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Life cycle cost analysis of new FRP based solar parabolic trough collector hot water generation system

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Abstract: Parabolic trough collectors (PTCs) are employed for a variety of applications including steam generation and hot water generation. This paper deals with the experimental results and an economic analysis of a new fibre reinforced plastic (FRP) based solar PTC with an embedded electronic controlled tracking system designed and developed for hot water generation in a restaurant in Madurai, India. The new collector performance has been tested according to ASHRAE Standard 93 (1986). The performance of a new PTC hot water generation system with a well mixed hot water storage tank is investigated by a series of extensive tests over ten months period. The average maximum storage tank water temperature observed was 74.91 °C, when no energy is withdrawn from the tank to the load during the collection period. The total cost of the new economic FRP based solar PTC for hot water generation with an embedded electronic controlled tracking system is Rs. 25000 (US$ 573) only. In the present work, life cycle savings (LCS) method is employed for a detailed economic analysis of the PTC system. A computer program is used as a tool for the economic analysis. The present worth of life cycle solar savings is evaluated for the new solar PTC hot water generation system that replaces an existing electric water heating system in the restaurant and attains a value of Rs. 23171.66 after 15 years, which is a significant saving. The LCS method and the MATLAB computer simulation program presented in this paper can be used to estimate the LCS of other renewable energy systems.

Key words: Economic analysis, Life cycle savings, Life cycle cost (LCS), Parabolic trough collector (PTC), Solar water heating system (SWHS)
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INTRODUCTION

Though the solar energy density is low and its availability is not continuous, it is now possible to harness this abundantly available energy very reliably for many purposes by converting it to usable heat or through direct generation of electricity. Solar water heating systems (SWHSs) have been commercialised in many countries of the world including India. India is in the sunny belt of the world. The country receives solar energy equivalent to more than 5000 trillion kW·h/a, which is far more than its total annual energy consumption. The daily average global radiation is around 5 kW·h/(m^2·d) with the sunshine time ranging between 2300 and 3200 h/a (TERI, 2001). SWHS is now recognised as a reliable product that saves substantial amounts of electricity or other conventional fuels, leads to peak load reduction and prevents emission of carbon dioxide, a major green house gas. Parabolic trough collectors (PTCs) are generally employed for a variety of applications such as industrial steam generation (May and Murphy, 1983) and hot water production (Kalogirou and Lloyd, 1992). Kalogirou and Lloyd (1992) reported that PTC can be more efficient and cost effective than conventional flat plate collectors for hot water production. Many researchers have investigated the benefits related to the employment of solar systems including studies regarding life cycle analysis of solar systems (Kablan, 2004; Crawford and Treloar, 2004; Ardente *et al.*, 2005; Tsilingiridis *et al.*, 2004).

In the present work, a new economic fibre reinforced plastic (FRP) based PTC with an embedded electronic controlled one axis solar tracking system has been designed and developed for generating hot water as a replacement of an existing electric water heating system in a restaurant in Madurai, India. The modeling of the new PTC system has been accomplished by performing optimization of the collector dimensions and selection of the receiver tube diameter (Valan Arasu and Sornakumar, 2005). The performance tests of the new FRP based PTC designed and developed for hot water generation have been carried out according to ASHRAE Standard 93 (1986) and reported by Valan Arasu and Sornakumar (2006). In this paper, an economic analysis of the new FRP based solar PTC hot water generation system replacing the existing electric water heating system, based on life cycle savings (LCS) method, is presented. A MATLAB computer program is developed to evaluate the present worth of solar savings over the optimal operation life of the PTC system.

