Optimum design of a solar water heating system

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Introduction

In view of the importance of energy availability for the prosperity of the people, solar energy has been recognized as the futuristic long term solution to the energy problems of the world. Although solar energy is abundant and freely available, however the solar energy utilization systems are not yet economically viable. Solar water heating systems are one of the most widespread solar energy applications. Solar water heating system has been designed for a hostel housing 150 people. The water heating energy load has been estimated and the optimum collector area has been determined on the basis of maximum cumulative solar saving (C_{SS}) that will accrue over the projected life of the system.

Estimation of heating load

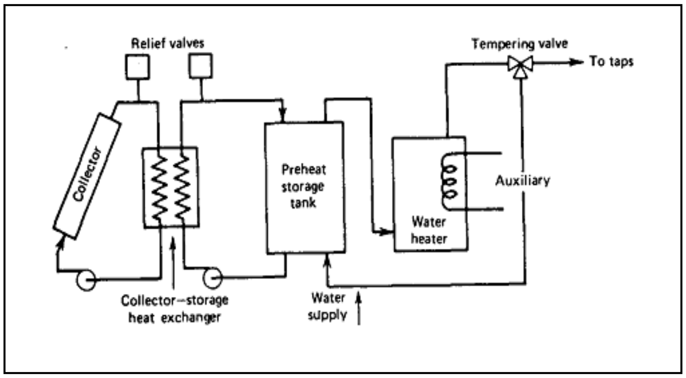
An estimate of load is made on the basis of number of person who needs hot water to be supplied. Investigators have specified various amounts of water per person per day, ranging between 40 to 50 liters at temperature between 50^0 to 60^0C. In order that the amount to be heated is kept low and this amount is heated to a relatively higher temperature, it has been assumed that hot water at around 75^0 is made available at the rate of 30 liters per day.

Assuming: Number of persons in the hostel : 150, Water to be heated to 85^0C by solar water heater, Water requirement : 30 liters/person/day.

Energy requirements as it varies for various months has been calculated from the following equation

$$E = mC_p(T_w-T_a) \qquad (1)$$

Where m is the mass of water to be heated, C_p is the specific heat of water, T_w is the temperature to which the water is required to be heated, T_a is the inlet/ambient temperature of water.



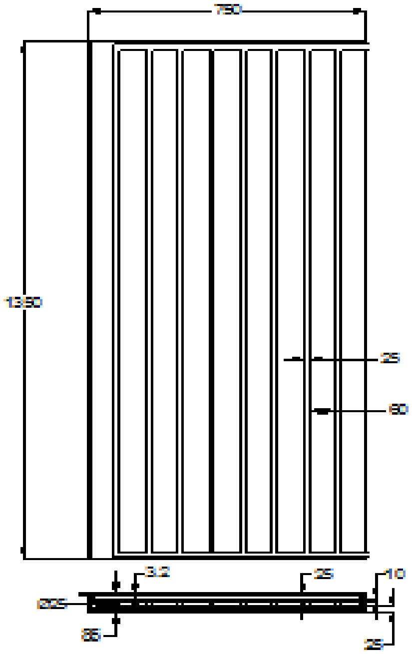


Fig.1 Layout of the system **Fig.2 drawing of a single flat plate collector**

Area of collector(A_c):	$1m^2$
Number of transparent cover:	1
Thickness of glass cover:	3.2 mm
Number of fluid pipe:	9
Thickness of insulation:	25 mm

the thermal efficiency of such a collector is given below:

$$\eta = F_R(\tau\alpha) - \frac{F_R * U_L(T_{fi} - T_a)}{I_{TT}} \qquad (2)$$

Where, $\tau_\alpha = \frac{\tau * \alpha}{1-(1-\alpha)\rho}$, $\tau = Transmittance$

$$\tau = \tau_r * \tau_a \qquad (3)$$

$$\tau_r = \frac{1-\rho}{1+\rho} \qquad (4)$$

$$\tau_a = e^{-kL} \qquad (5)$$

K=extinction coefficient = 0.0372 per m

L= length of light travel in glass = 0.0032 meter

$\alpha = Absorptance$ $\alpha = 1 - (\rho + \tau)$ (6)

