STUDY OF A PHOTOVOLTAIC–THERMAL SYSTEM—
THERMOSYPHONIC SOLAR WATER HEATER
COMBINED WITH SOLAR CELLS

RAM KUMAR AGARWAL and H. P. GARG
Centre of Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi-110 016, India

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Abstract—The theoretical study of a solar hybrid system is reported in this work. A photovoltaic thermal
(PV/T) hybrid system combines two different solar systems (thermal and photovoltaic) in one unit. The
end products of such a system are both thermal and electrical energy. For the study, a thermosyphon water
heater combined with solar cells is chosen. Experiments were performed for several days on the
thermosyphon water heater alone. A finite difference method is used to simulate the performance of the
solar water heater. The one day experimental data are used to determine the heat loss coefficients of the
collector unit and water tank. The predictions for other days are in excellent agreement with experimental
observations. The experimentally validated model is used to simulate the performance of the system when
it is converted into a hybrid system, i.e. solar cells are pasted directly over the absorber plate. The solar
cells are assumed to be in perfect thermal contact with the absorber and, at the same time, electrically
insulated from the absorber plate. Since the solar cell efficiency depends on temperature, a linear relation
has been used to calculate its variation with mean absorber plate temperature. The cell efficiency and the
absorber plate temperature are determined iteratively. The effect of some design parameters on the daily
cell efficiency is studied. The average cell efficiency is more or less independent of the cell area. However,
the thermal efficiency does depend on the cell area. The amount of water in the tank affects the system
performance significantly. Simulations are done for different water masses in the tank and also for different
amounts of water withdrawn at different times. The cell efficiency increases slightly with the increase in
water mass. It is shown that domestic hybrid solar water heaters (area > 2 m²) can generate sufficient
electrical energy round the year to run tube lights, television etc. for 5–6 h during the night.

Hybrid systems  Photovoltaic/thermal systems  Thermosyphon water heater  Flat plate collectors

NOMENCLATURE

\( A_c \) = Aperture area of collector (m²)
\( A_s \) = Surface area of storage tank (m²)
\( A_{cell} \) = Solar cell area (m²)
\( b \) = Flow tube spacing (m)
\( C_{Al} \) = Specific heat of aluminium (J/kg °C)
\( C_{Fe} \) = Specific heat of iron (J/kg °C)
\( C_p \) = Specific heat of absorber plate (J/kg °C)
\( C_w \) = Specific heat of water (J/kg °C)
\( D_i \) = Internal diameter of tube (m)
\( D_h \) = Internal diameter of header (m)
\( D_c \) = Internal diameter of connecting piping (m)
\( D_o \) = Internal diameter of storage tank (m)
\( F_e \) = Equivalent friction factor
\( f_p \) = Friction factor for collector absorber plate tube
\( f_h \) = Friction factor for collector header
\( f_c \) = Friction factor for connecting pipes
\( G \) = Heat removal factor
\( g \) = Acceleration due to gravity (m/s²)
\( h_i \) = Height of bottom of absorber plate (m)
\( h_t \) = Height of top of absorber plate (m)
\( h_p \) = Height of pipe where it enters upper part of storage tank (m)
\( h_l \) = Height of pipe from lower part of storage tank where it leaves storage tank (m)
\( h_s \) = Height of top of storage tank (m)
\( h_t \) = Height of storage tank (m)
\( K_e \) = Equivalent head loss due to bends, tees and restrictions
\( K_l \) = Head loss in absorber plate tube due to bends, tees and restrictions

†Author to whom correspondence should be addressed.
INTRODUCTION

Solar energy is used mainly in two forms, as thermal energy and as electrical energy. One of the most widely used thermal systems is the solar water heater. These are used in various sizes. In the domestic sectors, the collector area varies from 1 m² to a few metres square. In commercial applications like hotels etc., huge area water heaters are used. Photovoltaic cells are used for conversion of solar energy into electrical energy. In most applications, whether private or commercial, where thermal energy is used, invariably, electrical energy is also required. The electrical energy may be needed to run the pump which circulates the fluid through the thermal system or it may be used for lighting, fans etc. The thermal and photovoltaic systems when used at one place are installed normally as separate units. The efficiency of a thermosyphonic water heater is around 40% or more, whereas in a photovoltaic system, only 8–10% of the solar energy is utilized, the rest, about 90%, is wasted. A new approach calls for the design of more efficient solar systems producing both thermal and electrical energy.

