Life Cycle Cost Analysis and Carbon Credit Earned by Hybrid PV/T Solar Water Heater for Delhi Climatic Conditions

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Abstract: In this communication, a study has been carried out to evaluate the life cycle cost analysis and carbon credit earned by hybrid PV/T solar water heater. The study has been based on thermal, electrical and exergy output of water heater. The solar water heater is installed at Solar Energy Park, IIT Delhi. The annual energy and exergy gain have been evaluated by considering four types of weather conditions (A, B, C and D Type) of New Delhi and considering a case that the hot water is withdrawal two times in the afternoon and two times in the evening in a day. This paper gives the total carbon credit earned by hybrid PV/T water heater as per norms of Kyoto Protocol for Delhi climatic conditions.

We have found that (i) the cost/kWh is higher in case of exergy when compared with cost/kWh on the basis of thermal energy (ii) if this type of system is installed at 10% of the total residential houses in Delhi then the total carbon credit earned by PV/T water heater annually in terms of thermal energy is Rs. 105.6 cores and in terms of exergy is Rs. 10.2 cores respectively.

Keywords: Photovoltaic, exergy, thermal energy, cost analysis, carbon credit, solar collectors.

1. INTRODUCTION

The thermal energy has wider applications in the human's life. It can be generally utilized in the form of either low grade (low temperature) or high grade (high temperature). The temperature profiles of the photovoltaic (PV) module in a non-steady state condition with respect to time have studied [1]. The overall electrical efficiency of the PV module can be increased by increasing the packing factor (PF) and reducing the temperature of the PV module by using the thermal energy associated with the PV module [2, 3]. The carrier of thermal energy associated with the PV module may be either air or water. Once thermal energy withdrawal is integrated with the photovoltaic (PV) module, it is referred as hybrid PV/T system.

Photovoltaic–thermal (PV/T) technology refers to the integration of a PV module and conventional solar thermal collector in a single piece of equipment. The rationale behind the hybrid concept is that a solar cell converts solar radiation to electrical energy with peak efficiency in the range of 9–12%, depending on specific solar-cell type and thermal energy through water heating. More than 80% of the solar radiation falling on photovoltaic (PV) cells is not converted to electricity, but either reflected or converted to thermal energy. In view of this, hybrid photovoltaic and thermal (PV/T) collectors are introduced to simultaneously generate electricity and thermal power [4].

The PV/T water heating system, two types of combi-panel (hybrid PV/T) have been considered, namely:

a) The parallel plate configuration [5-8] and

b) The tube-in-plate configuration [3, 6, 9-12].

Chow [10] has concluded that the tube-in-plate absorber collector with single glazing is regarded as one of the most promising design. He has also concluded that the partial covered flat plate collector by PV module gives better thermal and electrical output from the photovoltaic thermal (PV/T) water heating system. He has concluded his findings on the basis of indoor simulation.

Zondag *et al*. [9] developed a model of a hybrid PV/T water collector and performed experimental studies of such systems for varying sizes. Recently Zondag [13] carried out rigorous review on research work of a PV-thermal collector and system, carried out by various scientists till 2006. The relations between energy and exergy, energy and sustainable development, energy policy making, exergy and the environment and exergy in detail are reported by [14]. The annual thermal and exergy efficiency and life cycle analysis of a hybrid PV/T air collector for different Indian climate conditions are reported by [15].

Energy consumption of a country is one of the indicators of its socio economic development. Per capita energy consumption in India is also one of the lowest in the world. It is about 30% of that in China, about 22% of that in Brazil and about 3.18% of that in USA. With development the per capita energy consumption is likely to increase. At present our annual economic growth rate is 8-10%, per annum. For energy India depends on oil and gas imports, which account for over 65% of its consumption; it is likely to increase further considering the economic development, rise in living condition of people and rising prices. Coal, which currently accounts for over 60% of India's electricity production, is the major source of emission of greenhouse gases and that of acid rains. In the business-as-usual scenario, India will ex-

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haust its oil reserves in 22 years, its gas reserves in 30 years and its coal reserves in 80 years [16]. More alarming, the coal reserves might disappear in less than 40 years if India continues to grow at 8% a year [16].

Carbon Credit Trading (Emission Trading) is an administrative approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants. A credit gives the owner the right to emit one ton of carbon dioxide. International treaties such as the Kyoto Protocol set quotas on the amount of greenhouse gases countries can produce. There are currently two exchanges for brought and sold of carbon credits: the Chicago Climate Exchange and the European Climate Exchange. European and Japanese Companies were the major buyers and China was the major seller of the carbon credits in 2005-06. Present market rate is fluctuating at € 20-22 in the European Climate Exchange [17].

2. EXPERIMENTAL SET UP AND OBSERVATIONS

In water heating system two flat plate collectors are connected in series. Specifications of flat plate collector are given in Table **1**. The whole absorber and glass cover is encased in an aluminum metallic box with 0.1 m glass wool insulation below the absorber to reduce bottom losses. The photograph of the system is shown in Fig. (**1**).

