



# Thermodynamic and techno-economic analysis of heat pipe ETC water heating system for Indian composite climate

## An experimental approach

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### Abstract

This paper presents the thermodynamic and techno-economic performance calculation of heat pipe evacuated tube collector (HP-ETC) solar water heating system by energy, exergy analysis and different economic parameters for Indian composite climate of Jammu. The HP-ETC solar water heating system of 1.69 m<sup>2</sup> was designed and fabricated for a family with an average size of six persons. The experiments were done for six different mass flow rates of working fluid (water) such as 20, 30, 40, 50 and 60 L per hour (LPH). The highest average energy and exergy efficiencies were obtained to be 72% and 5.2%, respectively, for 20 LPH, while the lowest values of respective parameters were 55% and 1.25% at 60 LPH flow rate. The maximum and minimum average outlet temperatures from collector were found to be 76.4 and 45 °C at 20 and 60 LPH, respectively. It has been observed that heat pipe ETC water heating system is better than direct flow evacuated tube collector-based water heating system. Also, the exergy efficiency was found to be much lower than energy efficiency for all the selected mass flow rates. The techno-economic analysis of heat pipe evacuated tube solar water heating system was done by three methods, namely annual cost, life-cycle savings and payback period. The cost of hot water production at desired temperature was found to be INR 0.12 per liter, whereas that of the electric geyser and gas geyser was INR 0.40 and 0.26, respectively. The payback period of heat pipe ETC solar water heater was estimated to be 4 years, which is much less than the life of HP-ETC solar water heating system.

**Keywords** Evacuated tube collector · Solar energy · Techno-economic analysis · Heat pipe · Energy analysis · Exergy analysis

### Introduction

In recent years, rapid depletion of conventional energy sources and environmental hazards led to the growth of renewable energy sources such as wind, solar and

geothermal. The utilization of systems based on renewable energy decreases greenhouse gas emissions and maintains ecological balance. Solar energy is considered to be a carbon-free, environmentally friendly, sustainable energy resource. Since 2006 as per Solar Energy Industrial Association, remarkable growth in the solar sector is observed; and in the last decade 60% annual growth rate in solar sector was also noticed [1]. Solar thermal collector system is a commercialized technology, and it is being adopted in most of the places in the world where economic factors and energy resources are favorable. Also, during the past few years, more emphasis has been paid on the saving of energy in buildings. Moreover, European countries have taken a number of actions [2] under various energy policies to reduce the energy consumption in buildings [3]. In a similar way, industry and research institute made a

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considerable effort to fabricate the environmentally friendly and efficient technologies, particularly in the renewable framework. One of the solar-based technologies, solar thermal collector, is the attractive solution owing to the peculiarity of being incorporated within the envelope of building.

The Indian Ministry of New Renewable Energy (MNRE) predicted that hot water demand for residential buildings is 84% of total energy consumption, whereas the demand in commercial and industrial sectors is 10 and 6%, respectively [4]. In order to reduce the consumption of energy and greenhouse gas emission in the residential buildings, there are different varieties of strategies available by energy retrofits [5, 6].

The solar water heating is one of the cost-effective and proven technologies which have the potential to reduce electrical energy consumption in the commercial and residential buildings [7]. As discussed above, harvesting of solar energy through solar collectors is the prominent option to meet the increasing demand for energy. Solar collectors are mainly classified into three categories: evacuated tube solar collector, flat-plate solar collector and concentrating collector. But in the residential sector, hot water demand is in the low-to-medium temperature range for different household applications (cleaning, bathing, washing, etc.). According to the current scenario of market, 78% of recently installed collectors are of evacuated tube type, owing to its high performance and low cost [8]. According to a report submitted by International Energy Agency, worldwide more than 50% out of total installed collectors are evacuated tube collector [9]. In last 20 years, evacuated tube collectors dominate the market over flat-plate solar collectors owing to the growth of low-cost sputtering technology for the fabrication of evacuated tubes. The characteristics such as low-cost installation and higher performance enabled ETC to be used for different applications. In these collectors, radiative and convective are very minimal. Higher exergy and energy efficiencies are the most important factors of design for double-glass evacuated tubes [10]. Kumar et al. [11] modeled the heat pipe evacuated tube collector to increase the generation of heat energy. They also fabricated and performed heat transfer analysis of solar collector. Sokhansefat et al. [12] performed economical and thermal analyses of ETC and found that the performance of ETC system is 41% higher than that of the FPC system. The annual heat gain in cold climate through ETC is also 30% higher than FPC in cold climate. Authors recommended using of ETC in cold climate. Abokersh et al. [13] performed a simultaneous investigation of evacuated tube collector-based finned, unfinned and forced recirculation solar water heating system. The results reveal that effective discharged energy from unfinned system and finned system is 35.8 and 47.7% higher than that of the forced recirculation solar water

heating system. The annual efficiency of forced recirculation solar water heating system, finned and unfinned system was 40.5%, 85.7% and 71.8%, respectively, and daily efficiency of respective systems was 20%, 33%, 26%, respectively. Ghaderian et al. [14] enhanced the thermal efficiency of evacuated tube solar collector by 14% when compared to water and CuO nanofluid (at 0.03% volume fraction) used as working fluids. Gan et al. [15] experimentally investigated the effect on the thermal performance of evacuated solar collector by varying the volume concentration of TiO<sub>2</sub> in working fluid (distilled water). They observed an enhancement in thermal conductivity in working fluid by increasing the concentration of nanoparticles. The optimum volume concentration is 0.5 vol%, at this concentration, and the thermal efficiency of the system increased by 44.85%. Li and Zhai [16] experimentally and numerically studied the performance of evacuated tube solar collector with composite PCM (expanded graphite by 3 mass% as additives in 97 mass% erythritol) as thermal energy storage. They found that thermal conductivity of erythritol was enhanced by 241.4% and average storage efficiency increased by 40.17% by mixing of 3 mass% of expanded graphite as an additive in erythritol. Daghigh and Shafieian [17] fabricated and tested evacuated tube collector-based solar drying system. They found that thermal performance of system is highly influenced by variation of mass flow rate. They observed the highest outlet temperature (45.5 °C) from dryer at a volume flow rate of 0.0328 m<sup>3</sup>/s. Pandey et al. [18] carried out a theoretical study of single-stage aqua-ammonia absorption refrigeration system driven by different solar collectors. They found that solar coefficient of performance, optimum cost and second-law efficiency of absorption system driven by evacuated tube solar collector is averagely lower by 11, 30 and 0.5% than system driven by parabolic trough collector at different ambient temperatures. Annual efficiency of a new version ETC system with tracking mechanism was studied by Teles et al. [19]. They found that minimum and maximum daily efficiencies of proposed system were 42% and 73%, respectively. In this experimental work, the annual efficiency of a new version ETC with tracking mechanism was found to be 61.5%. They observed that during a year, this collector can absorb thermal energy of about 961.3 kWh m<sup>-2</sup>. Abd-Elhady et al. [20] increased heat pipe condenser temperature and heating efficiency of ETC by the insertion of thermal oil in evacuated tubes and replaced heat pipe finned surface with foamed copper. It is reported that thermal oil not only improved the heat transfer rate but also acted a thermal storage media. Experimental investigation for the impact of graphene oxide nanoparticles in steam production by Ghafurian et al. [21]. The experimental outcomes revealed that the highest efficiency of the system was found to be 78.9%, while in

the case of water the corresponding value was observed to be 54%. The results of the study showed that evaporation flux rate increases when light intensity increases. Manoj et al. [22] worked on paraffin wax as a PCM and nanocomposite of paraffin wax with  $\text{SiO}_2$  nanoparticles. The experiment was performed to improve the efficiency of evacuated tube solar water heating system. They observed an improvement in the heat storage capacity of ETC-based solar water heater system by integrating with PCM and with nanocomposite PCM.