In concentrating photovoltaic systems where the concentration ratio is high, it is a common practice to cool the panels either by using passive means or active means by circulating water or air. Such systems are normally installed at places where hot water or hot air cannot be utilized fruitfully. The need is for a system which could be used in houses or at small commercial centres. One such system is a combined photovoltaic/thermal (PV/T) flat plate collector. Both kinds of energy, thermal as well as electrical, are produced simultaneously from a single collector unit. Such units would be particularly suitable for those solar applications where space is limited. The cost of a single unit is likely to be less than the combined cost of individual units. In the hybrid systems, bare cells are going to be used. In the photovoltaic panels, the process of encapsulation is expensive. It is hoped that the cost of pasting the cells would be less than the encapsulation cost. Further, in the hybrid systems, only one mounting stand will be needed.

Several authors have discussed flat plate PV/T systems [1–10]. The thermal energy is extracted either by liquid or air. The liquid PV/T systems are more efficient than the air PV/T systems [11]. In this work, a flat plate thermosyphonic solar water heater with solar cells is discussed. Experiments under different meteorological conditions were performed for several days on a thermosyphonic water heater system. The one day experimental data are used to determine two heat loss coefficients of the system. The model predictions for other days are in excellent agreement.
with experimental data. The experimentally validated model of the flat plate collector is then used to simulate the performance of the hybrid system. Solar cells are pasted directly over the absorber plate. The rear surface of the solar cell is metallic. It is necessary to choose a pasting material which should be thermally conductive and, simultaneously, an electrical insulator. The solar cells can be pasted over the absorber plate using a silicon dielectric heat transfer compound which is used as a heat sink material for transistors or other electrical devices. It has a relatively high thermal conductivity of 0.952 W/m °C.

The efficiency of the combined system would depend on several factors, like solar cell packing fraction, how much energy is transmitted by the solar cells to the absorber plate, mean absorber temperature etc. Since the efficiency of solar cells decreases as their temperature increases, an attempt is made to identify those design aspects which lead to the reduction of absorber temperature. The most important design parameter which affects the absorber temperature is the total water mass in the tank. The increase in water mass decreases the absorber temperature. The average daily cell efficiency increases, but at the same time, the maximum water temperature in the tank decreases. One must design a system with some predetermined maximum water temperature. In houses, for instance, water around 50°C is required for most applications. One of the operating strategies for lowering the absorber temperature could be to withdraw hot water at some suitable temperature and replace it with an equal amount of cold water. A lower absorber temperature would also improve the average thermal efficiency.

An important question in any PV/T system is where the electrical energy is going to be used and what the solar cell area should be to generate sufficient electrical energy for a given application [12]. The economics of any PV/T system will be determined largely by the solar cell area, because it would be the most expensive component of the hybrid system. The main aim of this investigation is to discuss a small area PV/T system and identify the electrical energy uses. For the study, the commonly used domestic thermosyphon solar water heater is chosen. It could be converted into a PV/T system. It could generate sufficient electrical energy to run some appliances, such as tube lights, fans, television etc.

**MATHEMATICAL MODEL**

The system has two separate units, a storage tank and a flat plate collector which are connected to each other by pipes. It is assumed that the pipes are well insulated, so that there is no heat loss through them. The inlet water temperature to the collector is the same as the water temperature at the bottom of the tank. The temperature of the water entering the tank is the same as that of the outlet water of the collector.