Table 1. Dimensions of Photovoltaic Thermal (PV/T) Solar Water Heating System

S No.	Components	Specifications
1.	Capacity of Storage Tank	200 Liters
2.	Collectors	Flat Plate, Tube in plate Type
3.	Area of Collector	2.16 m^2
4.	Tube Diameter	0.0125 m
5.	Tube Material	Copper Tubes
6.	Plate Thickness	0.002 m
7.	Air Gap	0.01 m
8.	Thickness of Insulation	0.1 m
9.	Thickness of Glass	0.004 m
10.	Angle of Collector	30^o
11.	PV Module	Glass to Glass Type
12.	Area of Module	0.66 m^2
13.	Area of Solar Cell	0.015 m^2
14.	Total Area of Solar Cell	0.54 m^2
15.	Non Packing Area	0.12 m^2
16.	No. of Solar Cells	36
17.	PV Module	75 W
18.	DC Motor	18 V, 60 W, 2800 RPM

A glass to glass photovoltaic (PV) module with an effective area of 0.66 m^2 is integrated at the bottom of one of the collector. In this case, solar radiation is transmitted through non-packing area of PV module and finally absorbed by the blackened absorber. Further, the thermal energy associated with PV module is transferred to absorber by convection for further heating of absorber. Water below absorber gets heated and moves in the upward direction. The outlet of water at the end of absorber which is covered with PV module (T_{fo1}, Fig. (**2**)) becomes inlet to glass-absorber combination. Such collector is referred a photovoltaic/thermal (PV/T) water collector.

The outlet of photovoltaic/thermal (PV/T) water collector (T_{fo2}) is further connected to the inlet of conventional flat plate collector for higher operation temperature shown in Fig. (**2**). Both collectors are connected to an insulated storage tank of capacity 200 liters. There is a provision of a DC water pump (18V, 60W, 2800RPM) connected to PV module to circulate the water between collectors and storage tank in a forced mode.

Performance of the hybrid PV/T water heater is evaluated by considering four types of weather conditions of New Delhi, are defined as:

Type A: The ratio of daily diffuse to daily global radiation is less than or equal to 0.25 and sunshine hours greater then or equal to 9 hours.

Type B: The ratio of daily diffuse to daily global radiation between 0.25 to 0.50 and sunshine hours between 7 to 9 hours.

Type C: The ratio of daily diffuse to daily global radiation between 0.50 to 0.75 and sunshine hours between 5 to 7 hours.

Type D: The ratio of daily diffuse to daily global radiation is greater than or equal to 0.75 and sunshine hours less then or equal to 5 hours.

The temperatures at inlet, outlet, water in storage tank and solar radiations are measured by data logger systems on minute basis.

3. THERMAL MODELING

In order to write the energy balance equation the following assumptions have been made:

- The heat capacity of photovoltaic/thermal (PV/T) collector has been neglected in comparison with the heat capacity of water in the storage tank.
- There is no temperature stratification in the water of the storage tank due to forced mode of operation.
- One dimension heat conduction is good approximation for the present study.
- The system is in quasi-steady state.
- The ohmic losses in the solar cell are negligible.

The energy balance equations for each component of (PV/T) solar water heating system are as follows:

(i) For Solar Cells of PV Module (Glass-Glass)

$$\alpha_c \tau_c \beta_c I(t) W dx = \left[U_{tc,a}\left(T_c - T_a\right) + h_{c,p}\left(T_c - T_p\right)\right] W dx + \tau_c \eta_c \beta_c I(t) \cdot W dx \quad (1)$$

Fig. (1). Photograph of a combined photovoltaic thermal (PV/T) glass to glass solar water heating system.

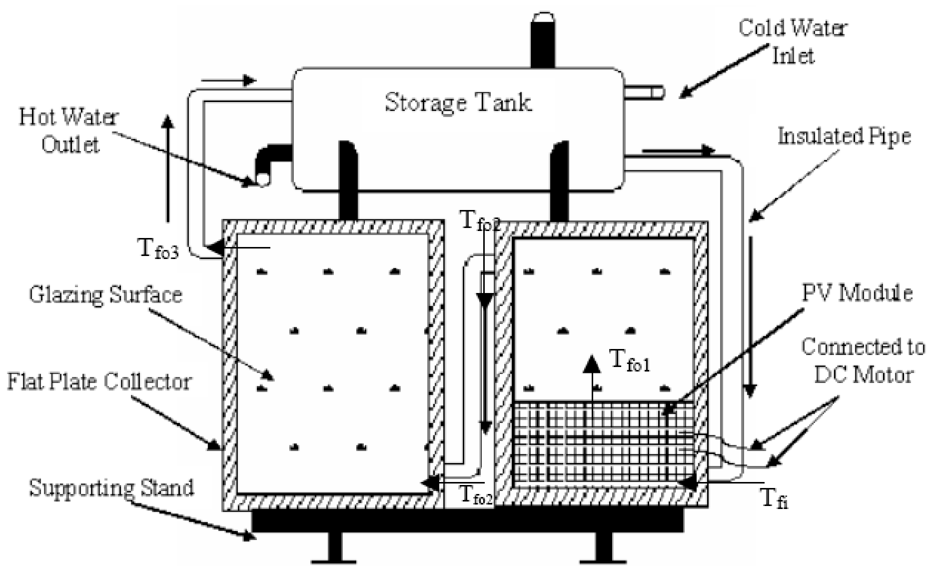

Fig. (2). Cross sectional view of a combined photovoltaic thermal (PV/T) solar water heating system.