DESCRIPTION OF PTC HOT WATER GENERATION SYSTEM

The newly developed FRP based PTC system employed for hot water generation is presented in Fig.1. The PTC system for hot water generation includes a FRP based PTC, a hot water storage tank (HWST) of well-mixed type and a circulating pump. The parabola trough with a rim angle of 90° of the new PTC hot water generation system is very accurately constructed of fiberglass material, and the method of construction of the trough is described by Valan Arasu and Sornakumar (2007). A new flexible solar reflector material (SOLARFLEX foil) (from Clear Dome Solar Systems Heating and Cooking Products, San Diego, CA, USA, http://www.cleardomesolar.com, 2003) with a reflectance of 0.974 is used in the present work. The solar receiver consists of a copper tube, a glass envelope and rubber cork seals at both ends of the glass envelope. The copper tube is coated with a heat resistant black paint and surrounded by a concentric glass cover with an annular gap of 0.5 cm. The rubber corks are incorporated at both ends of the receiver tube in the annular gap between the glass cover and the copper tube to achieve an airtight enclosure. Water from the storage tank is pumped through copper tube, where it is heated and then flows back into the storage tank. The PTC rotates around the horizontal north/south axis to track the Sun as it moves through the sky during the day. The axis of rotation is located at the focal axis. The tracking mechanism consists of a control system and a low speed 12 V DC motor. The input signals to the control system are obtained from light dependent resistors. The pump for maintaining the forced circulation is operated by an on-off controller (differential thermostat), which senses the difference between the temperature of the water at the outlet of the collector (T_{fo}) and the storage tank (T_l). The pump is switched on whenever this difference exceeds a certain value and off when it falls below a certain value. In the present work, the differential temperature controller value ($T_{fo}-T_l$) is set as +2 °C.

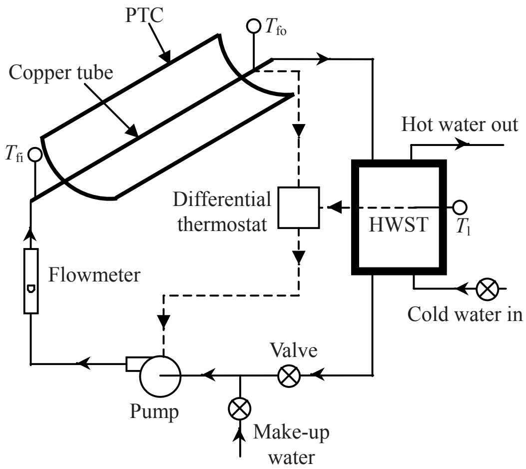

Fig.1 PTC with hot water storage tank

The new PTC system specifications are presented in Table 1. The actual initial cost of the new PTC system designed for the present research work is presented in Table 2.

In the present work, the experiments have been conducted on various sunny days from 10.00 to 16.00, Indian Standard Time (IST), over eight months with a mean solar beam radiation range of 550~750 W/m^2 and a mean ambient temperature range of 34~37 °C. The experimentally measured hourly storage tank water temperature values for a select sunny day of every month are presented in Table 3. The average maximum storage tank water temperature at 16.00, IST over the eight months period is 74.91 °C, when no energy is withdrawn from the tank to the load during the collection period and is well above the average hot water temperature (65 °C) of the existing electric heating system.

Table 1 Parabolic trough collector system specifications

Items	Value
Collector aperture (m)	0.8
Collector length (m)	1.25
Rim angle (°)	90
Focal distance (m)	0.2
Receiver diameter (mm)	12.8
Glass envelope diameter (mm)	22.6
Concentration ratio	19.89
Water flow rate (L/min)	1.0
Storage tank material	Stainless steel
Storage tank capacity (L)	35
Tank insulation material	Glass wool
Tank insulation thickness (cm)	5
Water pump (hp)	0.5

Table 2 Initial cost of PTC system

Item	Cost (Rs.)*
Parabolic trough fibreglass casting	2200
Reflective sheet	3000
Support structure	4000
Tracking mechanism	7000
Copper pipe receiver and glass envelope	800
Circulating pump (1/2 hp)	2000
Stainless steel storage tank with glass insulation	1000
Miscellaneous (piping, insulation, etc.)	5000
Total initial cost	25000

* Note: 1 USD=Indian Rupees (Rs.) 43.62, August 2005

Table 3 Experimentally measured hourly storage tank temperatures

Month	Storage tank temperature (°C) under different Indian Standard Time					
	11.00	12.00	13.00	14.00	15.00	16.00
March	43.65	53.28	60.41	65.83	70.34	74.66
April	49.77	57.94	65.53	71.19	74.81	77.67
May	47.65	55.84	62.24	67.61	72.35	76.31
June	42.21	51.32	59.29	66.42	72.83	78.45
July	41.06	49.87	57.01	62.51	67.02	70.68
August	45.22	55.83	62.88	68.13	71.94	75.15
September	42.21	49.86	56.62	63.11	67.02	70.11
October	46.18	53.88	60.78	66.50	72.45	76.23