*Thermosyphon water heater*

The system is basically governed by two instantaneous heat balance equations, one for the collector and the other for the tank [13–16]. The energy is absorbed only by the collector. Part of the solar energy falling on the collector is used in heating water, and the rest is lost. The tank does not absorb energy. It only loses energy. The energy balance equation for the collector is

\[ F_R A_c S(\alpha t) = U_T (T_w - T_s) + (M_w C_w + M_c C_p) \frac{\Delta T_w}{\Delta t}, \]

where \(\Delta T_w\) is the change in mean tank water temperature over a small time interval, \(\Delta t\). \(U_T\) is the total heat loss coefficient of the system and is defined as

\[ U_T = U_{in} A_i + U_{out} A_s + U_s A_s. \]

In our case, \(U_s\) is zero. In case the collector absorber plate, tubes, tank and piping are constructed of different materials, the \(M_w C_w\) term should be written \(\Sigma M_i C_{pi}\) and \(M_i\) is the mass and \(C_{pi}\) the specific heat of the material \(i\). \(C\), the total heat capacity of the system, is defined as

\[ C = M_w C_w + \Sigma M_i C_{pi}. \]
The energy balance equation for the storage tank is

\[ nhC_w(T_s - T_3) = (M_iC_{pi} + M_wC_w) \frac{\Delta T_m}{\Delta t} + U_s A_s(T_m - T_s). \]  

(3)

The above two equations are solved by a finite difference method. In this method \( \Delta T_m \) is replaced by

\[ T_m = T'_m - T_m. \]  

(4)

where \( T'_m \) is the mean water temperature after the time interval \( \Delta t \). Equations (1) and (4) are combined to give

\[ T'_m = \frac{(F_R A_sS(\alpha t) + U_sT_s)\Delta t}{C} + \left( 1 - \frac{U_s\Delta t}{C} \right) T_m. \]  

(5)

The mass flow rate of water through the collector is given by [15]

\[ m = \frac{(2.5T_m - 58.3)10^{-6}F(M_iC_{pi} + M_wC_w)\frac{\Delta T_m}{\Delta t} + U_sA_s(T_m - T_s)}{(GC_w)^{10}} \]  

(6)

where \( F \) is a function of the height of various points of the collector from the ground level, Fig. 1. It is given by

\[ F = 2(h_2 - h_1) - (h_2 - h_1) - \frac{(h_3 - h_1)^2}{(h_2 - h_1)}. \]  

(7)

\( G \) is a function of the collector geometry and is given by

\[ G = \frac{16(F_L/D_i + K_e)}{\pi^2g\rho^2D_i^4N^2}, \]  

(8)

\[ F_L = f_i + f_nD_iN^2 \left( \frac{L_n}{L_i} \right) \left( \frac{D_i}{D_n} \right)^3 + f_nD_iN^2 \left( \frac{L_n}{L_i} \right) \left( \frac{D_i}{D_n} \right)^3, \]  

(9)

\[ K_e = K_i + K_nN^2 \left( \frac{D_i}{D_n} \right)^4 + K_nN^2 \left( \frac{D_i}{D_n} \right)^4. \]  

(10)

Fig. 1. Schematic layout of thermosyphonic solar water heater.
The inlet $T_1$ and outlet $T_2$ water temperatures of the collector are given by [15]

$$T_1 = T_m + \frac{1}{2} \frac{G \Delta h^2}{(2.5 T_m - 58.3) \times 10^{-6} \; \text{F}}.$$  (11)

$$T_2 = T_m + \frac{1}{2} \frac{G \Delta h^2}{(2.5 T_m - 58.3) \times 10^{-6} \; \text{F}}.$$  (12)

Two kinds of efficiencies are defined [17, 18], one for the collector alone and another for the whole system. The instantaneous collector efficiency is defined as

$$\eta_{\text{col}} = \frac{\dot{m} C_w (T_2 - T_1)}{S A_c}.$$  (13)

The efficiency for the water tank, or the thermal efficiency of the system, is defined as

$$\eta_{\text{thermal}} = \frac{M_w C_w (T_{\text{inital}} - T_{\text{final}})}{A_c \int_0^t s \, dt},$$  (14)

where $T_{\text{inital}}$ is the temperature of the water in the tank up to a time $t$ and $T_{\text{final}}$ is the tank water temperature at the onset of the insolation.