(ii) For Blackened Absorber Plate Temperature Below the PV Module (Glass-Glass)

$$\alpha_p\left(1-\beta_c\right)\tau_g^2 I\left(t\right)+h_{c,p}\left(T_c-T_p\right)=h_{p,f}\left(T_p-T_f\right) \tag{2}$$

(iii) For Water Flowing Through an Absorber Pipe Below the PV Module (Glass-Glass)

The energy balance of flowing water through absorber pipe is given by,

$$\dot{m}_f C_f \frac{dT_f}{dx}dx = F'h_{p,f}\left(T_p-T_f\right)Wdx \tag{3}$$

The rate of thermal energy available at the end of absorber PV module (glass-glass) is evaluated as,

$$\dot{Q}_{u,m}=A_m F_{Rm}\left(PF_2\left(\alpha\tau\right)_{m,eff} I\left(t\right)-U_{L,m}\left(T_{fi}-T_a\right)\right) \tag{4}$$

(iv) The Rate of Thermal Energy Available at the End of First Collector

Following Duffie and Beckman [18] and Tiwari [19], the rate of thermal energy available from the first flat plate collector can be evaluated as,

$$\dot{Q}_{u,c1}=A_{c1}F_{Rc1}\left(\left(\alpha\tau\right)_{c1,eff} I\left(t\right)-U_{L,c1}\left(T_{fo1}-T_a\right)\right) \tag{5}$$

Here, $T_{fo1} = T_{fi} + \frac{\dot{Q}_{u,m}}{\dot{m}_f C_f}$

(v) The Rate of Thermal Energy Available at the End of Second Collector

An expression for the rate of thermal energy available at the end of second collector will be as follows;

$$\dot{Q}_{u(m+c1+c2)} = \dot{m}_f C_f \left(T_{fo3} - T_{fi}\right)$$

$$\dot{Q}_{u,c2} = A_{c2} F_{Rc2} \left(\left(\alpha\tau\right)_{c2,eff} I\left(t\right) - U_{L,c2}\left(T_{fo2} - T_a\right)\right) \quad (6)$$

Here, $T_{fo2} = T_{fi} + \frac{\dot{Q}_{u,m}}{\dot{m}_f C_f} + \frac{\dot{Q}_{u,c1}}{\dot{m}_f C_f}$

On solving the Eqs. (4), (5) and (6) we get,

$$\dot{Q}_{u(m+c1+c2)} = \begin{bmatrix} A_m F_{Rm} PF_2 \left(\alpha\tau\right)_{m,eff}\left(1-K_1\right) + \\ A_{c1} F_{Rc1}\left(\alpha\tau\right)_{c1,eff}\left(1-K_2\right) + \\ A_{c2} F_{Rc2}\left(\alpha\tau\right)_{c2,eff} \end{bmatrix} I\left(t\right) - \begin{bmatrix} A_m F_{Rm} U_{L,m}\left(1-K_1\right) + \\ A_{c1} F_{Rc1} U_{L,c1}\left(1-K_2\right) + \\ A_{c2} F_{Rc2} U_{L,c2} \end{bmatrix} \left(T_{fi1} - T_a\right) \quad (7)$$

where, $K_1 = \left[\frac{A_{c1}F_{Rc1}U_{L,c1}}{\dot{m}_f C_f} + \frac{A_{c2}F_{Rc2}U_{L,c2}}{\dot{m}_f C_f} - \frac{A_{c1}F_{Rc1}U_{L,c1}A_{c2}F_{Rc2}U_{L,c2}}{\left(\dot{m}_f C_f\right)^2}\right]$

and $K_2 = \left[\frac{A_{c2}F_{Rc2}U_{L,c2}}{\dot{m}_f C_f}\right]$

(vi) Energy Balance for Complete Water Heating System

The rate of thermal energy available at the outlet of second collector is fed into insulated storage tank, and then the energy balance of whole system will be,

$$\dot{Q}_{u,(m+c1+c2)} = M_w C_w \frac{dT_w}{dt} + \left(UA\right)_{tk}(T_w - T_a) \quad (8)$$

The above equation can be solved by assuming $T_{fi} = T_w$ due to perfectly insulating connecting pipes. Using Eq. (7) the tank water temperature can be obtained by as,

$$(\alpha\tau)_{eff} I(t) - (UA)_{eff}(T_w - T_a) = M_w C_w \frac{dT_w}{dt} + \left(UA\right)_{tk}(T_w - T_a) + \dot{m}_w C_w (T_w - T_a)$$

or, $\frac{dT_w}{dt} + aT_w = f\left(t\right)$

where, $a = \frac{\left[\left(UA\right)_{eff} + \left(UA\right)_{tk} + \dot{m}_w C_w\right]}{M_w C_w}$

and $f\left(t\right) = \frac{\left(\alpha\tau\right)_{eff} I\left(t\right) + \left[\left(UA\right)_{eff} + \left(UA\right)_{tk} + \dot{m}_w C_w\right] T_a}{M_w C_w}$

On solving the above differential equation the expression for tank water temperature can be obtained as,

$$T_w = \frac{f\left(t\right)}{a}\left(1 - e^{-at}\right) + T_{w0} e^{-at} \quad (9)$$

(vii) Energy Analysis

The energy analysis is based on the first law of thermodynamics, and the expression for total thermal gain can be defined as,

$$\sum \dot{Q}_{u,total} = \sum \dot{Q}_{u,thermal} + \frac{\sum \dot{Q}_{u,electrical}}{0.38} \quad (10a)$$

Overall thermal output from a PV/T system = thermal energy collected by the PV/T system + (Electrical output / çpower) where, çpower is the electric power generation efficiency for a conventional power plant.

