/R12) + (1/R14))$$

$$R3 = 1 / ((1/R11) + (1/R13) + (1/R14))$$

$$R4 = 1 / ((1/R12) + (1/R13) + (1/R14))$$

$$R5 = 1 / ((1/R11) + (1/R12))$$

$$R6 = 1 / ((1/R11) + (1/R13))$$

$$R7 = 1 / ((1/R11) + (1/R14))$$

$$R8 = 1 / ((1/R12) + (1/R13)) \text{ Not needed as the step difference is negligible}$$

$$R9 = 1 / ((1/R13) + (1/R14))$$

$$R10 = 1 / ((1/R13) + (1/R14))$$

$$R11 = \text{Fixed resistance value derived using proprietary Formula of Claim 1.}^*$$

$$R12 = \text{Fixed resistance value equal to } 1.20 \times R11^*$$

$$R13 = \text{Fixed resistance value equal to } 1.50 \times R11^*$$

$$R14 = \text{Fixed resistance value equal to } 2.00 \times R11^*$$

$$R15 = 1 / ((1/R11) + (1/R12) + (1/R13) + (1/R14))^{**}$$

[0085] \* these are the fixed values of resistance for the four (4) pronged heating element

[0086] \*\* this value is used for AC operation using grid power

[0087] With reference to FIGS. 6 and 12B, the direct current load resistance  $R_{loadDC}$  39 and the alternating current load resistance  $R_{loadAC}$  38 for the switching circuit 35 are selected by the switch configurations, defined by the binary bits, in the column "Switch RS." Each of the binary bits indicates the status of the associated switches for the fixed resistors R11, R12, R13, and R14. For example, for the direct current power source 31, the control system 16, based on the output from direct current power source 31, closes the DC switch 43, opens the AC switch 44, and sets the binary code to 1010. With the binary code set to 1010, the associated switches for fixed resistors R11 and R13 are closed, and the direct current load resistance  $R_{loadDC}$  39 equals the parallel combination of fixed resistors R11 and R13, equals resistance R6, and equals 35.72 ohms (FIG. 12A, line R6). As a further

example, for the alternating current power source 32, the control system 16 closes the AC switch 44, opens the DC switch 43, and sets the binary code to 1111. With the binary code set to 1111, the associated switches for fixed resistors R11, R12, R13, and R14 are closed, and the alternating current load resistance  $R_{loadAC}$  38 equals the parallel combination of fixed resistors R11, R12, R13, and R14, equals resistance R15, and equals 19.85 ohms (FIG. 12B, line R15).

[0088] Turning to FIGS. 9A and 9B, the control system 16 is programmed to implement the control method 50 that controls the selection of the optimized resistance for either the direct current power source 18 or the alternating power source 32. The control method 50 has a Main Command Logic Routine 52, a Sampler Logic Subroutine 54 and a Read Power Subroutine 56. The control method 50 begins at loop step 58 of the Main Command Logic Routine 52. The internal processor of control system 16 steps through the logic sequence continually while the system has power applied and is in operation. Using the example of the operational resistance values of the 4 resistor configuration 2 of FIG. 12B, each resistance value corresponds to a "Mode" of operation of the solar photovoltaic water heating system 10. There are therefore 15 distinct operating modes each corresponding to a lineup of resistors that have been connected in parallel to set a different resistance value depending on the direct current power available for 14 of the modes and one mode where all fixed resistance values R11, R12, R13, and R14 are switched on in parallel thereby creating an optimized resistance for operation of the resistance heating element 15 in the storage tank using power supplied by the alternating current power source 32.

[0089] Starting from loop step 58 of the main command logic routine 52, the routine 52 moves to step 60 where the routine 52 sets the resistance to Mode 14 (R14 of configuration 2, FIG. 12B), the highest value for the resistance of the resistance heating element 15. From step 60, the routine 52 moves to step 62, where routine 52 imposes a two second delay. From step 62, the routine 52 moves to step 64, and branches to step 104 of the Read Power Subroutine 56. From step 104, the subroutine 56 moves to step 106. At step 106, the subroutine 56 uses the highest resistance value R14 to read power available from the photovoltaic array 31. The power (P) available from the photovoltaic array 31 is determined by measuring the voltage (V) from the photovoltaic array 31 and then calculating the power from the photovoltaic array 31 by using the formula  $P_{current} = V^2 / R$  wherein resistance is a function of the Mode at the time  $P_{current}$  is determined. Once the current power ( $P_{current}$ ) from the photovoltaic array 31 has been determined at step 106, the subroutine 56 moves to step 108 and branches to step 66 of the routine 52.