$\rho = Reflectance$ $$\rho = \left(\frac{1-n}{1+n}\right)^2 \tag{7}$$

n= Reflective index of low iron tempered glass = 1.54

$$F_R = \left(\frac{m * c_p}{A_C * U_L}\right)\left[1 - e^{-\left[\frac{A_C * U_L * F'}{m * c_p}\right]}\right] \tag{8}$$

$F' = Collector\ efficiency\ factor = .85$

$A_c = 1m^2$, $C_p = 4.2$ KJ/kg-K, M = 0.014 $m^3/s/m^2$collector(normal)

$$U_L = U_B + U_T + U_E \tag{9}$$

U_L= overall loss coefficient, U_B = bottom loss coefficient, U_T = top loss coefficient

U_E = side loss coefficient (negligible)

$$U_B = \frac{k}{\delta} \tag{10}$$

T_a = ambient temperature, T_p = plate temperature, T_{pm} = mean temperature of plate

$$U_T = \left[\frac{N}{\frac{c}{T_{pm}}\left[\frac{T_{pm} - T_a}{n + f}\right] * e} + \frac{1}{h_w}\right]^{-2} + \frac{\sigma\left(T_{pm}{}^2 + T_a{}^2\right)\left(T_{pm} + T_a\right)}{\left(\epsilon_p + 0.00591\, n * h * w\right)^{-1} + \frac{2n + f - 1 + .33\epsilon_p}{\epsilon * g} - N} \tag{11}$$

N = number of covers = 1, $\epsilon_p = Emissivity\ of\ plate\ material$ = 0.75,

$\epsilon_g = Emissivity\ of\ glass$ = 0.94, *e= 0.43(1-100/T_{pm})*

$$c = 520\left(1 + 0.00051 * \beta^2\right) \tag{12}$$

$\beta = Tilt\ angle\ in\ radian$ = 0.7 radians (40^0)

$$f = \left(1 + 0.089h_w - 0.1166h_w * \epsilon_p\right) \tag{13}$$

$h_w = wind\ convection\ heat\ transfer\ coefficient$

$$h_w = 5.7 + 3.8v \tag{14}$$

$v = velocity\ of\ wind$, $\sigma = 5.67 * 10^{-8}$, $I_{ff} = intensity\ of\ solar\ radiation$

K = thermal conductivity = 0.032 W/m^2 K

ECONOMIC ANALYSIS

For economic optimization of a solar thermal energy system to be installed for heating of water, the savings which will accrue annually and on a long term basis, are been calculated.

SOLAR FRACTION

Solar fraction is defined as a fraction of the load supplied by solar energy.

Monthly Solar Fraction f= $\frac{Energy\ Colected\ in\ amonth}{Energy\ Lost\ in\ a\ month}$

If f>1 then value of f is to be taken unity. Annual solar fraction is defined as

Annual Solar Fraction f'= $\sum_{n=1}^{n=12} \frac{E_{Loss} f}{E_{loss}}$ (15)

The f-chart method will be used to calculate the the solar fraction of each month and the total solar fraction of the year for an assumed collector area. The parameters required for determining the solar fraction are :

$X = F_R U_L (T_{Req} - T_a) D t A_c / L$ & (16)

$Y = F_R (ta) H_T N A_c / L$ (17)

Where:

F_R = collector heat exchanger efficiency factor[2]
U_L = collector overall loss coefficient ($W/m^2\ {}^0C$)
Dt = total number of seconds in month
T_a = monthly average ambient temperature (${}^0C$)
T_{ref} = empirically derived reference temperature (100^0C)
L = monthly total heating load for space heating and hot water (J)
H_T = monthly average daily radiation incident on collector surface per unit area (J/m^2)
N = days in month
(ta)= monthly average transmittance-absorptance product

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (18)$$

Annular solar fraction is given by:

$$f' = \frac{\sum f_i L_i}{\sum L_i} \quad (19)$$

Fuel savings brought about as a result of this fraction is given by $C_f f'E$. Using an assumed value of C_f=0.0005 Rs/kJ (Rs 10per kg coal of calorific value of 20000kJ/kg), the fuel savings for all months are calculated. Table1 shows the values of fuel saving for different assumed values of collector areas

S. No.	Area (m^2)	Fuel saving, $C_f f_s E$ (Rs)
1	50	82124
2	75	113535
3	100	139356
4	125	159565
5	150	172869
6	200	181376
7	225	187300
8	250	192318
9	275	196473
10	300	199576
11	325	202123
12	350	204255
13	375	205807

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Table 1:Values of fuel saving for different assumed values of collector areas

CUMULATIVE SOLAR SAVINGS

A few financial criteria have been proposed and utilized for assessing and enhancing sunlight based vitality framework. One of them is life cycle sparing or aggregate sunlight based sparing.