This is so because electrical energy is a high-grade form of energy which is required for operation of DC motor. This electrical energy has been converted to equivalent thermal by using electric power generation efficiency as 0.38 for a conventional power plant [6].

In the case of withdrawal from tank the thermal energy output from the tank can be written as,

$$\dot{Q}_{u,thermal} = \dot{m}_w C_w \left(T_w - T_a\right) \quad (10b)$$

(viii) Exergy Analysis

The exergy analysis is based on the second law of thermodynamics, which includes accounting the total exergy inflow, exergy outflow and exergy destructed from the system.

The general exergy balance for a collector can be written as,

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \quad (11)$$

or, $\sum \dot{E}x_{in} - \sum (\dot{E}x_{thermal} + \dot{E}x_{electrical}) = \sum \dot{E}x_{dest}$

where,

$$\dot{E}x_{in} = A_c \times N_c \times I(t) \times \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_s}\right)^4\right] \text{ [20]}$$

$\dot{E}x_{thermal} = \dot{Q}_u \left[1 - \frac{T_a + 273}{T_{fo} + 273}\right]$ and

$$\dot{E}x_{electrical} = \eta_c \times A_c \times N_c \times I(t)$$

where, A_c is area of collector and T_s is the Sun temperature in Kelvin.

In addition to the above equations the relations used for defining the design parameters and the values of design parameters are shown in appendix I and Table **2** respectively.

Table 2. Design Parameters of Photovoltaic Thermal (PV/T) Collector and Storage Tank

Parameters	Values
A_{C1}	2.16 m^2
A_{C2}	1.5 m^2
A_m	0.66 m^2
C_f	4190 J/kg K
D	0.0125 m
F'	0.968
F_{Rc1}	0.95
F_{Rc2}	0.94
F_{Rm}	0.96
h	1000 W/m^2
$h_{c,p}$	5.7 W/m^2
$h_{p,f}$	100 W/m^2
PF_1	0.375
PF_2	0.965
K	204 W/m K
$\dot{m}$	0.06 kg/sec
M_w	200 kg
U_L	6 W/m^2
U_{L1}	3.56 W/m^2 K
U_{LC1}	6 W/m^2
U_{LC2}	6 W/m^2
U_{Lm}	3.44 W/m^2 K
$U_{t\,c,a}$	9.5 W/m^2 K
$(UA)_{tk}$	4.38 W/ K
V	1 m/s
W	0.125 m
α_c	0.9
τ_c	0.95
β_c	0.83
η_c	0.12
α_p	0.8
τ_g	0.95

4. LIFE CYCLE COST ANALYSIS AND ENERGY METRICS

(i) Embodied Energy Consumption

Embodied energy analysis shows the total energy consumed in manufacturing of the product. It includes material production energy, the transportation energy, the solar cell /module fabrication energy, the human energy, installation energy, maintenance energy and the finally disposal/salvage energy. The detailed list of embodied energy is given in Table **3**.

(ii) Energy Payback Time (EPBT)

Energy payback time is the ratio of the total energy consumed in production and installation of the system (E_{in}) to the total energy out (E_{out}).

$$T_{epb} = \frac{E_{in}}{E_{out}} \tag{12}$$

(iii) Energy Production Factor (EPF)

It is used to predict the overall performance of the system. This is defined as the ratio of the output energy and the input energy which predicts the overall performance of the system. Energy production factor is defined by two types

(i) On annual basis, and

$$\chi_a = \frac{E_{out}}{E_{in}} \tag{13a}$$

or, $\chi_a = \dfrac{1}{T_{epb}}$

If $\chi_a \to 1$, for $T_{epb} = 1$ the system is worthwhile otherwise it is not worth from energy point of view.

(ii) On life time basis.

$$\chi_L = \frac{E_{out} \times T}{E_{in}} \tag{13b}$$

(iv) Life Cycle Conversion Efficiency (LCCE)

This is the net energy productivity of the system with respect to the solar input (radiation) over the life time of the system, (T years) given by

$$\phi(t) = \frac{E_{out} \times T - E_{in}}{E_{sol} \times T} \tag{14}$$

(v) Annualized Uniform Cost (Unacost)

Annualized uniform cost is defined as a product of present value of the system and capital recovery factor (CRF) [19].

$$Unacost = Net\ present\ value \times Capital\ recovery\ factor \tag{15}$$

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1}$$

here, n = no. of years and i = interest rate per year.