ELECTRIC WATER HEATING SYSTEM DESCRIPTION

The existing electric water heating system in a restaurant has a cuboid tank (L=1130 mm, W=310 mm, H_t=300 mm) containing an electric heating coil. The electric water heating system arrangement is shown in Fig.2. The electric coil is immersed in the water column of height (H_w) 10 cm and placed at the center of the water tank as shown in Fig.2. Four bowls, each of diameter 20 cm and height 25 cm, containing food are placed on the water, which is heated by the heater. Hence, the cooked foods are kept warm and fresh.

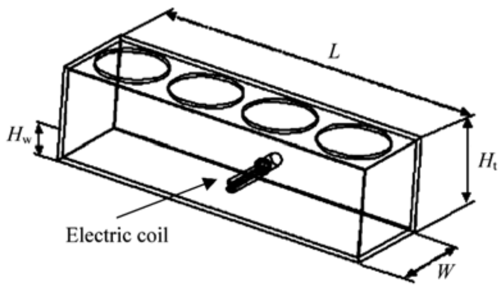

Fig.2 Electric water heating system arrangement

Volume of heater tank (L×W×H_t)=1130×310×300×10^{-9}=0.10509 m^3;

Volume of water in heater tanks (L×W×H_w)=1130×310×100×10^{-9}=0.03503 m^3;

Volume of water to be heated=35.03 L (approximately 35 L).

The heater is on for about 30 min until the water in the tank attains a sufficient temperature so as to keep the dish warm. The average hot water temperature was measured as 65 °C. The heater is turned on at regular intervals over the canteen working hours of 8 h and is observed to be consuming 5 kW·h/d. At the tariff (TNEB, 2005) 5.8 Rs./(kW·h), the cost of electricity is 29.0 Rs./d. The heater is in use for 275 d in a year. So the annual electricity cost for the electric heater is Rs. 8000.

COMPONENTS OF TOTAL COST OF SOLAR SYSTEM

Life cycle cost (LCC)

Solar thermal devices and systems are generally characterised by high initial costs and low annual operating costs. An economic evaluation of a solar system is of comparing an initial known investment with estimated future operating costs. To study the economic feasibility of a system, different methods could be used to evaluate the different figures of merit of the systems, such as net present value (NPV) method, LCS method, the annual cost (AC) method, the payback period method, etc. (Tiwari, 2002). The method employed for the economic analysis in the present work is LCS method. This method takes into account the time value of money and allows detailed consideration of the complete range of costs. Life cycle cost (LCC) is the sum of all the costs associated with a solar thermal energy system over its lifetime in terms of money value at the present instant of time and takes into account the time value of money (Kalogirou, 1996). The LCS for a solar heating system is defined as the difference between the LCC of a conventional heating system and the LCC of the solar heating system. This is equivalent to the total present worth of the gains from the solar system compared to the conventional heating system.

Initial cost

The initial cost (IC) of a solar thermal system is the cost of the equipments and installation. Solar collectors contribute significantly to the IC. The IC is the sum of two components: area dependent cost (ADC) and area independent cost (AIC). Multiplying the ADC (cost per unit collector area) with the total collector area A_{tc} would give a cost related to the size of the system. The total system IC can be obtained by adding the AIC and is given by

$$IC=(ADC\times A_{tc})+AIC. \quad (1)$$

Annual cost and annual solar savings

The annual cost of a solar system is the sum of a number of factors. These include the cost of electrical energy consumed by auxiliary equipments like pumps and the auxiliary energy system like electric heaters, repayment on the loan availed to install the system, maintenance of the system, local taxes and tax deductions. Tax deductions may be related to the interest payable on the loan repayment or to the annual depreciation permitted on the system.

In order to evaluate the economic viability of a solar system, one has to calculate the savings, which will accumulate annually and on a long-term basis as a result of installing the solar system. On annual basis, the solar system would help in saving conventional energy in the form of fuel or electricity.