The novelty of the research work lies in the design, better performance and evaluation of the HP-ETC system for the particular climatic conditions with techno-economic evaluation. As can be seen from the above brief literature review, very few experimental studies are available on HP-ETC-based solar water heating system and its techno-economic analysis for composite climate of India. No one performed experimental study for this technology under composite climate of India. Also, the designed heat pipe-based solar water heating system has been studied and optimized for different mass flow rates, viz., 20, 30, 40, 50 and 60 L per hour (LPH) in respect of energy and exergy analyses. This is very useful to achieve the low-to-medium temperature range applications through different flow rates, and same system can be used for residential and commercial applications such as water heating, swimming pool heating and solar cooking. Three different methods of economic analysis, namely annual cost, life-cycle savings and payback period, have been used for the comprehensive evaluation of the designed system for the better techno-economic analysis.

## Experimental

The experimental investigation of the present study was carried out in outdoor condition of Shri Mata Vaishno Devi University, Katra, India (longitude =  $32.9417^\circ\text{N}$ , latitude =  $74.9541^\circ\text{E}$ ), faced toward the south direction and tilted by an angle of  $45^\circ$ . One of the evacuated tubes of solar collector comprised of two concentric borosilicate glass tubes with vacuum in the order of  $5 \times 10^{-2}$  Pa in the annulus space between outer transparent glass tubes and selectively coated inner absorber tube. The outer glass tube is transparent for least reflection, and absorber tube is coated with black coating (Al-N/Al) for better absorption of sun radiation.

The evacuated tubes equipped with heat pipe along with aluminum fins increase the heat transfer rate and a spring clips set that clamps the heat pipe with the absorber tube. The solar collector consists of such types of 20 sets of tubes which are further connected to the manifold.

When sunlight in the form of solar radiation hits the surface of the absorber tube, absorbed heat is transfer to

pins of heat pipe. The moment when heat is transfer from fins to heating zone (evaporator section) of heat pipe, the low-boiling heat transfer fluid starts to vaporize and move to the cooling zone (condenser section). Finally, transfer of heat takes place from the condenser section to water flowing in the manifold. The specification of components and instrumentation used in solar water heating system is given in Tables 1 and 2. The experimental investigation was carried out with six different mass flow rates of water.

The water was supplied by a 20-W water pump from cold-water tank, and flow rate was controlled by control valve. The mass flow rate of water was measured by needle valve rotameter. The water coming out from the collector was collected in the insulated tank for further use. The inlet temperature, outlet temperature, ambient temperature and tank temperatures were recorded after every 1-min time interval. The complete layout of experimental setup is shown in Fig. 1.

The instrument used for recording and measurement of temperature was Masibus 85xx + data logger with temperature sensors. The global solar radiation data for every 1-min time interval were gathered from Solar Radiation Resource Assessment (SRRRA) station, Katra.

## Thermodynamic analysis of evacuated tube collector

In this section, thermodynamic analysis of ETC system is presented. The experimental results have been investigated by a set of equations under the following assumptions:

- All equations were developed under the steady-state test method for thermodynamic study of ETC system.
- The specific heat of working fluid was assumed to be constant.
- It was considered that effect of kinetic and potential energy is negligible.
- The difference in pressure across the manifold was considered to be zero.
- The heat transfer direction to the system was assumed to be positive.

## Energy analysis

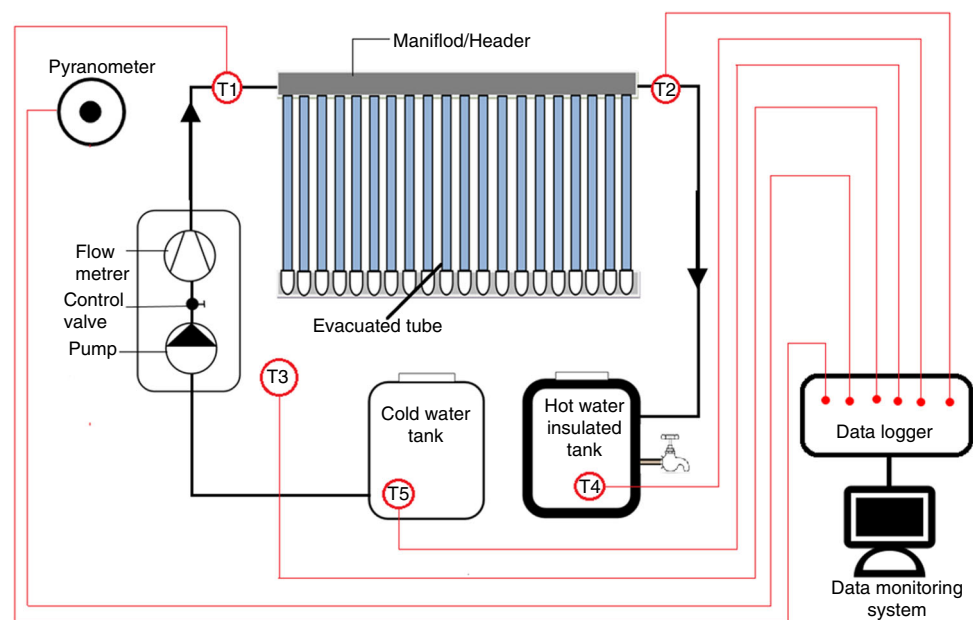
Energy analysis is an essential part to obtain the actual performance of any thermal system. There are two methods to calculate the efficiency of thermal collectors: transient test method and steady-state test method. The boundary conditions for input parameters such as inlet temperature, ambient temperature and solar radiation incident at particular site remain constant during the latter method; and for the former method, the boundary conditions of

**Table 1** Design parameters of HP-ETC solar water heater

Type	Parameter	Value/material
Solar collector	Aperture area	1.504 m <sup>2</sup>
	No. of evacuated tubes	20
Evacuated tube	Vacuum tube material	Borosilicate glass
	Evacuated tubes types	All glass evacuated tubes
	Evacuated tubes thickness	2.2 mm
	Coating of absorber	Three target ALN/SS/Cu
	Absorber tube length	1700 mm
	Outer diameter of absorber tube	47 mm
	Outer diameter of outer tube	58 mm
Heat pipe	Material of heat pipe	Copper
	Thickness of copper pipe	0.7 mm
	Diameter of condensing section	14 mm
	Length of condenser section	63.5 mm
	Length of evaporator section	1600 mm
	Diameter of evaporator section	9.52 mm
	Working fluid in heat pipe	Water

**Table 2** Specification of instrumentation

Parameter	Instrument	Accuracy	Full scale
Temperature	RTD temperature sensors	± 0.5 °C	– 50 to 600 °C
Mass flow rate	Rotameter	± 0.5%	4–100 LPH
Pumping of working fluid	Pump	–	0–500 LPH

**Fig. 1** Schematic diagram of the experimental setup

parameters are free to change. The thermal performance test of solar collector system was performed under steady-state conditions. The energy incident on solar collector can be expressed as [23, 24]:

$$\dot{Q}_r = I_s A_{ab} N_{hp}, \quad (1)$$

where  $\dot{Q}_r$  (J s<sup>-1</sup>), the rate at which energy is incident on solar collector;  $A_{ab}$  (m<sup>2</sup>), absorber area of single evacuated tube;  $I_s$  (W m<sup>-2</sup>), solar radiation intensity at specific site;  $N_{hp}$  number of heat pipes.