The existence cycle cost (LCC) is the total of the all cost related with a vitality conveyance framework over its life time or a chose time of investigation, in the present rupee, and considers time estimation of cash. The essential thought of life cycle cost is that foreseen future expenses are taken back to introduce cost (reduced) by ascertaining what amount would need to be contributed at the market rebate rate to have the assets accessible when they were required. An existence cycle cost investigation incorporates expansion while assessing future costs.

The general thought is that life cycle reserve funds (LCS) (net present worth) are the contrast between the existence cycle expenses of a traditional fuel-just framework and the existence cycle cost of the sun powered in addition to assistant vitality framework.

The Cumulative sun powered investment funds over a time of 'n' years is gotten by summing the present worth of the yearly sunlight based sparing and thinking about the underlying initial installment.

If:

C_A = Collector cost (in Rs/m^2)
C = Collector cost (in Rs)
f_l = Fraction taken as loan
d_l = Interest rate on loan
n_l = Pay back period of loan in yrs (n_l=10 yrs)
$E_{\text{Total Loss}}$ = Annual energy load
f' = Annual solar fraction
$f'E_{\text{Total loss}} = G$ = Annual saving of conventional energy
c_f = Cost of conventional energy (in Rs per MJ)
i_f = Rate of increase every year
M = Annual maintenance cost (in Rs)
i_m = Rate of increase in maintenance cost
d = Market discount rate
r_d = Depreciation rate
r_t = Income tax rate

Considering a solar energy system such that:

1. The system requires a total investment C of which a fraction f_l is taken as loan. The interest rate on loan is d_l and the loan is to be paid back in equal installments over a period of n years.

   Total Investment C= Unit cost of collector x Area of collector

   Total Investment C= C_A x A_c
2. The yearly vitality load to be met be E Total Loss and expect that the close planetary system supplies a portion f' of this heap. This would result in a yearly sparing of (f' E Total Loss) of ordinary vitality. Expect that the expense of this vitality is cf per unit of vitality and that it increments at the rate of if consistently.
3. The close planetary system requires upkeep cost M every year and this will increment at the rate of im consistently.
4. The expense findings are permitted both on the intrigue part of the yearly credit reimbursement portion and additionally on devaluation of the framework. The deterioration is thought to be at a uniform rate r¬d every year. The pay charge rate is r_t.

In any year j

Fuel savings = $c_f\,(1+i_f)^{j-1}\, f'\, E_{\text{Total Loss}}$

Annual repayment on loan = $\frac{d_l f_l C}{[1-\frac{1}{(1+d_l)^n}]}$ if $j \leq n$

Maintenance charges= $(1+i_m)^{j-1}\,M$

Tax deduction on the interest = $[1-\frac{(1+d_l)^{j-1}-1}{(1+d_l{}^{n})-1}]\, r_t\, d_l\, f_l\, C$ if $j \leq n$

component of loan repayment

Tax deduction on depreciation = $r_t\, r_d\, C$ if $j \leq \frac{1}{r_d}$

Thus annual solar savings in the year j=

$$c_f\,(1+i_f)^{j-1}\, f'\, E_{\text{Total Loss}} - \frac{d_l f_l C}{[1-\frac{1}{(1+d_l)^n}]} - (1+i_m)^{j-1} M + [1-\frac{(1+d_l)^{j-1}-1}{(1+d_l{}^{n})-1}]\, r_t\, d_l\, f_l\, C + r_t\, r_d\, C \qquad (20)$$

The cumulative solar saving over a period of n years is obtained by summing up the present worth of the annual solar savings and considering the initial down payment. Thus