Annual mortgage payment

The mortgage payment is the annual value of money required to cover the funds borrowed at the beginning to install the system. This includes principal and interest payment. The estimation of the annual mortgage payment (AMP) can be found by dividing the amount borrowed by the present worth factor (PWF) (Stoecker, 1989). Assume that the system requires a total IC of which either full or a fraction is taken as mortgage amount (MA). The mortgage interest rate is MIR and the mortgage is to be paid back in equal instalments over a mortgage period (MP) in years. The PWF in any year N is

$$PWF=\frac{(1+MIR)^N-1}{MIR(1+MIR)^N},$$

and AMP is expressed as

$$AMP=\frac{MA}{PWF}. \quad (2)$$

Annual fuel savings

Let the first year fuel cost savings be FFS and this cost increases at FIR (annual fuel cost inflation rate) every year. The annual fuel cost savings (AFS) in any year N is

$$AFS=FFS(1+FIR)^{N-1}. \quad (3)$$

Annual maintenance cost

The solar system will normally require some annual expenditure by means of maintenance, local taxes and insurance, etc. Let the first year maintenance cost is FMC and this cost increases at the rate of MR (annual rate of increase in maintenance cost) every year. The annual maintenance cost (AMC) in any year N is

$$AMC=FMC(1+MR)^{N-1}. \quad (4)$$

Annual electricity cost

The cost of electrical energy required for running auxiliary equipment, i.e. first year parasitic cost (FPC) is obtained by multiplying the pump power (PP) by the operation hours (OH) and by the price of electricity (EC) (Kalogirou, 1996). This cost is also increased at an inflational rate, i.e. annual rate of increase in electricity cost (EIR) every year. The annual parasitic cost (APC) in any year N is

$$APC=FPC(1+EIR)^{N-1}, \tag{5}$$

where $FPC=PP\times OH\times EC$.

Annual tax deductions

Let us assume that tax deductions are allowed both on the interest component of the annual loan repayment instalment (IA) and on depreciation of the system. The annual depreciation (AD) is assumed to be at a uniform rate every year and the annual rate of income tax is RT. The equation used for the estimation of annual tax savings (ATS) is

$$\begin{cases} ATS = RT(IA + AD), \\ AD = IC / N_{\max}, \end{cases} \tag{6}$$

where $N_{\max}$ is the time in years after which the system is entirely discarded, i.e. maximum life time and is taken as 20 years (MNES, 2006).

Thus the annual solar savings (ASS) is (Kalogirou, 1996)

$$ASS=AFS-AMP-AMC-APC+ATS. \tag{7}$$

Present worth of annual solar savings

The present worth of annual solar savings (PWASS), if the annual market discount rate is MDR, in any year N is (Stoecker, 1989)

$$PWASS=ASS/(1+MDR)^{N}. \tag{8}$$

The LCS over life time (LT) of a system is the sum of PWASS over the period plus the present worth of salvage value (PWSV) at the end of its lifetime minus the initial down payment (DP) made at the time of installation of the solar system (Sukhatme, 2003). Thus

$$LCS = \sum_{N=1}^{LT} PWASS(N) + PWSV - DP, \tag{9}$$

where $PWSV$ is given by (Crawford and Treloar, 2004):

$$PWSV = \frac{SV}{(1+MDR)^{LT}}, \tag{10}$$

where SV is the salvage value of the system.

Salvage value of a system

The various system components, e.g., body structure, glass wool insulation, etc. may be reused even after the useful life of the system is over. The market value at the end of useful life of the system is known as salvage value (SV). The SV of the system is dynamic with its assumed life time. Hence assuming linear depreciation of the system with time, then the SV at time N could be expressed as (Kablan, 2004),

$$SV=IC-AD\times N. \tag{11}$$

SIMULATION PROGRAM

The case study is taken for the new FRP based PTC hot water generation system. The IC of the system, presented in Table 2, is Rs. 25000 and is set up with an initial DP of 100% of the initial investment. The MA is nil. The cost of electrical energy saved in the first year (FFS) is estimated as Rs. 8000 and this cost increases at the annual fuel cost inflation rate (FIR) of 4%. The first year maintenance cost (FMC) is assumed as 2% of the IC and this expense increases at the annual rate of increase in MR of 4%. The power consumption (PP) of the water circulating pump (1/2 hp) and motor of the tracking system (1/8 hp) is 0.46 kW and is estimated to work for approximately 2200 h/a (OH). The electricity cost (EC) is 5.8 Rs./(kW·h) (TNEB, 2005) and this cost is expected to rise at the annual rate of increase in electricity cost (EIR) of 4%. Tax deductions are permissible both on the interest component of the annual loan repayment instalment and on depreciation of the system. The interest component of the annual loan repayment instalment (IA) is nil and the annual depreciation (AD) of the system is Rs. 1250. The maximum life time ($N_{\max}$) is taken as 20 years (MNES, 2006). The annual rate of income tax (RT) is 30%. Finally the annual market discount rate (MDR) is 8%. The objective here is to calculate the PWSS for this system over an optimal operation