The useful energy gained by solar collector may be expressed as [25]:

$$\dot{Q}_u = \gamma_{go}\gamma_{gi}\beta_{ab}I_sA_{ab}N_{hp}, \tag{2}$$

where  $\gamma_{go}, \gamma_{gi}$ , transmittance of outer and inner tube;  $\beta_{ab}$ , absorptivity of absorber tube. The useful energy collected by working fluid from solar collector is given by [26]:

$$\dot{Q}_{uf} = \dot{m}_w C_{Pw} \Delta T_w, \tag{3}$$

where  $\dot{Q}_{uf}$  ( $J s^{-1}$ ), the rate of useful energy gained by water;  $C_{Pw}$  ( $J kg^{-1} K^{-1}$ ), specific heat of water at constant pressure;  $\dot{m}_w$  ( $kg s^{-1}$ ), mass flow rate of water;  $\Delta T_w$  (K), temperature difference of water across the collector.

The instantaneous thermal efficiency of solar collector is expressed as the ratio of useful energy gained by fluid from solar collector to total energy incident on solar collector which can be written as [27, 28]:

$$\eta_{th} = \frac{\dot{Q}_{uf}}{\dot{Q}_r}, \tag{4}$$

where  $\eta_{th}$ , thermal efficiency of system.

### Exergy analysis

Energy analysis of solar collector gives an idea about an amount of conservation of energy. However, energy analysis provides no information that how much performance of system is degraded. Hence, exergy analysis is a tool through which design, optimization and evaluation of the performance of energy systems can be done. It is based on second law of thermodynamics. The equation for exergy balance undergoing steady-state process for control volume can be expressed as [29]:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_d = \sum \dot{E}x_{out} \tag{5}$$

or

$$\dot{E}x_d = \pm \sum \dot{W} - \sum (\dot{E}x_{massout}) + \sum (\dot{E}x_{massin}) - \left[ \left( \sum \dot{Q} \left( 1 - \frac{T_{amb}}{T} \right) \right)_{out} - \left( \sum \dot{Q} \left( 1 - \frac{T_{amb}}{T} \right) \right)_{in} \right]$$

Exergy received by solar collector can be written as [25]:

$$\dot{E}x_c = Q_r \left[ 1 + \frac{1}{3} \left( \frac{T_{amb}}{T_{sr}} \right)^4 - \frac{4}{3} \left( \frac{T_{amb}}{T_{sr}} \right) \right], \tag{6}$$

where  $\dot{E}x_c$  (W), exergy received by solar collector;  $T_{sr}$  (K); source temperature, i.e., temperature of sun;  $T_{amb}$  (K), ambient or surrounding temperature of system. Exergy received by working fluid (Water) can be evaluated as [29]:

$$\dot{E}x_{uf} = T_{amb} \dot{m}_f \left[ \frac{(\psi_{fo} - \psi_{fi})}{T_{amb}} - (s_{fo} - s_{fi}) \right], \tag{7}$$

where  $\dot{E}x_{uf}$  (W), useful exergy absorbed by working fluid (water);  $\psi_{fi}$  ( $J kg^{-1}$ ),  $s_{fi}$  ( $J kg^{-1} K^{-1}$ ), enthalpy and

entropy of water at inlet of collector;  $\psi_{fo}$  ( $J kg^{-1}$ ),  $s_{fo}$  ( $J kg^{-1} K^{-1}$ ), enthalpy and entropy of water at outlet of collector. The difference in enthalpy and entropy of working fluid flowing through manifold can be given as [30]:

$$\psi_{fo} - \psi_{fi} = C_{Pw} \Delta T_w \tag{8}$$

and

$$s_{fo} - s_{fi} = C_{Pw} \ln \frac{T_{wo}}{T_{wi}}, \tag{9}$$

where  $T_{wo}$  (K), outlet temperature of water;  $T_{wi}$  (K), inlet temperature of water. Thus, exergy or second-law efficiency can be given as the ratio of useful exergy to exergy incident on collector [31, 32].

$$\eta_{ex} = \frac{\dot{E}x_{uf}}{\dot{E}x_c} = \frac{T_{amb} \dot{m}_f \left[ \frac{(\psi_{fo} - \psi_{fi})}{T_{amb}} - (s_{fo} - s_{fi}) \right]}{Q_r \left( \frac{T_{sr} - T_{amb}}{T_{sr}} \right)} \tag{10}$$

### Techno-economical analysis

As per the survey conducted in residential buildings of Indian composite climate of Jammu, the demand for hot water for different household applications such as cleaning, washing, bathing, cooking is fulfilled by either gas geyser (GG) or electric geyser (EG). It is found that less than 3% of residential buildings in India use solar water heater for household applications. Authors performed techno-economic analysis of the conventional system (GG and EG) and HP-ETC solar water heater. Based on the Indian market survey, Table 3 enlists the comparison of features of GG, EG and HP-ETC solar water heater.

In this section, economic analysis of HP-ETC solar water heater, GG and EG is performed. Besides this, optimal life of operation of each of the systems and when each of the systems is more economical than other system is also reported. The specifications of these three systems are given in Table 4.

The economic analysis of a system is evaluated by three methods. The first one is annual cost method (ACM) [29], in which water heating cost per liter by GG, EG and HP-ETC solar water heater is compared. As the cost of electricity and LPG varies over the entire life of systems (GG and EG), this method does not completely capture the comparison of economics by heating through considered methods. Thus, for calculating the economic benefits of HP-ETC solar water heater, it is necessary to evaluate the saving of HP-ETC solar water heater per day in the base year, namely second method [30]. The people will not be interested to procure the system if payback period is long

**Table 3** Comparison of conventional- and solar energy-based water heating system

S. nos.	Feature	EG	GG	HP-ETC solar water heater
1	Initial capital cost	Little expensive: cost INR 10,000–12,000	Economical: cost INR 4000–6000	Expensive: Cost INR 25,000–30,000
2	Safety	Safe	Completely unsafe: strictly not recommended on the basis of safety	Very safe
3	Space requirement	Wall mounting space is enough	Require additional place to keep the LPG cylinder and proper ventilation	Space required at rooftop
4	Life span range	7–10 years	4–6 years	8–10 years
5	Installation	Easy	Difficult as you need to connect the LPG and should arrange outlet for fumes	Easy
6	Technology	Electricity	Gas burning	Solar energy
7	Pollution	Pollution due to the production by coal	May release carbon monoxide which needs to be vented out carefully	No pollution
8	Warranty	At least 2 years	1–2 years	1–2 years
9	Time required to heat the water	Little more	Faster	Little more

**Table 4** Specification of HP-ETC solar water heater, EG and GG

System	Parameters	Value
HP-ETC solar water heater	Initial capital investment after subsidy	INR 21,000*
	Life	10 years
	Yearly maintenance cost	10% of $C_Y$
EG	Initial cost	INR 10,000*
	Efficiency of electric coil	80%
	Life span	10 years
	Yearly maintenance cost	5% of $C_Y$
GG	Initial cost	INR 4800*
	Life span	6 years
	Efficiency of gas geyser	60%
	Yearly maintenance cost	10% of $C_Y$

\*US\$1 ~ INR 70

even though significant long-term savings are possible [31]. Hence, payback period method which is the third method is also very important to discuss in this section [32].

**Annual cost method**

Annual cost method is adopted because systems under consideration for comparison have different lifetimes. In general, by taking time value of money concept into consideration, the system’s yearly cost ( $C_Y$ ) may be written as [33]:

$$C_Y = C_{YF} - F_{SF} * V_S + C_I * F_{CR} + C_{YM}, \tag{11}$$

where  $C_{YF}$ , yearly cost of fuel [INR];  $V_S$ , system salvage value at the end of its operation life;  $C_I$ , system initial cost [INR];  $C_{YM}$ , yearly cost for maintenance [INR year<sup>-1</sup>].