Cumulative Solar Saving (CSS) =

$$-(1-f_l)\,C + G\sum_{j=1}^{j=n}\frac{(1+i_f)^{j-1}}{(1+d)^j} - \frac{d_l f_l C}{[1-\frac{1}{(1+d_l)^n}]}\sum_{j=1}^{j=n}\frac{1}{(1+d)^j} - M\sum_{j=1}^{j=n}\frac{(1+i_m)^{j-1}}{(1+d)^j}$$

$$+ r_t d_l f_l C\sum_{j=1}^{j=n}\frac{1}{(1+d)^j}[1-\frac{(1+d_l)^{j-1}-1}{(1+d_l)^n-1}] + r_t r_d C\sum_{j=1}^{\frac{1}{r_d}}\frac{1}{(1+d)^j} \qquad (21)$$

On summing the progression, we get Cumulative Solar Saving (CSS) =

$$-(1-f_l)\,C + \frac{G}{(d-if)}[1-\{\frac{(1+if)}{(1+d)}\}^n] - \frac{dl\, fl\, C}{[1-\frac{1}{(1+dl)^{nl}}]d}[1-\frac{1}{(1+d)^{nl}}] - \frac{M}{(d-im)}[1-\frac{(1+im)^n}{(1+d)^n}] + r_t d_l f_l C$$

$$[\frac{(1+dl)^{nl}}{(1+d)^{nl}}\frac{1}{d}\{\frac{(1+d)^{nl}-1}{(1+dl)^{nl}-1} - \frac{1}{\{(1+dl)^{nl}-1\}}\frac{1}{(d-dl)}\{1-\frac{(1+dl)^{nl}}{(1+d)^{nl}}\}\}] + \frac{rt\, rd\, C}{d}[1-\frac{1}{(1+d)^{\frac{1}{rd}}}] \qquad (22)$$

n is the number of years at which CSS is to find out

for above equation $n \geq n_l$, $n \geq (1/r_d)$, $d \neq i_f$, $d \neq i_m$ & $d \neq d_l$

Table 2 Values of variable Parameters

S. no	Description	Parameter	Value
1	Specific heat of water (kJ/kg-K)	C_p	4.2
2	Thermal conductivity for glass wool (W/m-K)	K_w	0.69
3	Transmittivity absorbtivity product	$\tau\alpha$	0.81

4	Collector efficiency factor	F’	0.85
5	Depreciation rate	r_d	0.25
6	Income tax rate	r_t	0.55
7	Maintenance cost(Rs)	M	5% of initial cost
8	Rate of increase of maintenance cost	i_m	0.05
9	Initial down payment factor	fl	0.2
10	Rate of increase of fuel cost	i_f	0.04
11	Payback period(years)	n_l	10
12	Ambient Temperature(°C)	T_a	From graph
13	Solar Intensity(W/m^2)	H_s	From graph
14	Collector cost(Rs)	C_A	8000
15	Fuel cost(Rs/KJ)	c_f	0.0005
16	Market discount rate	D	0.1

DETERMINATION OF OPTIMUM COLLECTOR AREA:

The physical dimensions of the solar water heater can be determined from design consideration and the economic analysis of the entire system can be carried out to determine Cumulative Solar Savings. This analysis can be then used to determine the optimum size of the heating system. It may be noted that the results needed to be presented in terms of optimum solar collector area (A_c). For this purpose a step by step procedure has been followed which is given below:

Annual solar fraction is calculated

$$f = \frac{Energy\ collected\ in\ a\ month}{Energy\ lost\ in\ a\ month}$$ (Using: f=1 when f >1.)

Annual solar fraction is defined as $$f' = \frac{\sum f_i L_i}{\sum L_i} \qquad (23)$$

Cumulative solar saving is calculated for the desired range of collector area obtained from above equation

Total Investment C= Unit cost of collector x Area of collector

Total Investment C= C_A x A_c (24)

Cost of conventional fuel saved in first year= C_f x $f'E_{lost\ yearly}$

Cumulative Solar Saving (CSS) =

$$-(1-f_l)\,C+\frac{G}{(d-if)}\left[1-\left\{\frac{(1+if)}{(1+d)}\right\}^{n}\right]-\frac{dl\,fl\,C}{\left[1-\frac{1}{(1+dl)^{nl}}\right]*d}\left[1-\frac{1}{(1+d)^{nl}}\right]\quad -$$