The equations are solved on a ICL-2900 computer system. The time interval is taken as 10 s. Earlier calculations were done for a longer time interval. It was found that the solutions converge for 10 s.

The programme is written in such a way that, when the water temperature in the tank becomes a maximum, i.e. the outlet water temperature of the collector becomes less than the inlet water temperature, the mass flow rate becomes zero. This happens at around 4 p.m. After this time, the water temperature in the storage tank decreases because heat is lost continuously from the tank. There is a back flow valve in the system which prevents reverse flow.

Photovoltaic/thermal system

The aim of this work is to simulate the performance of the system. A thermosyphon water heater is converted into a hybrid system or the solar cells are pasted directly over the absorber area. Part of the solar radiation falling on the collector area is now absorbed by the solar cells. It is assumed that

(i) The radiative properties of the absorber plate and the front part of the cells are the same. For the non-selective black absorber surface, the emittance and absorptance is around 0.9. The literature survey indicates that the absorptivity of the array of a photovoltaic panel can be as high as 0.95. The emittance, however, is not as high as 0.9, but a value of 0.7 has been used. For simplicity, we have taken both absorptance and emittance of the solar cell surface equal to 0.9.

(ii) The part of the insolation which is not converted into electrical energy is transmitted to the absorber plate and is absorbed there. As a consequence of this assumption, the energy reaching the absorber is equal to the total energy over the absorber minus the energy converted into electrical energy.

(iii) The solar cells are in perfect thermal contact with the absorber plate. It implies that the cell temperature is the same as the absorber temperature.

In a hybrid system, a new parameter, that is, cell area, appears. The system performance will now depend on the cell area. A dimensionless parameter $P$ is defined as

$$P = \frac{A_{\text{cell}}}{A_c}.$$  (15)
Two shapes of solar cells are available, square and circular. If square-shaped cells are used, then the whole of the absorber area can be covered by solar cells or P can be 1. The square cells are expensive and normally not available in the Indian market. For circular cells of 10 cm diameter, the maximum absorber area covered by the solar cells will be about 75%, or a maximum value of P will be 0.75. In the presence of the solar cells, equation (1) is modified. It can be written as

\[ F_n(xr)SA_t(1 - \eta_e P) = U_t(T_m - T_a) + (M_m C_m + M_m C_p) \frac{\Delta T_m}{\Delta t}, \]  

(16)

where \( \eta_e \) is efficiency of the solar cells at the mean absorber temperature, \( T_p \). Equation (16) follows directly from the first assumption. The cell efficiency is a function of its temperature. The variation of cell efficiency with temperature is calculated from the following relation [3–5]

\[ \eta_e = \eta_e[1 - \beta_e(T_p - T_c)], \]

(17)

where \( \eta_e = 10\% \) is the cell efficiency evaluated at the reference temperature, \( T_c = 25^\circ C \). \( \beta_e \) is a constant given by

\[ \beta_e = \frac{1}{(T_c - T_r)} = 0.0041. \]

(18)

\( T_r \) is the cell temperature at which the efficiency drops to zero, which is taken as 270°C. The temperature of the absorber plate is given by

\[ T_p = \frac{SA_t(xr(1 - \eta_e P) - \eta_oa)}{U_t A_t} + T_a. \]

(19)

The above equation is valid so long as the thermosyphon flow is non-zero. When the thermosyphon flow stops, the solar insolation absorbed by the plate increases the temperature of both the absorber plate and that of the stagnant water. At this point, since no heat is removed by the water, the temperature of the absorber plate and water would become equal under this assumption. The equation which governs the plate temperature is

\[ (M_m C_m + M_o C_p) \frac{dT_p}{dt} + U_t(T_p - T_a) = S\pi (1 - \eta_e P). \]

(20)

An iterative method is used to solve the system equations. The method followed is shown in Fig. 12.