The terms  $F_{SF}$  and  $F_{CR}$  are the sinking fund factor and capital recovery factor, respectively. These two terms can be expressed as [33]:

$$F_{SF} = \frac{j}{[(j + 1)^k - 1]} \tag{12}$$

$$F_{CR} = \frac{(j + 1)^k * j}{[(j + 1)^k - 1]}, \tag{13}$$

where  $j$ , interest rate [INR];  $k$ , operational life of system.

The yearly cost of fuel for HP-ETC solar water heater is the cost of electrical energy consumed for water heating

when solar radiation is not available where the yearly fuel cost for GG and EG is the cost of electricity and LPG gas used throughout the year to meet hot water requirement to an average family at desired temperature. Before calculation for annual fuel cost, the daily hot water requirement for an average family has to be evaluated. The energy required to meet daily hot water requirement for an average family can be expressed by the following equation:

$$E_{DHR} = C_w * (T_{wo} - T_{wi}) * A_{DHP} * A_{FS}, \tag{14}$$

where  $A_{DHP}$ , average hot water requirement per day per person [L person<sup>-1</sup> day<sup>-1</sup>];  $A_{FS}$ , average size of family.

Therefore, yearly fuel cost of HP-ETC solar water heater and EG can be evaluated according to following equation:

$$C_{YF} = \frac{n * E_{DHR} * C_{el}}{\eta_{el}}, \tag{15}$$

where  $n$ , number of days electricity used to meet the hot water requirement [days];  $C_{el}$ , cost of electricity;  $\eta_{el}$ , efficiency of electrical coil.

The yearly fuel cost for GG can be evaluated according to the following equation

$$C_{YF} = \frac{C_{LPG} * E_{DHR} * 365}{CV_{LPG} * \eta_{GG}}, \tag{16}$$

where  $C_{LPG}$ , cost of LPG;  $CV_{LPG}$ , calorific value of LPG [kWh kg<sup>-1</sup>];  $\eta_{GG}$ , efficiency of GG.

The system salvage value changes with operating time ( $k$ ) of the system. Thus, by considering that depreciation of the system with time is linear in nature, the salvage value can be written as:

$$V_S(k) = k * C_I \left[ \frac{1}{k} - \frac{1}{k_{max}} \right], \tag{17}$$

where  $k_{max}$ , time after which system is completely discarded [Year]

In order to make the analysis simpler, as per market survey it is found that yearly maintenance cost for HP-ETC solar water heater and EG is 10% of yearly capital cost, whereas in the case of GG it is 5% of the yearly capital cost. As in the introduction stage, both systems are under guarantee for 3 years and very little maintenance cost is incurred.

### Life-cycle savings

In the life-cycle saving method, firstly base year saving per day for solar water heater is determined; then, the present worth of yearly savings during the life span of system is evaluated.

### Saving per day

The saving per day by using of HP-ETC solar water heater can be computed firstly by difference in cost of production of hot water per liter by conventional system (EG and GG) and HP-ETC solar water heater then this saving is multiply by hot water requirement in a day

$$S_l = C_{cs,l} - C_{SWH,l}, \tag{18}$$

where  $S_l$ , savings in hot water production per liter [INR];  $C_{cs,l}$ , cost of production of hot water per liter by conventional systems (EG or GG) [INR];  $C_{SWH,l}$ , cost of production of hot water per liter by HP-ETC solar water heater [INR], where

$$C_{cs,l} = \frac{C_{Y,cs}}{P_{cs,y}} \tag{19}$$

$$C_{SWH,l} = \frac{C_{Y,SWH}}{P_{SWH,y}} \tag{20}$$

$$S_{day} = S_l A_{DHP} A_{FS}, \tag{21}$$

where  $C_{Y,cs}$  and  $C_{Y,SWH}$  annual cost of production of hot water [INR], respectively;  $P_{cs,y}$  and  $P_{SWH,y}$  hot water production per year by conventional and HP-ETC solar water heater system, respectively [L];  $S_{day}$  savings in hot water production per day [INR].

### Present worth of yearly savings

The yearly saving for hot water production at desired temperature in the  $k$ th year can be determined by Eq. (22). The present worth of yearly savings in the  $i$ th year can be evaluated through Eq. (23) [34].

$$S_i = S_{day} D_n (1 + f)^{i-1}, \tag{22}$$

where  $S_i$ , yearly benefits for HP-ETC solar water heater in the  $i$ th year [INR];  $D_n$ , number of working days per year of HP-ETC solar water heater;  $f$ , inflation rate

$$P_i = M_{pi} S_i, \tag{23}$$

where  $P_i$ , present worth of yearly benefit in  $i$ th year [INR];  $M_{pi}$  factor of present worth for  $i$ th year.

For  $i$ th year, the factor of the present worth can be written as

$$M_{pi} = \frac{1}{(1 + j)^i} \tag{24}$$

The life-cycle saving is calculated by summing the annual savings of the present worth over the life of the considered systems.

### Payback period

Payback period is the length of time required for an investment to recover its initial capital cost in terms of savings. To evaluate the economic feasibility of HP-ETC solar water heater in India, the payback period can be calculated by following equation [34]

$$PB_N = \frac{\ln\left[1 - \frac{C_i}{S_1}(j - f)\right]}{\ln\left(\frac{1+f}{1+j}\right)}, \tag{25}$$

where  $PB_N$ , payback period for  $N$  years;  $S_1$ , benefit during first year (INR)

### Results and discussion

The experimental investigation was carried out in the typical composite climate zone of India. The investigation was done in the month of March with different mass flow rates, viz., 20, 30, 40, 50 and 60 LPH. On the basis of collected data, thermodynamic and techno-economic analyses have been performed. The calculations have been carried out by a set of Eqs. (1–25) and graphs are plotted among selected performance parameters. In this section, variation of ambient temperature, inlet temperature, outlet temperature, efficiencies (energy and exergy) and solar radiation with time has been discussed for considered mass flow rates. Moreover, the comparison of energy and exergy efficiency for different flow rates has been presented and discussed. In this section, results obtained from techno-economic analysis are also discussed.

Figure 2a, b depicts the variation of efficiencies, solar intensity, ambient temperature and inlet water temperature with respect to time for 20 LPH.

Figure 2a shows that solar intensity reached its peak value of  $920 \text{ W m}^{-2}$  at 13:00 P.M. For this specific day, extreme fluctuations were observed in the solar radiation. As shown in Fig. 2a, since morning (10:00 to 11:30 A. M.) solar radiation increased with very less fluctuations. After that, very large fluctuations in solar intensity (from 11:30 A.M. to 16:30 P.M.) were observed. Due to this, variations in efficiencies (energy and exergy) were also found. It is found that instantaneous energy and exergy efficiencies were in the range of 2–10% and 55–90%, respectively. The variation in ambient temperature and inlet water temperature of the same day was found in the range of 26–33 °C and 28–38 °C, respectively.

For the water mass flow rate of 30 LPH, Fig. 3a illustrates the variation in efficiencies and Fig. 3b gives the variation in solar intensity, ambient temperature and inlet water temperature versus time. The experiment was started at 10:00 A.M. when solar intensity reached  $1100 \text{ W m}^{-2}$ . The experimental setup with mass flow rate of 30 LPH attained its highest instantaneous energy and exergy of 83% and 6.68%, respectively. On this day, the intensity of solar radiation was bright; however, the inlet water temperature was observed with fluctuations due to a high variation in the wind velocity. The inlet water temperature and ambient temperatures were varied in the range of 26–32 °C and 25–29 °C, respectively.