Let P is present value and R_1, R_2,…..R_n is operational, maintenance and pump replacement cost per year and $R_{3,1}$, $R_{6,2}$,….$R_{n,n}$ is black painting, cleaning and glass replacement cost in every three year. Then the net present value is evaluated as,

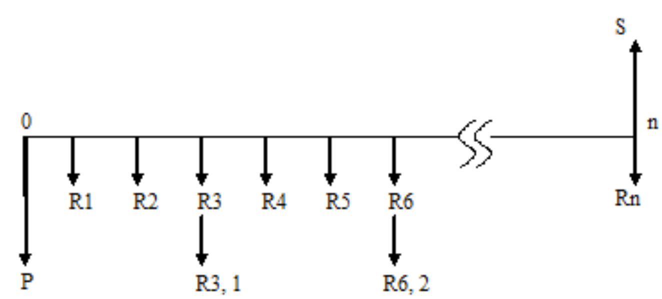

Table 3. Break up of Embodied Energy of Different Components of Fabrication of Hybrid (PV/T) Solar Water Heater

Components	Items	Quantity	Total Weight (kg)	Embodied Energy (MJ/kg)	Total Embodied Energy	
					MJ	kWh
Storage tank	Storage tank	1	18.0	36.1	649.8	180.5
	Glass wool	23 m^2	0.1 m^3	139 MJ/m^3	13.9	3.86
	Al sheet	1	1.2	170	204	56.7
	Mild steel stand	1	14	34.2	478.8	132.7
	Brass water tap	1	0.2	62.7	12.54	3.48
Flat plate Collector Quantity 2	Copper riser 1/2″	20×1.8 = 36m	8.2	81.0	664.2	184.5
	Header 1″	4×1.15 = 4.6m	3.8	81.0	307.8	85.5
	Al box	2	10	199.0	1990.0	552.0
	Cu sheet	2	11	132.7	1460	405.6
	Glass cover toughened 4mm	2 (3.75m^2)	0.01464 m^3	66020 MJ/m^3	966.5	268.3
	Glass wool	13 m^2	0.064 m^3	139 MJ/m^3	8.89	2.5
	Nuts / bolts/screws	32	1	31.06	31.06	8.6
	Union /elbow	8	1.5	46.8	70.2	19.5
	Nozzle/flange	8	1	62.1	62.1	17.3
	Mild steel stand	1	40	34.2	1368	380
	paint	1L	1L	90.4	90.4	25.1
	Rubber gasket	18m	4.2	11.83	49.7	13.8
	G I pipes 1/2″		9.5	44.1	418.9	116.4
	Al frame 1″	12m	2.5	170	425	118
	Al sheet 24 gauge		2.5	170	425	118
PV module	Glass to glass	1	0.66 m^2	3528/ m^2	2328.5	646.8
	BOS			720.0	720.0	200
Water pump	Copper wire		0.150	110.19	16.5	4.6
	Copper commuter	2	0.04	70.6	2.8	0.78
	Si-steel armature	1	0.05	*	*	*
	Wire insulation	2	0.01	*	*	*
	Motor body(SS)	1	0.100	36.1	3.61	1.0
	Casing (brass)	1	0.300	62.0	18.6	5.2
	bearings	2	0.030	*	*	*
	Steel shaft	1	0.050	12.5	0.625	0.17
	Impellers(plastic)	1	*	*	*	*
	Nuts/screws/flange		0.100	31.06	3.1	0.86
Total					**12790.63**	**3552.95**

$$Net\ Present\ Value = P + R_1 \times \left[\frac{(i+1)^n - 1}{i(i+1)^n}\right]_{i,n} + R_{3,1} \times \left[\frac{1}{(i+1)^n}\right]_{i,3} + R_{6,2} \times \left[\frac{1}{(i+1)^n}\right]_{i,6} + R_{9,3} \times \left[\frac{1}{(i+1)^n}\right]_{i,9} + \dots\dots\dots\dots - S \times \left[\frac{1}{(i+1)^n}\right]_{i,n} \qquad (16)$$

5. RESULT AND DISCUSSION

Eq. (9) and (10b) have been computed using MATLAB software for evaluating the thermal energy gain from the tank by considering the A, B, C and D type conditions and Eq. (10a) has been used for calculating the monthly thermal energy gain. The electrical energy is converted into thermal energy and the variation of total thermal energy gain is shown in Fig. (**3**). Figure shows that the overall annual gain is 2720.1 kWh, however the maximum gain is obtained in May month and minimum is obtained in December month due to the availability of solar radiation. The variation in gain of different weather conditions (A. B, C and D Type) for a month depends upon the number of days belongs to that

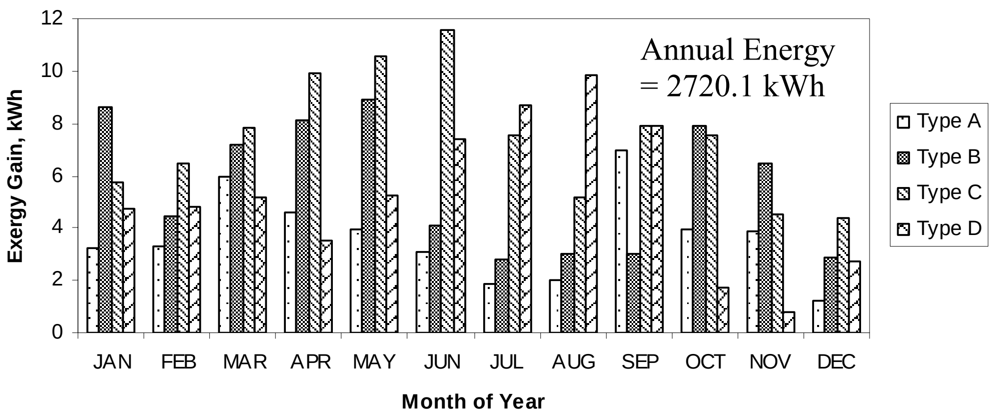

Fig. (3). Monthly variation of thermal energy gain in kWh.