The electrical energy generated by the hybrid panel is stored in a battery for use during the night for running television, fan or lighting. The instantaneous photovoltaic energy generated by the panel is given by

\[ P_e = S\eta_e A_{sel}. \]

(21)

The total daily photovoltaic energy is obtained by integrating equation (21). About 90% of this energy is stored in a battery. Another kind of loss may occur during the transfer of energy to the battery. Energy is not transferred to the battery at the voltage corresponding to the maximum power point. When circular cells of 10 cm diameter are used, 1 m² of absorber plate can have a maximum of 127 cells. If only half of the absorber is covered or \( P = 0.5 \), then 63 cells can be placed over the absorber. Each cell has \( V_{oc} \approx 0.55 \text{ V} \). To charge a battery of 12 V, the charging voltage should be around 15 V. With the proper arrangement of cells in series and parallel, 15 V output from the panel can be obtained near the maximum power point. Thus, this source of error can be eliminated to a large extent. When an appliance uses energy from the battery only about 80% of the stored energy is used or about 70% of the energy generated by the photovoltaic panel is converted into useful energy. The average daily solar cell efficiency is defined as

\[ \eta_{sel} = \frac{\text{Total output electrical energy}}{\text{Total solar insolation}} = \frac{\int P_e \, dt}{A_{sel} \int S \, dt}. \]

(22)
The daily efficiency of the PV/T system is defined as

\[
\eta_{\text{PV/T}} = \frac{\text{Total thermal energy} + \text{Total electrical energy}}{\text{Total insolation over the collector}}.
\] (23)

\[
\eta_{\text{PV/T}} = \frac{M_u C_v (T_{\text{mea.}} - T_{\text{amb}}) + \int_{t_1}^{t_2} P_{\text{e}} \, dt}{A_c \int S \, dt}.
\] (24)

**EXPERIMENTAL SETUP**

The unit (shown in Fig. 2) was installed at I.I.T., New Delhi, India. The collector consists of a single-glazed aluminium flat plate absorber. It consists of sixteen, 1.5 m long, 1.9 cm outer diameter galvanized iron tubes brazed longitudinally at 10 cm pitch across an aluminium sheet. The total harnessing area of the collector is 2.13 m². The tubes are joined at the ends by 2.54 cm outer diameter G.I. headers. The entire absorber plate is painted black and placed inside a metallic box insulated at the bottom with 10 cm thick fibre glass insulation. The absorber unit is placed inclined at about 45° facing south (optimum tilt for Delhi for winter use) and connected to an insulated galvanized iron (G.I.) sheet storage tank via 2.54 cm outer diameter insulated G.I. pipes. The storage tank is 1.5 m long and 36 cm in diameter. The surface area of the tank is 1.91 m² and all of this surface is affixed a 8.0 cm uniformly thick layer of glass wool. The physical data of the system are shown in Table 1.

**EXPERIMENTAL PROCEDURE**

The experiment was performed on several clear days. The solar radiation was measured by an Eppley Pyranometer on the tilted collector at 45° facing due south. The ambient temperature was measured automatically by a Kipp & Zonen/BD-8/multirange recorder. To start the experiment, the storage tank was filled by fresh tap water in the early morning. In a thermosyphonic solar energy water heater, the heat transfer fluid (water) circulates between the collector and the water storage tank due to the action of bouyancy forces. The temperature of the storage water in the tank is measured at an interval of 4 h with an accuracy of 0.1°C. The data were taken from 6 a.m. (first day) to 6 a.m. of the next day.