The variation in efficiencies and input parameters (solar radiation, inlet temperature and ambient temperature) is shown in Fig. 4a, b, respectively, for a mass flow rate of 40 LPH. It can be seen that solar radiation attained its peak value of  $1012 \text{ W m}^{-2}$  at 12:48 P.M. The intensity of solar radiation was found with less fluctuations from 11:00 A.M. to 13:30 P.M. But after 13:30 P.M., it was decreased at a very fast rate. Energy and exergy efficiencies have been

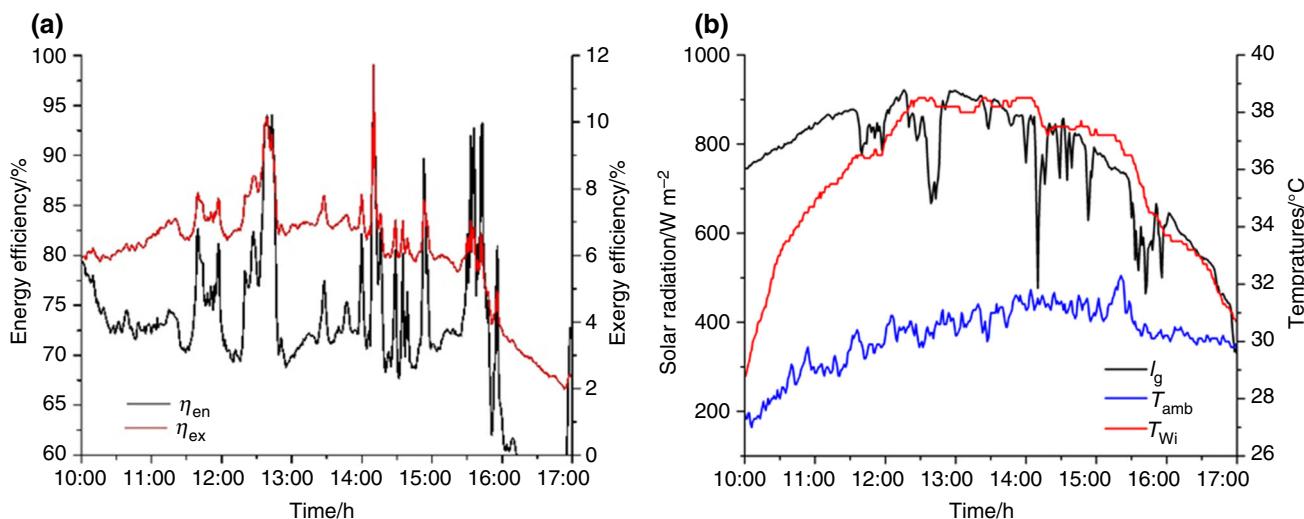


Fig. 2 Variation with time for a efficiencies and b solar radiation and temperatures for 20 LPH



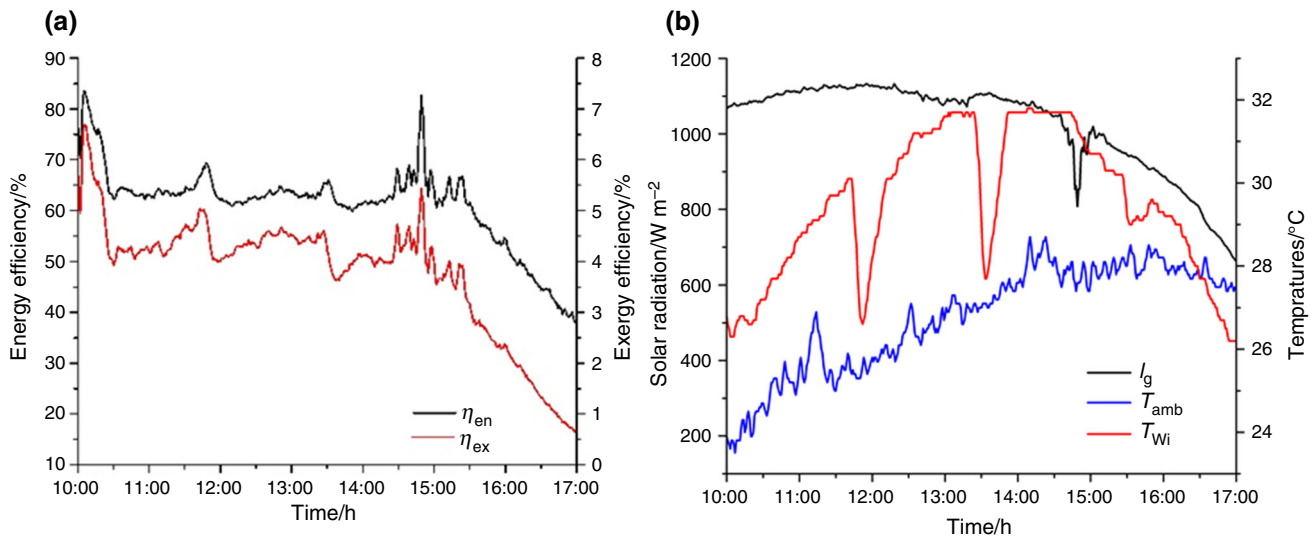


Fig. 3 Variation with time for a efficiencies and b solar radiation and temperatures for 30 LPH

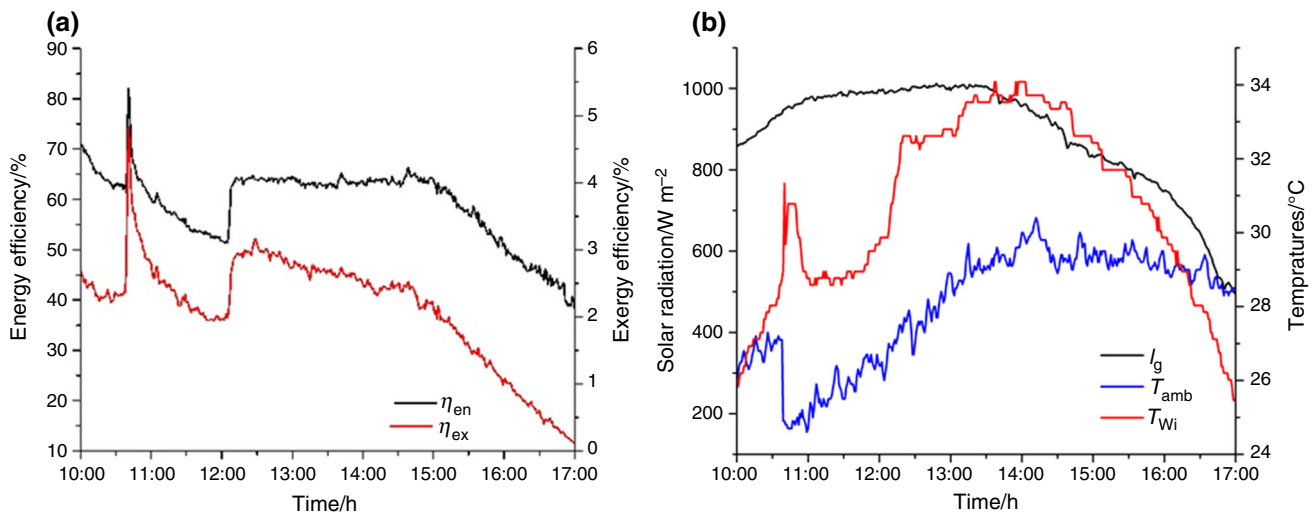


Fig. 4 Variation with time for a efficiencies and b solar radiation and temperatures for 40 LPH

calculated for 40 LPH, and these were found in the range of 38–82% and 0.9–5%, respectively.

The variation of efficiencies for 50 and 60 LPH water mass flow rate is presented in Figs. 5a, 6a, respectively, while for corresponding flow rates variation of input parameters (solar radiation, inlet water temperature and ambient temperature) is shown in Figs. 5b, 6b, respectively. It is found that for 50 and 60 LPH mass flow rates, solar radiation was extremely fluctuating in nature between 15:00 P.M. to 17:00 P.M. and 11:30 A.M. to 13:30 P.M., respectively. The reason behind this was diverse fluctuations in solar radiation for the said periods.