$$-\frac{M}{(d-im)}\left[1-\frac{(1+im)^{n}}{(1+d)^{n}}\right]+r_t d_l f_l C\left[\frac{(1+dl)^{nl}}{(1+d)^{nl}}\frac{1}{d}\left\{\frac{(1+d)^{nl}-1}{(1+dl)^{nl}-1}-\frac{1}{\{(1+dl)^{nl}-1\}}\frac{1}{(d-dl)}\left\{1-\frac{(1+dl)^{nl}}{(1+d)^{nl}}\right\}\right\}\right]$$

$$+\frac{rt\,rd\,C}{d}\left[1-\frac{1}{(1+d)^{\frac{1}{rd}}}\right] \qquad (25)$$

n is the number of years at which CSS is to find out n=10

For above equation $n \geq n_l$, $n \geq (1/r_d)$, $d \neq i_f$, $d \neq i_m$ & $d \neq d_l$

The values of C_{SS} have been obtained for desired range of collector area for the fixed values of variable parameters i.e. cost of collector, cost of conventional fuel, market discount rate & rate of interest.

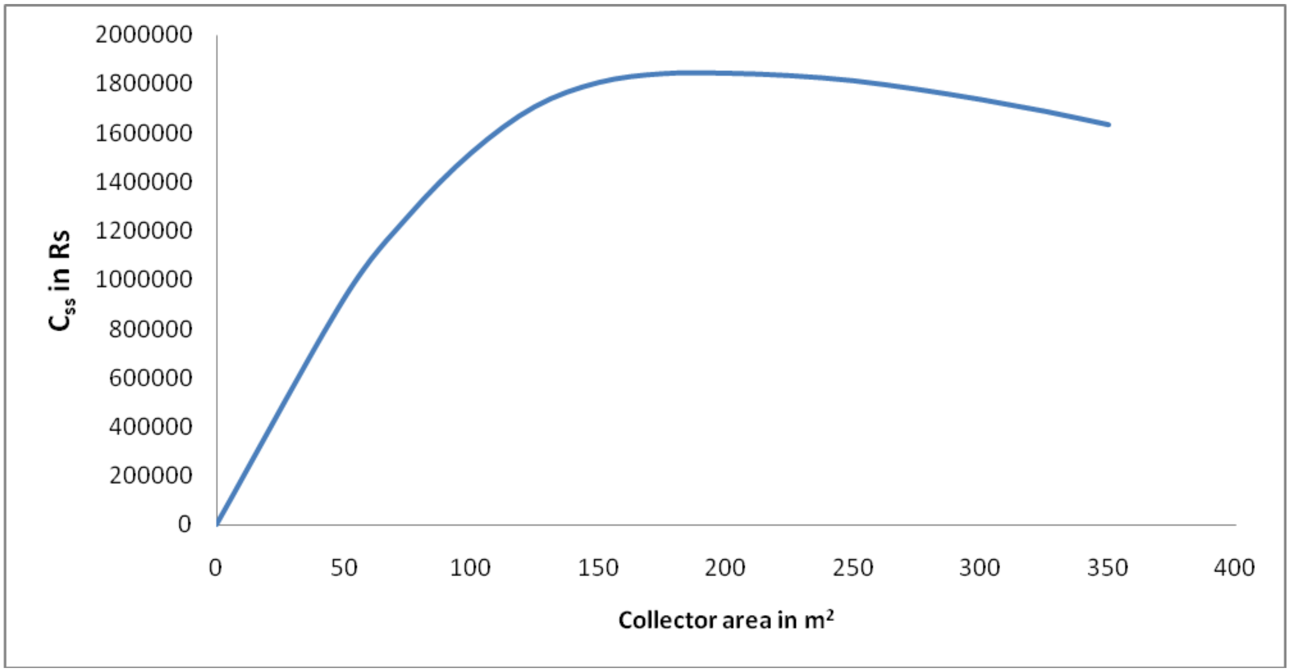

Fig.18 Graph between cumulative solar saving with area of collector

Those values have been plotted in fig 18 and optimum area of collector has been determined to be 195 m^2 (say 200 m^2). A schematic diagram of the system has been shown in fig 19 which shows a set of 25 collectors, the actual system will be an extended one with 200 collectors.

CONCLUSION

An optimized solar water has been designed for a hostel having capacity of 150 persons. The most important single parameter, the collector area has been determined based upon cumulative solar savings. A water heating system consisting of 200 collectors, each having an effective area of 1 m^2 has been found to be most economical.

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