![Fig. 2. Photograph of thermosyphonic solar water heater.](image-url)
### Table 1. Numerical values of design parameters of the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>$A_e$ m$^2$</td>
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</tr>
<tr>
<td>$g$ m$^s^{-1}$</td>
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</tr>
<tr>
<td>$M_w$ kg</td>
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</tr>
<tr>
<td>$h_0$ m</td>
<td>0.10</td>
</tr>
<tr>
<td>$h_1$ m</td>
<td>1.13</td>
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<tr>
<td>$n$</td>
<td>16</td>
</tr>
<tr>
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<tr>
<td>$h_2$ m</td>
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<tr>
<td>$C_m$ J/kg°C</td>
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<tr>
<td>$h_3$ m</td>
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<td>$h_5$ m</td>
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<tr>
<td>$D_o$ m</td>
<td>2.54 x 10^{-2}</td>
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</tr>
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<tr>
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<td>0.36 x 10^{-2}</td>
</tr>
<tr>
<td>$L_p$ m</td>
<td>3.48</td>
</tr>
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</table>

### RESULTS AND DISCUSSION

The experimental data on the thermosyphonic water heater were taken on 31st March 1988, 14th May, 1988 and 30th August, 1988. Since the simulations are done using a finite difference method, the solar insolation and ambient temperature are required at 10 s intervals. These are calculated by the Fourier series method. The solar insolation and ambient temperature data are fitted by using six harmonics in a Fourier series. These coefficients are later used to determine about two inputs at the desired time intervals.

** Determination of $U_L$ and $U_S$ **

In the model, there are two heat transfer coefficients $U_L$ and $U_S$ which are unknown. The overall heat loss coefficient of the tank can be calculated from the variation of the water temperature in the tank from 4 p.m. to 6 a.m. During this period, heat is lost only from the tank because, after the temperature of the water in the tank becomes a maximum, water stops circulating through the collector. The water temperature becomes a maximum around 4 p.m. In Fig. 3, the experimental data from 4 p.m. to 6 a.m. are shown together with the predicted data for several values of $U_S$. It is seen that $U_S = 3.0$ W/m$^2$ °C gives the best fit.

![Fig. 3. The tank water temperature as a function of time (from 4 p.m. to 6 a.m.) for several values of tank heat loss coefficient, $U_S$.](image)
During the day-time, heat is lost both from the solar collector and the tank. Since $U_s$ is determined from the night data, $U_L$ could be determined from the day data. The predicted tank temperature from 7 a.m. to 4 p.m. is shown in Fig. 4 for several values of $U_L$ and $U_s = 3.0 \text{ W/m}^2 \cdot \text{°C}$. It is seen that the best fit is obtained for $U_L = 6.0 \text{ W/m}^2 \cdot \text{°C}$.

For two other days, the experimental and predicted results for $U_L = 6.0 \text{ W/m}^2 \cdot \text{°C}$ and $U_s = 3.0 \text{ W/m}^2 \cdot \text{°C}$ are shown in Fig. 5. It is seen that the agreement between the three sets is very good. It is also seen from the maximum storage temperature for the three days, March (60° C), May
(69.2°C) and August (65.5°C), that the meteorological conditions are not similar for the 3 days. This gives us confidence that the values of $U_L$ and $U_S$, as determined, will be good for all weather conditions.

**Water heater with solar cells**

The calculations reported in this work are for the 14th May, 1988 data unless otherwise stated. The hourly solar radiation and ambient temperature are shown in Fig. 6.

In Fig. 7, the temperature of the water in the tank as a function of time is shown for four different cell areas. It is seen that the maximum water temperature decreases as the cell area goes up. However, the difference in temperature for the two cases, $P = 0$ and $P = 1$, is very little. The maximum temperature for $P = 0$ is about 68°C, while for $P = 1$, it is about 65°C. In all the cases, the water temperature becomes a maximum around 4 p.m.

The cell efficiency as a function of time is shown in Fig. 8. It is seen that the cell efficiency decreases with time and is a minimum when the solar insolation is a maximum. At this time, the absorber temperature is a maximum. After this hour, the cell efficiency increases until the water temperature becomes a maximum. The cell efficiency decreases suddenly afterwards, but after a little while, starts increasing. When the water temperature in the tank becomes maximum, the water flow rate through the collector becomes zero. The solar insolation is still falling on the collector.
Fig. 8. The variation of solar cell efficiency and collector efficiency with time.