[0090] At step 66, the routine 52 compares the previously determined power from the photovoltaic array 31 to the current power from the photovoltaic array 31 ( $P_{previous} = P_{current}$ ). From step 66, the routine 52 moves to decision step 68, where the routine 52 determines if the current Mode is less than 15 and the routine 54 at step 94 is sampling the power from the photovoltaic array 31 using combinations the fixed resistor R11, R12, R13, and R14 to create progressively lower resistances. If at step 68 the routine 52 determines that the current Mode is less than 15 and subroutine 54 at step 94 is sampling to a lower resistance, the routine 52 follows the yes branch to step 72. If on the other hand, the routine 52 determines that Mode is greater than 15 or the subroutine 54 is sampling to higher resistances, the

routine 52 follows the no branch to step 70. At step 72, the routine 52 sets  $M_{diff}=+1$ . The term “ $M_{diff}$ ” means the difference by which the Mode changes when determining the next power reading by means of subroutine 56. Particularly, at step 72 the routine 52 decreases the resistance by reconfiguring the fixed resistors R11, R12, R13, and R14 to create a lower value of total resistance. Lowering the resistance is accomplished by turning on the next resistance value in parallel with the previous Mode resistance value, i.e. changing from R14 to R13 in FIG. 12B (0001 to 0010).

[0091] If at step 68 the determination is no, then the routine 52 moves to step 70 where the routine 52 determines if the Mode is greater than 1 and sampling is to a higher resistance. If at step 70 the routine 52 determines that the Mode is greater than 1 and the subroutine for is sampling toward higher resistances, the routine 52 follows the yes branch to step 74. At step 74, the routine 52 sets  $M_{diff}=-1$ , i.e. the routine 52 subtracts one resistance value to change the Mode to a higher resistance. If at step 70 the condition is not satisfied, the routine 52 follows the no branch to step 78, which then returns the routine 52 to the beginning at step 58.

[0092] After the routine 52 has processed  $M_{diff}$  at either step 72 or step 74, the routine 52 moves to step 76 that branches to step 80 of subroutine 54. In the Sampler Logic Subroutine 54, the subroutine 54 sets  $Mode=Mode+M_{diff}$ . From step 82 of subroutine 54, the subroutine 54 proceeds to step 84 where the subroutine 54 sets the resistors associated with the Mode ( $Mode+M_{diff}$ ). Particularly, the fixed resistors R11, R12, R13, and R14 are selected in accordance with the switch configurations shown in FIG. 12B. From step 84, the subroutine 54 proceeds to step 86 that imposes a 0.1 second delay. After the delay at step 86, the subroutine 54 proceeds to step 88, and then branches to step 104 of subroutine 56. The Read Power Logic Subroutine 56 again determines the power value for the photovoltaic array 31 as previously described. Once the subroutine 56, has completed its operation, control is transferred from step 108 back to step 88 any of the subroutine 54.

[0093] From step 88, the subroutine 54 proceeds to step 90. At step 90, the subroutine 54 determines if  $P_{current}$  is greater than  $P_{previous}$ . If at step 90  $P_{current}$  is greater than  $P_{previous}$ , the subroutine 54 follows the yes branch to step 92. At step 92, the subroutine 54 sets  $Mode=Mode+M_{diff}$ . Once the Mode has been set at step 92, the subroutine 54 proceeds to step 94 where the sampling direction of the resistance is switched and a 0.1 second delay is imposed at step 96. From step 96, the subroutine 54 moves to step 98. At step 98, the subroutine 54 sets  $Mode=Mode-M_{diff}$ . From step 98, the subroutine 54 proceeds to step 100, where the sampling direction for the resistance is again switched. From step 100, the subroutine 54 proceeds to step 102, which returns to step 76 of the routine 52. From step 76, the routine 52 proceeds to step 78, and then returns to the beginning at step 58.

[0094] If on the other hand, at step 90  $P_{current}$  is less than  $P_{previous}$ , the subroutine 54 follows the no branch to step 98. At step 98, the subroutine 54 sets  $Mode=Mode-M_{diff}$ . From step 98, the subroutine 54 proceeds to step 100, where the sampling direction for the resistance is again switched. From step 100, the subroutine for proceeds to step 102, which returns to step 76 of the routine 52. From step 76, the routine 52 proceeds to step 78, and then returns to the beginning at step 58. Consequently, method 50 continues sampling the power from the photovoltaic array 31 until a change is detected against the power trend. The control determination

and switching process continues by constantly sampling values at varying time intervals as determined by the change rate of solar irradiance.

[0095] The programmable control system 16 of the present invention also monitors the water temperature and the water pressure in the storage tank 10. Particularly, the storage tank 10 includes a temperature sensor 28 and a pressure sensor 14. The temperature sensor 28 and the pressure sensor 14 are connected to the control system 16. When the water temperature in the storage tank 10 falls below a preselected minimum temperature, the control system 16 connects either the direct current power source 18 or the alternating current power source 32 to the resistance heating elements 15. Once the water temperature in the storage tank tenant reaches a maximum temperature based on the data received from the temperature sensor 28, the control system 16 disconnects either the direct current power source 18 or the alternating current power source 32 to the resistance heating elements 15. Once the direct current power source 18 has been disconnected from the resistance heating elements 15, the direct current power source 18 can be diverted to a direct current power takeoff 30 that can be used to charge batteries, to power an inverter, or to drive a second resistance heating load such as a hot water space heating system. The control system 16 further monitors the data from the pressure sensor 14 so that the pressure in the storage tank 10 remains in a preselected safe pressure range. If the pressure in the water storage tank 10 rises above the preselected pressure range, the control system 16 disconnects either the direct current power source 18 or the alternating current power source 32 from the resistance heating elements 15. If the pressure continues to rise in the water storage tank 10, the pressure relief safety valve 23 will open relieving the pressure in the storage tank 10. Further, if the pressure drops below the preselected pressure range, the control system 16 disconnects either the direct current power source 18 or the alternating current power source 32 from the resistance heating elements 15 so that the water in the storage tank 10 does not begin to boil at a low-pressure.