type. Similarly Eq. (11) has been computed for evaluating the monthly exergy gain, sum of electrical energy and thermal exergy. The overall annual exergy gain is 263.3 kWh, which is shown in Fig. (**4**). The monthly variation of overall energy and exergy gain are shown in Table **4**.

Eq. (12), (13a,b), (14) and (15) have been used for evaluating the Energy payback time (EPBT), Energy production factor (EPF), Life cycle conversion efficiency (LCCE) and Annualized uniform cost of the system in terms of thermal energy and exergy. The capital cost (P) and salvage value (S) of hybrid (PV/T) solar water heater are shown in Table **5**.

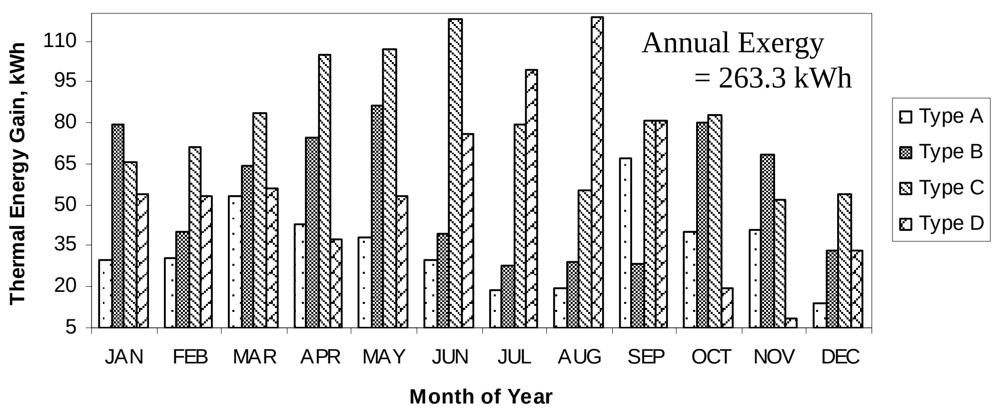

Fig. (4). Monthly variation of exergy gain in kWh.

Table 4. Monthly Variation of Overall Energy and Exergy Gain

Month	Thermal Energy	Electrical Energy	Thermal Exergy	Overall Exergy	Thermal Eq. =(Ele/0.38)	Overall Thermal Energy
January	195.5	12.76	9.63	22.39	33.58	229.08
February	165.2	11.28	7.77	19.05	29.70	194.90
March	218.1	14.69	11.49	26.18	38.66	256.76
April	221.7	14.44	11.78	26.22	38.01	259.71
May	243.4	15.67	13.0	28.67	41.24	284.64
June	225.1	14.51	11.71	26.22	38.19	263.29
Jully	192.8	12.28	8.6	20.88	32.32	225.12
August	191.7	11.64	8.3	19.94	30.64	222.34
September	220.0	14.23	11.5	25.73	37.43	257.43
October	188.4	12.84	8.31	21.15	33.80	222.20
November	143.2	10.11	5.54	15.65	26.60	169.80
December	113.5	8.10	3.09	11.19	21.32	134.82
Total	**2318.6**	**152.57**	**110.72**	**263.29**	**401.5**	**2720.1**

Table 5. Capital Cost (P_s), Salvage Value (S_s) and Maintenance Cost (M_s) of Hybrid (PV/T) Solar Water Heater

Components	Qty in kg	Hybrid (PV/T) Solar Water Heater	Salvage Value of Different Components (S_S) at the Inflation Rate of 4% (Present Values of Scrap for, Iron @Rs15/kg, Aluminum@Rs80/kg and Copper@Rs250/kg)		
		Rs..	After 10 Year Iron Scrap @ Rs. 22/kg Aluminum @ Rs. 118/kg Copper @ Rs. 370/kg	After 20 Year Iron Scrap @ Rs. 33/kg Aluminum @ Rs. 175/kg Copper @ Rs. 548/kg	After 30 Year Iron Scrap @ Rs. 49/kg Aluminum @ Rs. 259/kg Copper @ Rs. 811/kg
Storage tank @ Rs. 90/kg	18	1620	2124	3150	4662
Glass wool @ Rs. 60/m^2	0.1m^3	1320	*	*	*
Al sheet @ Rs. 165/kg	1.2	198	142	210	311
Mild steel stand	14	700	308	462	686
Total cost of tank		**3838**	**2574**	**3822**	**5659**
Flat plate collectors (2)					
Copper riser @ Rs. 380/kg	8.2	3116	3034	4496	6650
Cu Header @ Rs. 380/kg	3.8	1440	1406	2082	3081
Al sheet @ Rs. 165/kg	12	2160	1416	2100	3108
Al angle1” 12m	2.5	450	295	437	647
Cu sheet @ Rs. 360/kg	11	4070	4070	6028	8921
Toughened glass 4mm	3.75m^2	4340	*	*	*
Glass wool @ Rs. 60/m^2	0.064m^3	840	*	*	*
G.I. pipes ½	9.3	500	205	307	456
Mild steel stand	40	2000	880	1320	1960
G.I. elbow/union	1.5	300	33	50	75
Nozzle/flange	1	200	22	33	49
Total cost of FPC		**19416**	**11361**	**16851**	**24872**
PV module	*	16000	500	500	500
D C Water pump	*	1000	The salvage value of pump deducted during purchase of new pump after each 10 year		
Paint 1lts(black)	1L	125	*	*	*
Fabrication/Cartridge charges	*	2000	*	*	*
Capital cost (Rs)		**42379**	**14435**	**21173**	**31031**