Fig. 9. The effect of water mass and the fraction of collector area, P, covered by solar cells, on the average daily solar cell efficiency, average daily thermal efficiency, average daily PVT efficiency and maximum storage temperature.
Since no heat is removed by the water from the collector, the absorber temperature, instead of decreasing, increases. A sudden increase in the plate temperature decreases the cell efficiency.

The cell efficiency and, hence, electrical energy output is a function of the absorber plate temperature. It can be increased by lowering the absorber temperature. There are two possible methods which could be employed to achieve this objective. One could look for those design parameters which affect the thermal efficiency most. Out of all possible system parameters, the amount of water in the tank affects the absorber temperature the most.

The cell efficiency as a function of total water mass is shown in Fig. 9. Also shown in the same figure is the maximum water temperature. As expected, the cell efficiency increases and the water temperature decreases with an increase in the water mass.

It is seen from Fig. 9, that for $M_w = 200$ kg, the maximum water temperature is 61.8°C. In houses, water at such high temperature is normally not required. Furthermore, hot water is needed during the day time. Water at 40°C may be needed or it may be drawn at some fixed time of the day, say at noon. If some amount of hot water is drawn and an equal amount of cold water is put into the system, the average system temperature would decrease. This operational strategy would increase the cell efficiency. In Fig. 10, the water temperature as a function of time is plotted when 25%, 50%, 75% or 100% of the water is withdrawn at noon, or 2:00 p.m. In Fig. 11, the cell efficiency, thermal efficiency and total system efficiency as a function of the amount of water withdrawn at noon and 2 p.m. are shown. The cell efficiency increases with the amount of water withdrawn at noon and 2 p.m.

**UTILIZATION OF ELECTRICAL ENERGY**

The electrical energy generated by the cells could be utilized directly, or first stored in a battery. The second alternative should be preferred because the panels do not generate power at a constant rate.

The energy generated by the panels is stored in a battery. Some energy is lost in the charger. The d.c. output of the battery is first converted into a.c. Some energy is also lost here. The efficiency

![Graphs showing water temperature changes](image-url)
Fig. 11. The effect of water withdrawn at 12 a.m. or 2 p.m. and fraction of collector area, $P$, covered by solar cells on average daily solar cell efficiency, average daily thermal efficiency and average daily PVT efficiency.

of an appliance like a tube light or a fan is not 100%. Some energy would also be lost here. If all the various intermediate energy losses are taken into account, then only about 70% of the photovoltaic output is converted into useful energy. In Table 2, the useful available energy for some combinations is shown. The average cell efficiency is more or less independent of $P$. For $P = 1$, the photovoltaic output energy is about four times that for $P = 0.25$ and twice that for $P = 0.50$. This is an interesting result. One can calculate the available energy for any one value of $P$. For other values of $P$, the available energy can be easily calculated. It is seen that for $P = 0.75$ (maximum area of solar cells when 10 cm diameter circular cells are used) about 577.0 Wh/day useful energy is available.

Normally, in domestic applications, the collector area is between 2 and 3 m². For 2 m² collector area and for $P = 0.75$, about 542.0 Wh/day of electrical energy would be available. This is sufficient to run 3 tube lights of 20 W for 6 h and 1 black and white T.V. of 30 W for 4 h. In India, television transmission for rural areas is about 4 h. If bigger collectors are used, then one could use more appliances.
Table 2. Useful electrical energy with different fraction area of collector covered by solar cells

<table>
<thead>
<tr>
<th></th>
<th>$M_a = 150\text{ kg}$</th>
<th>$M_a = 200\text{ kg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$ 0.25 0.50 0.75 1.0</td>
<td>$P$ 0.25 0.50 0.75 1.0</td>
</tr>
<tr>
<td>Average cell efficiency</td>
<td>8.21 8.23 8.25 8.27 8.38 8.39 8.41 8.42</td>
<td>273.6 548.4 824.3 1101.6 279.0 559.3 840.3 1121.6</td>
</tr>
<tr>
<td>Total available energy (Wh/day)</td>
<td>273.6 548.4 824.3 1101.6 279.0 559.3 840.3 1121.6</td>
<td>191.5 383.9 577.0 771.1 195.5 391.5 588.1 785.2</td>
</tr>
<tr>
<td>Useful or actual energy (Wh/day)</td>
<td>191.5 383.9 577.0 771.1 195.5 391.5 588.1 785.2</td>
<td>513.9 515.0 515.9 517.2 523.9 525.2 526.0 526.6</td>
</tr>
<tr>
<td>Available energy (Wh/day m$^2$)</td>
<td>513.9 515.0 515.9 517.2 523.9 525.2 526.0 526.6</td>
<td>273.6 548.4 824.3 1101.6 279.0 559.3 840.3 1121.6</td>
</tr>
</tbody>
</table>