Figures 5b and 6b show that the ambient temperature was varied in the range of 19–26 °C and 23–27 °C for 50 and 60 LPH mass flow rates, respectively, whereas for

corresponding flow rates the range of variation in the inlet temperature was 22–29 °C and 25–29 °C, respectively.

Figure 7 illustrates the variation of outlet temperature with time for considered flow rates (20, 30, 40, 50 and 60 LPH). It is found that the outlet temperature increased with time then decreased slowly during evening hours. Due to the intermittent nature of solar intensity and fluctuations in inlet water and ambient temperatures, at some points the variation in outlet temperatures also has been observed.

The results reveal that the outlet temperature is highly influenced by the mass flow rate of working fluid and proportional to solar intensity. The averaged highest and lowest outlet temperatures from collector were found to be 76.4 °C and 39 °C at mass flow rates of 20 and 60 LPH, respectively.

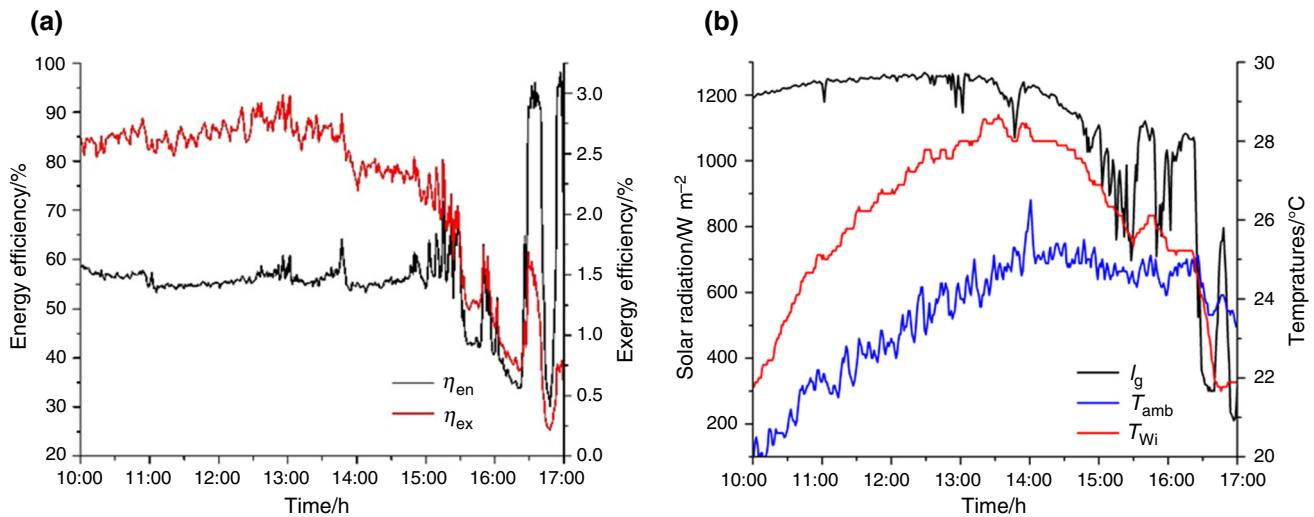


Fig. 5 Variation with time for **a** efficiencies and **b** solar radiation and temperatures for 50 LPH

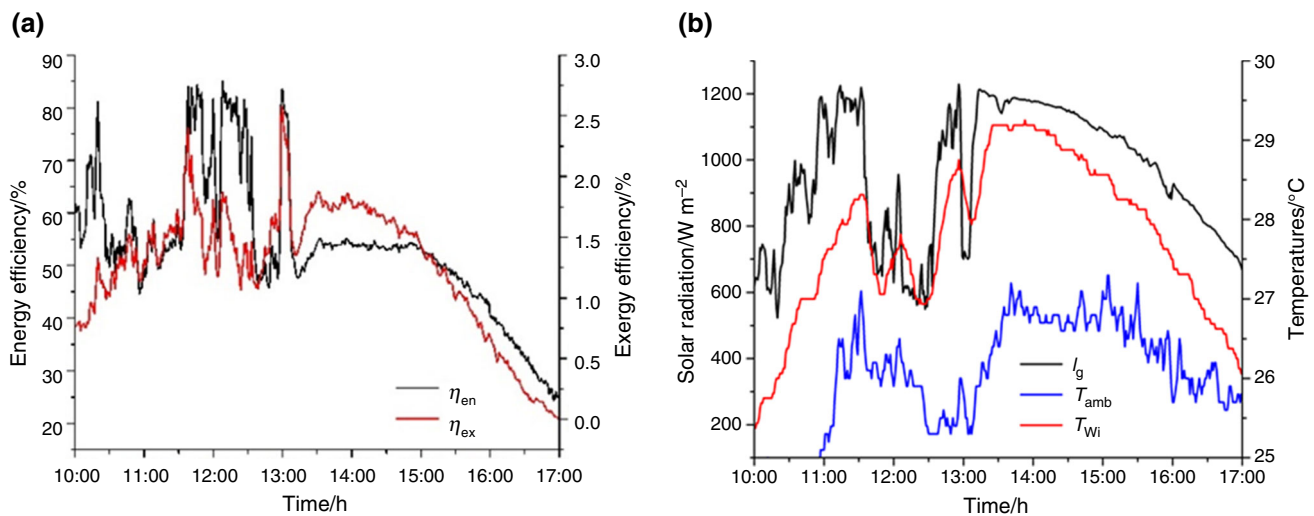


Fig. 6 Variation with time for **a** efficiencies and **b** solar radiation and temperatures for 60 LPH

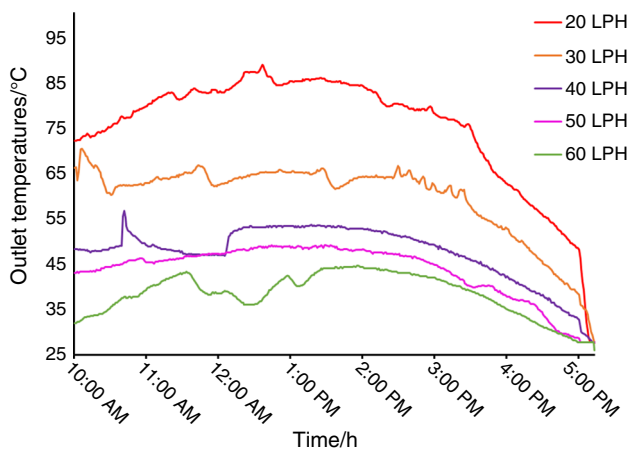
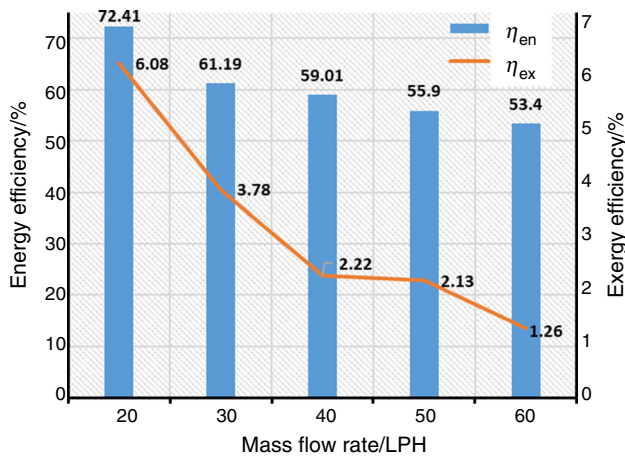


Fig. 7 Variation of outlet temperature versus time for different mass flow rates

The effect of mass flow rate on energy and exergy efficiencies is illustrated by Fig. 8.