[0096] The control system 16 is programmable, either through a direct interface or remotely through a remote interface, and can be programmed to collect operating data including, but not limited to, the temperature and pressure data over time, the power delivered to the resistance heating elements 15, the amount of energy delivered to the resistance heating elements 15 by the direct current power source 18 over time, and the amount of energy delivered to the resistance heating elements 15 by the alternating current power source 32 over time. Such data can be stored locally by the control system 16 or it can be transmitted to a remote data acquisition system (not shown) either over a wired network or a wireless network. Further, with advanced internal programming, the control system 16 is capable of learning to optimize energy delivery. For example, the control system 16 can monitor the time of day, the solar irradiance 19, and the temperature of the storage tank 10 and thereby determine the optimal time to switch from the direct current power source 18 to the alternating current power source 32 by means of the switching circuit 34, switches 41 and 42 or by means of the switching circuit 35, switches 43 and 44. Further, the time of the day, from around 2-3 pm to 5-6 pm depending on geographic location, offers the greatest chance that the solar array 31 will provide sufficient energy to bring the storage tank 10 to its maximum temperature in which case the alternating current power source 32 will not be used thereby increasing the

efficiency of the solar photovoltaic water heating system 1. The time periods above are also the less likely time periods in which a high consumption of hot water will be used while the sun is still out.

[0097] Turning to FIG. 10, the graph shows an idealized power curve (power from the direct current photovoltaic power source 31 versus load resistance) that defines the maximum power point, i.e., the point of optimum transfer of energy from the power source to the resistance load where the load resistance is infinitely variable. The graph in FIG. 10 compares the idealized power curve to the operating curve for the solar photovoltaic water heating system 1 of the present invention. Particularly, the graph in FIG. 10 shows that by matching the resistance using the switching circuits 34 and 35, the performance of the solar photovoltaic water heating system 1 of the present invention closely tracks the idealized power curve.

[0098] FIGS. 11A and 11B show plots of the step changes in the load resistance that occurs when using the formula and method of the present invention. To maximize energy delivery by maximum power point matching, the steps in the changes of the load resistance must be in as equal incremented values as possible. Resistance values that have changes that create anything other than a smooth curve will vary the load resistance above or below the maximum power point matching for a given level of solar irradiance. Resistance values that cause points to deviate from a smooth curve plotting will cause losses of energy delivery to the medium being heated.

[0099] FIGS. 13A-13C are examples of data tables derived from measured and published performance information regarding photovoltaic panels. The data then is used to determine the various photovoltaic water heating system operating parameters, which in turn is used to determine the resistance values of the heating rods 29.

[0100] While the invention has been described in connection with heating water, the invention has applicability to heating other media for storing energy. Further, while this invention has been described with reference to preferred embodiments thereof, it is to be understood that variations and modifications can be affected within the spirit and scope of the invention as described herein and as described in the appended claims.

We claim:

- 1. A solar photovoltaic water heating system comprising:
  - a. a solar photovoltaic panel for producing direct current power;
  - b. a water storage tank including:
    - i. a cold water inlet;
    - ii. a hot-water outlet; and
    - iii. a variable resistance heating element having an electrical resistance; and
  - c. a control system connected between the solar photovoltaic panel and the variable resistance heating element and configured to vary the resistance of the variable resistance heating element to match the direct current power supplied by the solar photovoltaic panel.
- 2. The water heating system of claim 1, wherein the variable resistance heating element comprises an array of individual fixed resistance heating rods and the control system is configured to switch the array of individual fixed resistance heating rods into a plurality of single and parallel connections in order to vary the resistance of the variable resistance heating element.
- 3. The water heating system of claim 2, wherein the water heating system further includes a switching network connected to the individual fixed resistance heating rods and controlled by the control system to switch the array of individual fixed resistance heating rods into a plurality of single and parallel connections in order to vary the resistance of the variable resistance heating element.
- 4. The water heating system of claim 1, wherein the water heating system further comprises a alternating current power source for producing alternating current power connected to the control system, and wherein the control system is configured to alternatively connect the direct current power from the solar photovoltaic panel or the alternating current power from the alternating current power source to the variable resistance heating element.
- 5. The water heating system of claim 1, wherein the water heating system further includes a mixing valve having a first hot water inlet connected to the hot water outlet, a second cold water inlet connected to the cold water inlet via a cold water shunt, and a mixing valve outlet for delivering a mixture of hot and cold water to a consumer water system and wherein the control system controls the mixing valve and therefore the mixture of hot and cold water to the consumer water system.

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