operation life time (LT) of 15 years.

The MATLAB program calculates the value of total PWSS, called "life cycle solar savings" from one year to the next. This is done by substituting values on N ranging from 1 to 15 in Eq.(9). The result of the program indicates that by investing in the PTC hot water generation system as a replacement of the existing electric water heating system, one would save Rs. 23171.66 over a time period of 15 years, which is a reasonable saving. Solar savings for each year (ASS) is computed using Eq.(7) and is shown in Fig.3. Each year's solar savings is brought to a present worth using Eq.(8) with MDR=8%. The variation of life cycle solar savings with the number of years is plotted in Fig.4. It is seen that the life cycle solar savings(LCS) increases rapidly and becomes positive at the end of six years because of the electrical energy cost savings and attains the value of Rs. 23171.66 after 15 years.

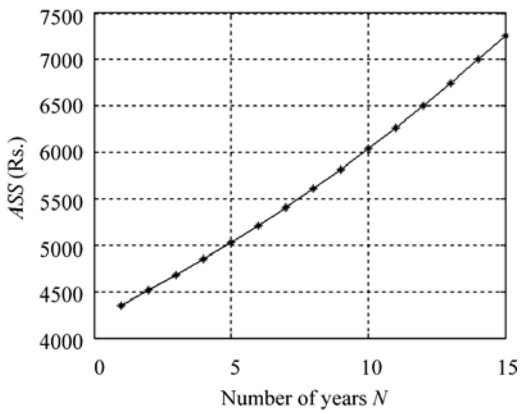

Fig.3 Variation of annual solar savings (*ASS*) with number of years (*N*)

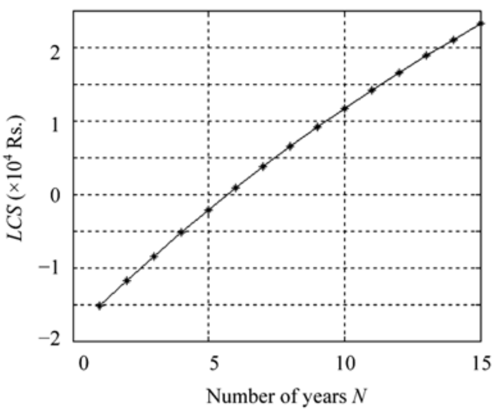

Fig.4 Variation of life cycle solar savings (*LCS*) with number of years (*N*)

CONCLUSION

The performance of a newly designed and developed FRP based PTC with a newly developed embedded electronic controlled one axis solar tracking system and a well mixed hot water storage tank for hot water generation in a restaurant in Madurai, India, is investigated by a series of extensive tests. The average maximum storage tank water temperature over the testing period observed was 74.91 °C, when no energy is withdrawn from the tank to the load during the collection period. The total cost of the new economic FRP based solar PTC for hot water generation with an embedded electronic controlled tracking system is Rs. 25000 (US$ 573) only. Economic analysis of the new PTC hot water generation system replacing the existing electric heating system based on life cycle savings (LCS) method is presented in detail in this paper. A computer simulation program is used as a tool for fast estimation of LCS of the new PTC system. The annual solar savings (ASS) of the new PTC hot water generation system is significant and increases with number of years. The life cycle solar savings of the new PTC system increases rapidly and becomes positive at the end of six years because of the electrical energy cost savings, and attains the value of Rs. 23171.66 after 15 years, which is a significant saving. Thus the new FRP based solar PTC hot water generation system is more economic than the existing electric water heating system in the restaurant in Madurai, India. The LCS method and the MATLAB computer simulation program presented in this paper can be used to estimate the LCS of other renewable energy systems.

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