It is observed that energy and exergy efficiencies have attained its highest values of 72.41% and 6.08%, respectively, for 20 LPH mass flow rate. The second highest value of energy and exergy efficiencies was found to be 61.19% and 3.78% for 30 LPH mass flow rate. The average value of energy efficiency for 40, 50 and 60 LPH was found to be 59.01, 55.9 and 53.4, respectively, and exergy efficiency for the corresponding mass flow rate was 2.22, 2.13, 2.2 and 1.26%, respectively. Thus, thermal efficiencies of HP-ETC solar collector were found to be the best at 20 LPH mass flow rate, i.e., 20 LPH is the optimum mass flow rate for 20 tubes HP-ETC collector. This was due to the fact that thermal losses at this flow rate were minimal compared to other considered flow rates.



**Fig. 8** Comparison of energy and exergy efficiencies for different mass flow rates

The energy efficiency of the system was higher than exergy efficiency; this is due to not considering the losses associated with system during the energy analysis. However, the exergy analysis of a particular system considered all irreversibility/losses associated with the system. Thus, exergy analysis represents quality of energy rather than quantity.

**Techno-economical of solar water heater**

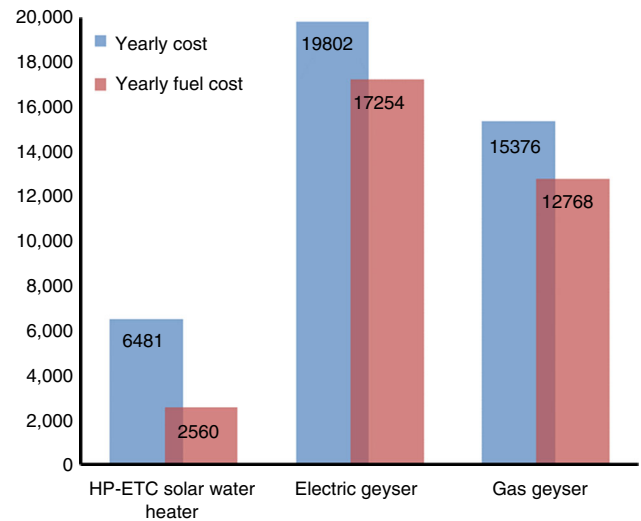
The parameters for economic analysis of conventional (GG and EG) and HP-ETC solar water heater based on situation in India are shown in Table 5. As mentioned, there are three methods through which the economic analysis of systems is performed and these methods are discussed as follows.

**Annualized cost method**

By this method, the yearly cost of conventional (GG and EG) and HP-ETC solar water heater has been calculated. Based on economical parameters (given in Table 5) of Indian market, the economic analysis of the systems has been carried out.

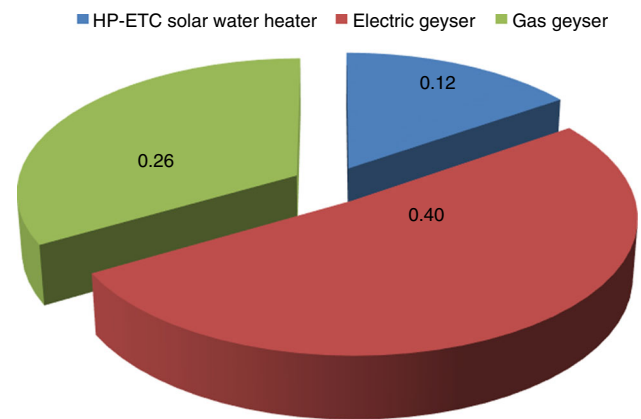
**Table 5** Economical parameters of Indian market

Parameters	Values
Interest rate	9%
Inflation rate	3%
Average daily hot water requirement per person	25 L
Average family size	6
Average daily solar radiation	5.25 kWh m <sup>-2</sup> day <sup>-1</sup>
Cost of electricity per kWh	INR 5.25
Cost of LPG per kg	INR 40
Calorific value of LPG	12.87 kWh kg <sup>-1</sup>



**Fig. 9** Comparison of yearly cost and yearly fuel cost of different systems

The economic analysis of solar water has been performed by considering that the system can easily operate for 300 days in a year in a composite climate zone of country such as India. Figure 9 depicts the comparison of the yearly cost and yearly fuel cost for HP-ETC solar water heater with an auxiliary system, EG and GG. Based on the



**Fig. 10** Comparison of cost of production of hot water per liter by different systems

**Table 6** Economics of HP-ETC solar water heater—present worth of annual saving, annual saving and present worth of cumulative annual saving with respect to EG and GG for each year during the life of HP-ETC solar water heater

Year	Annual saving with respect to electric geyser (INR)	Annual saving with respect to gas geyser (INR)	Present worth of annual saving with respect to electric geyser (INR)	Present worth of annual saving with respect to gas geyser (INR)	Present worth of commutative saving with respect to electric geyser (INR)	Present worth of commutative saving with respect to gas geyser (INR)
1	11,974	5987	10,985	5493	10985	5493
2	12,333	6167	10,380	5190	21,365	10,683
3	12,703	6352	9809	4905	31,174	15,588
4	13,084	6542	9269	4635	40,443	20,223
5	13,477	6738	8759	4379	49,202	24,602
6	13,881	6940	8277	4138	57,479	28,740
7	14,297	7149	7821	3911	65,300	32,651
8	14,726	7363	7391	3695	72,691	36,346
9	15,168	7584	6984	3492	79,675	39,838
10	15,623	7812	6599	3300	86,274	43,138

specifications of different systems and economical parameters, the highest values of yearly capital cost and yearly fuel cost were calculated to be INR 19802 and 17254 for EG. On the other hand, compared to other conventional water heaters (EG and GG) the values of yearly capital cost (INR 6481) and yearly fuel cost (INR 2560) were the lowest for HP-ETC solar water heater.

Similar to yearly capital and yearly fuel cost, also the cost of production of hot water per liter by different systems has been evaluated. It is observed from Fig. 10 that the cost of hot water per liter by HP-ETC solar water heater, EG and GG is INR 0.12, 0.40 and 0.26, respectively.

### Life-cycle savings

The present worth of annual savings, annual savings and cumulative present worth of annual savings with respect to EG and GG for each year of the life of HP-ETC solar water heater is shown in Table 6. The approximate value of cumulative present worth of HP-ETC solar water heater was evaluated to be 86 and 43 thousand rupees with respect to EG and GG, respectively. The subsidized initial cost of HP-ETC solar water heater is INR 21000. Therefore, by investing INR 21000 in a HP-ETC solar water heater, 86 and 43 thousand rupees can be saved in comparison with EG and GG. The evaluation was done by considering that life of solar water heater is 10 years. However, savings can be extended after the life of the HP-ETC solar water heater.

### Payback period

The payback period is the time span required for an investment to recover its initial outlay in terms of savings. From Eq. (25), the payback period of HP-ETC solar water

heater has been calculated. The initial capital investment on HP-ETC solar water heater of INR 21000 can be recovered in 4 years of operation. Therefore, HP-ETC solar water heater can supply the hot water to a desired temperature free of cost after 4 years.

### Conclusions

In this communication, heat pipe evacuated tube solar water heater is designed and constructed according to a family with an average size of six persons. The experimental setup was tested under Indian composite climate of Jammu for five different mass flow rates of water. Based on thermodynamic and techno-economic analysis, the following conclusions are drawn. It is discovered that evacuated technology has got excellent prospects to be used as green technology and should be addressed meticulously. The conclusions of present study are given as follows:

1. The maximum average energy and exergy efficiencies of ETC system were 72% and 5.2%, respectively, for 20 LPH, while minimal values of respective efficiencies were 55% and 1.25% for 60 LPH among the considered mass flow rates.
2. The maximum and minimum average outlet temperatures from collector were found to be 76.4 and 45 °C for 20 and 60 LPH water mass flow rates, respectively.
3. The cost of hot water production at desired temperature was found to be INR 0.12 per liter, whereas by electric geyser and gas geyser was INR 0.40 and 0.26, respectively.
4. The payback period of heat pipe ETC solar water heater system was estimated to be 4 years.