Operational, maintenance and pump replacement cost = Rs. 1000/- per year.
Black painting, cleaning and glass replacement = Rs. 3500/- every three year.

The life cycle conversion efficiency and annualized uniform cost (Rs./kWh) of the system are evaluated by considering the life time (n) of the system as 10, 20 and 30 years and money is worth 10% per year. Result shows that the annualized uniform cost in Rs./kWh decreases and Life cycle conversion efficiency and Energy production factor increases with increase in life time of the system. Detailed results are shown in Tables **6** and **7**.

Table 6. Energy Pay Back Time and Energy Production Factor on Annual Basis by Considering the Annual Thermal Energy and Exergy of the System

	Energy Pay Back Time (EPBT)	Energy Production Factor (EPF)
Energy	1.3 Years	0.769
Exergy	13.5 Years	0.074

5.1. Carbon Credit Earned by PV/T Solar Water Heater

(a) Thermal Energy

Total power produced per annum = 2720.1 kWh

= 2.72 MWh

If the unit cost of electricity is Rs. 5.5 then,

The cost of energy produced = 2720.1 × 5.5 = Rs. 14,960.55 per annum

Average annual carbon emission reduction per MWh of electricity produced for the top 100 solar voltaic power plants, the data of electricity produced in MWh and emission reduction per annum for which are available. Which comes to 0.982 tons of carbon dioxide emission reduction per MWh of electricity produced [17]. However 40% is transmission and distribution losses and 20% loss is due to the inefficient electric equipments used.

Table 7. Annualized Uniform Cost, Life Cycle Conversion Efficiency and Electricity Production Factor on Life Time Basis for n = 10, 20 and 30 Years by Considering the Annual Thermal Energy and Exergy of the System

No. of Years	Energy			Exergy		
	Annualized Uniform Cost (Rs./kWh)	Life Cycle Conversion Efficiency (LCCE)	Energy Production Factor (EPF)	Annualized Uniform Cost (Rs./kWh)	Life Cycle Conversion Efficiency (LCCE)	Energy Production Factor (EPF)
10 Years	2.94	0.317	7.65	30.4	–	0.741
20 Years	2.43	0.34	15.31	25.1	0.0114	1.48
30 Years	2.33	0.349	22.97	24.2	0.0194	2.22

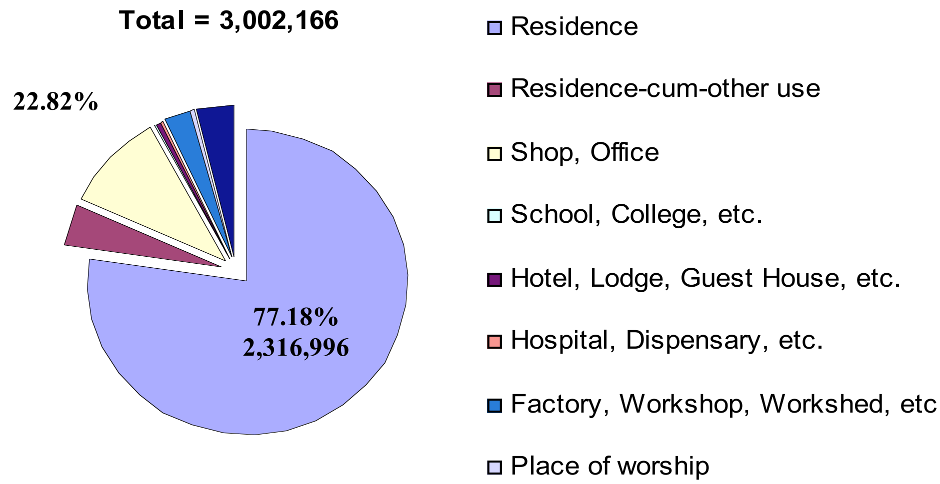

Fig. (5). Percentage variation of occupied census houses in Delhi. (*Source: Census of India 2001*).

Then, the total figure comes to be around = 0.982 + 0.4 + 0.2

= 1.58 tons of CO_2.