So far, the results discussed are for a single day of the year. The question arises how, over the year, the available photovoltaic energy would vary. Since insolation does not remain constant over a month, for the purpose of the calculations, normally an average monthly day is recommended. Because of the non-linearity of the declination in various months, we have to predict the performance for various months. Hence, we have to select a day in a month which should represent the weighted average of the declinations for that particular month. This may not necessarily be the 15th (middle) of each month. These days, given in the table, are functions of the weighted mean declination for that respective month. The calculations for every month for the average monthly day are shown in Table 3. The collector is kept at the optimum tilt calculated for Delhi [19]. The global horizontal average monthly insolation and ambient temperature are taken from Ref. [20]. These are converted to the plane of the collector by the method of Khucher [21]. It is seen that the average cell efficiency varies slightly, being maximum in August and minimum in May. The variation is very little. For design purposes, one could take an average value for the whole year. The maximum photovoltaic output is in the months of March, April, October, and November, and is a minimum during the months of January, June, July and August. A collector with area 2 m$^2$ would produce sufficient energy to run 3 tube lights and 1 television or 1 fan for 4–5 h.

Fig. 12. Computer flowchart.
Table 3. Useful electrical energy available from the hybrid collector (per m²) for an average monthly day

<table>
<thead>
<tr>
<th>Water mass in the tank</th>
<th>( M_w = 150 \text{ kg} )</th>
<th>( M_w = 200 \text{ kg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total available energy (Wh/day m²)</td>
<td>Useful energy (Wh/day m²)</td>
</tr>
<tr>
<td><strong>Recommended day of the month</strong></td>
<td><strong>Optimum tilt (deg)</strong></td>
<td><strong>Solar radiation intensity (kWh/day m²)</strong></td>
</tr>
<tr>
<td>January 17</td>
<td>52.5</td>
<td>6.14</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.62</td>
</tr>
<tr>
<td>February 16</td>
<td>44.0</td>
<td>6.61</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.69</td>
</tr>
<tr>
<td>March 16</td>
<td>52.0</td>
<td>6.94</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.61</td>
</tr>
<tr>
<td>April 15</td>
<td>16.5</td>
<td>7.06</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.49</td>
</tr>
<tr>
<td>May 15</td>
<td>4.0</td>
<td>7.14</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.23</td>
</tr>
<tr>
<td>June 11</td>
<td>0.0</td>
<td>6.30</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.38</td>
</tr>
<tr>
<td>July 17</td>
<td>0.0</td>
<td>5.33</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.71</td>
</tr>
<tr>
<td>August 16</td>
<td>6.0</td>
<td>5.01</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.84</td>
</tr>
<tr>
<td>September 15</td>
<td>23.0</td>
<td>5.95</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.63</td>
</tr>
<tr>
<td>October 15</td>
<td>43.0</td>
<td>6.76</td>
</tr>
<tr>
<td>November 14</td>
<td>52.5</td>
<td>6.89</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.58</td>
</tr>
<tr>
<td>December 10</td>
<td>56.0</td>
<td>6.27</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8.50</td>
</tr>
</tbody>
</table>

For the months May, June, July, August, the optimum tilt is 45°, 45°, and 45°, respectively. However, in the table, calculations are reported for 15° as no meaningful thermosyphon flow will occur for tilt less than 15°.
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REFERENCES