## References

- Shukla R, Sumathy K. Design approach of a density-driven solar water heater system. *Therm Anal Calorim.* 2019;136:113–20.
- Energy Climate and Change World Energy Outlook Special Report: Special Report on Energy and Climate Change. 2015. <https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf>. Accessed 26 Jan 2019.
- da Graça Carvalho M. EU energy and climate change strategy. *Energy.* 2012;40:19–22.
- Solar water heaters in India: market assessment studies and surveys for different sectors and demand segments submitted to Project Management Unit Global Solar Water Heating Project Ministry of New and Renewable Energy. 2010. [https://mnre.gov.in/sites/default/files/uploads/greentech\\_SWH\\_MarketAssessment\\_report.pdf](https://mnre.gov.in/sites/default/files/uploads/greentech_SWH_MarketAssessment_report.pdf). Accessed 26 Jan 2019.
- Hasanabadi S, Sadrameli SM, Soheili H, Moharrami H, Heyhat MM. A cost-effective form-stable PCM composite with modified paraffin and expanded perlite for thermal energy storage in concrete. *Therm Anal Calorim.* 2019;136:1201–16.
- Nikoofard S, Ismet Ugursal V, Beausoleil-Morrison I. Technoeconomic assessment of the impact of window improvements on the heating and cooling energy requirement and greenhouse gas emissions of the Canadian housing stock. *Energy Eng.* 2014;140:1–8.
- Nikoofard S, Ismet Ugursal V, Beausoleil-Morrison I. An investigation of the technoeconomic feasibility of solar domestic hot water heating for the Canadian housing stock. *Solar Energy.* 2014;101:308–20.
- Chopra K, Tyagi VV, Pandey AK, Sari A. Global advancement on experimental and thermal analysis of evacuated tube collector with and without heat pipe systems and possible applications. *Appl Energy.* 2018;228:351–89.
- Mauthner F, Weiss W, Spörk-Dür M. A solar heat worldwide, Markets and Contribution to the Energy Supply 2014. <https://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2016.pdf>.
- Hossain MS, Saidur R, Fayaz H, Rahim NA, Islam MR, Ahamed JU, Rahman MM. Review on solar water heater collector and thermal energy performance of circulating pipe. *Renew Sustain Energy Rev.* 2011;15:3801–12.
- Siva Kumar S, Mohan Kumar K, Sanjeev Kumar SR. Design of evacuated tube solar collector with heat pipe. *Mater Today.* 2017;4:12641–6.
- Sokhansefat T, Kasaeian A, Rahmani K, Heidari AH, Aghakhani F, Mahian O. Thermoeconomic and environmental analysis of solar flat plate and evacuated tube collectors in cold climatic conditions. *Renew Energy.* 2018;115:501–8.
- Abokersh MH, El-Morsi M, Sharaf O, Abdelrahman W. On-demand operation of a compact solar water heater based on U-pipe evacuated tube solar collector combined with phase change material. *Solar Energy.* 2017;155:1130–47.
- Ghaderian J, Sidik NAC, Kasaeian A, Ghaderian S, Okhovat A, Pakzadeh A, Samion S, Yahya WJ. Performance of copper oxide/distilled water nanofluid in evacuated tube solar collector (ETSC) water heater with internal coil under thermosyphon system circulations. *Appl Therm Eng.* 2017;121:520–36.
- Gan YY, Ong HC, Ling TC, Zulkifli NWM, Wang C-T, Yang Y-C. Thermal conductivity optimization and entropy generation analysis of titanium dioxide nanofluid in evacuated tube solar collector. *Appl Therm Eng.* 2018;145:155–64.
- Li B, Zhai X. Experimental investigation and theoretical analysis on a mid-temperature solar collector/storage system with composite PCM. *Appl Therm Eng.* 2017;124:34–43.
- Daghigh R, Shafieian A. Energy–exergy analysis of a multipurpose evacuated tube heat pipe solar water heating–drying system. *Exp Therm Fluid Sci.* 2016;78:266–77.
- Pandya B, Kumar V, Matawala V, Patel J. Thermal comparison and multi-objective optimization of single-stage aqua-ammonia absorption cooling system powered by different solar collectors. *Therm Anal Calorim.* 2018;133:1635–48.
- de Paula Ribeiro Teles M, Ismail KAR, Arabkoohsar A. A new version of a low concentration evacuated tube solar collector: optical and thermal investigation. *Solar Energy.* 2019;180:324–39.
- Abd-Elhady MS, Nasreldin M, Elsheikh MN. Improving the performance of evacuated tube heat pipe collectors using oil and foamed metals. *Ain Shams Eng J.* 2017;9:2683–9.
- Ghafurian MM, Niazmand H, Ebrahimnia-Bajestan E, Nik HE. Localized solar heating via graphene oxide nanofluid for direct steam generation. *J Therm Anal Calorim.* 2019;135:1443–9.
- ManojKumar P, Mylsamy K. Experimental investigation of solar water heater integrated with a nanocomposite phase change material. *J Therm Anal Calorim.* 2019;136:121–32.
- Michael Joseph Stalin P, Arjunan TV, Matheswaran MM, Sadanandam N. Experimental and theoretical investigation on the effects of lower concentration CeO<sub>2</sub>/water nanofluid in flat-plate solar collector. *Therm Anal Calorim.* 2019;135:1–16.
- Tyagi VV, Pandey AK, Kothari R, Tyagi SK. Thermodynamics and performance evaluation of encapsulated PCM-based energy storage systems for heating application in building. *Therm Anal Calorim.* 2014;115:915–24.
- Daghigh R, Shafieian A. Theoretical and experimental analysis of thermal performance of a solar water heating system with evacuated tube heat pipe collector. *Appl Therm Eng.* 2016;103:1219–27.
- Hamdan MO, Al-Omari S-AB, Oweimer AS. Experimental study of vortex tube energy separation under different tube design. *Exper Therm Fluid Sci.* 2018;91:306–11.
- Ayompe LM, Duffy A, McKeever M, Conlon M, McCormack SJ. Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. *Energy.* 2011;36:3370–8.
- Garg K, Khullar V, Das SK, Tyagi H. Parametric study of the energy efficiency of the HDH desalination unit integrated with nanofluid-based solar collector. *Therm Anal Calorim.* 2018;135:1465–78.
- Esfahani MR, Languri EM. Exergy analysis of a shell-and-tube heat exchanger using graphene oxide nanofluids. *Exper Therm Fluid Sci.* 2017;83:100–6.
- Pandey AK, Tyagi VV, Rahim NA, Kaushik SC, Tyagi SK. Thermal performance evaluation of direct flow solar water heating system using exergetic approach. *Therm Anal Calorim.* 2015;121:1365–73.
- Bahremand D, Ameri M. Energy and exergy analysis of different solar air collector systems with natural convection. *Renew Energy.* 2015;74:357–68.
- Gill J, Singh J. Energetic and exergetic performance analysis of the vapor compression refrigeration system using adaptive neuro-fuzzy inference system approach. *Exp Therm Fluid Sci.* 2017;88:246–60.
- Baneshi M, Bahreini SA. Impacts of hot water consumption pattern on optimum sizing and techno-economic aspects of residential hybrid solar water heating systems. *Sustain Energy Technol Assess.* 2018;30:139–49.
- Sreekumar A. Techno-economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables. *Energy Convers Manag.* 2010;51:2230–8.

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