The carbon dioxide emission reduction = 2.72 × 1.58

= 4.3 tons

If carbon dioxide emission reduction is at present being traded @ € 20/tons, then the carbon emission reduction by water heater comes to

= 4.3 × 20 × 53 = Rs. 4558 per annum (where, € 1 = Rs. 53)

(b) Exergy

Total power produced per annum = 263.3 kWh

= 0.263 MWh

If the unit cost of electricity is Rs. 5.5 then,

The cost of energy produced = 263.3 × 5.5 = Rs. 1,448.5 per annum.

The carbon dioxide emission reduction = 0.263 × 1.58

= 0.4155 tons

If carbon dioxide emission reduction is at present being traded @ € 20/tons, then the carbon emission reduction by water heater comes to

= 0.4155 × 20 × 53 = Rs. 440.47 per annum (where, € 1 = Rs. 53) The Percentage variation of occupied census houses in Delhi [21] are shown in Fig. (**5**). The percentage of residence houses is 77.18% (2,316,996). If we assumed that the only 10% of the residence houses are installed PV/T hybrid water heater then the total carbon emission reduction by theses houses comes to

= 4558 × 231,700 = Rs. 105.6 corers per annum (in terms of thermal energy),

and

= 440.47 × 231,700 = Rs. 10.2 corers per annum (in terms of exergy).

CONCLUSION

This paper gives the detailed analysis of overall annual energy and exergy gain from hybrid PV/T solar water heating system. The annualized uniform cost/kWh is higher in case of exergy when compared with cost/kWh on the basis of thermal energy. If this type of system is installed only at 10% of the total residential houses in Delhi then the carbon credit earned by the system in terms of thermal energy is Rs. 105.6 cores and in terms of exergy is Rs. 10.2 cores annually. This system will increase the total carbon emission reduction and overall carbon credit earned as per the norms of Kyoto Protocol if it is integrated in a building.

ABBREVIATIONS

A = Area, m^2

C = Specific heat, J/kg K

F' = Flat plate collector efficiency factor, dimensionless

F_R = Flow rate factor, dimensionless

h = Heat transfer coefficient, W/m^2

PF_1 = Penalty factor first, dimensionless

PF_2 = Penalty factor second, dimensionless

I (t) = Incident solar intensity, W/m^2

K = Thermal conductivity, W/m K

$\dot{m}_f$ = Rate of flow of water mass in collector, kg/sec

$\dot{m}_w$ = Withdrawal flow rate of water from tank, kg/sec

M_w = Mass of water, kg

$\dot{Q}_u$ = Rate of useful energy transfer, kW

$U_{t\,c,a}$ = An overall heat transfer coefficient from solar cell to ambient through glass cover, W/m^2 K

U_{L1} = An overall heat transfer coefficient from blacken surface to ambient, W/m^2 K

V = Air velocity, m/s

Subscripts

a = Ambient

c = Solar cell

c1 = First collector

c2 = Second collector

eff = Effective

f_i = Inlet fluid

f_o = Outgoing fluid

g = Glass

m = Module

p = Plate

tk = Water tank

Greek Letters

α = Absorptivity

$(\alpha\tau)_{eff}$ = Product of Effective absorptivity and transmittivity

β = Packing factor

η_i = An instantaneous thermal efficiency

τ = Transmitivity

APPENDIX I

Following Duffie and Beckman [18] and Tiwari [19], the flat plate collector efficiency is given by

$$F' = \frac{1}{\dfrac{W \times U_L}{\Pi D h} + \dfrac{W}{D + \left(W - D\right)F}}$$

where, $F = \dfrac{\tanh\left[m\left(W-D\right)\right]/2}{\left[m\left(W-D\right)\right]/2}$ *and* $m = \sqrt{\dfrac{U_L}{K\delta}}$

Now, the flow rate factor (F_R) given by

$$F_R = \frac{\dot{m}C_f}{A_c U_L F'}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m}C_f}\right)\right]$$

In modeling equations, we use the following relations for defining the design parameters, which is shown in Table 2.

$$\left(\alpha\tau\right)_{m,eff} = PF_1\left(\alpha\tau\right)_{1,eff} + \left(\alpha\tau\right)_{2,eff}$$

Here,

$$\left(\alpha\tau\right)_{1,eff} = \left(\alpha_c - \eta_c\right)\beta_c\tau_c \; and \left(\alpha\tau\right)_{2,eff} = \alpha_p\left(1 - \beta_c\right)\tau_g^2$$

and the penalty factors due to glass cover of PV module (PF_1) and absorber below PV module (PF_2) are defined as,

$$PF_1 = \frac{h_{c,p}}{U_{t\,c,a} + h_{c,p}} \; and \; PF_2 = \frac{h_{p,f}}{U_{L1} + h_{p,f}}$$

$$U_{t\,c,a} = 5.7 + 3.8V,\; U_{L1} = \frac{U_{t\,c,a}\cdot h_{c,p}}{U_{t\,c,a} + h_{c,p}},$$

$$U_{Lm} = \frac{U_{L1}\cdot h_{p,f}}{U_{L1} + h_{p,f}}$$

$$h_{c,p} = 5.7 + 3.8V,\; V = 0\,m/s$$

The values of h, $h_{p,f}$, α_c, τ_c, β_c, η_c, α_b and τ_g are taken from [12, 18, 19].

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