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Energy, Exergy, Economic and Enviroeconomic Analysis of an Eco-Friendly Solar Still Made of Locally Available Materials

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Abstract:

An ecofriendly single slope solar still made of locally available materials has been investigated for its energy, exergy, economic and enviroeconomic performance in the climatic conditions of Rajkiya Engineering College, Azamgarh (latitude 25.75° N, longitude 82.94° E), Uttar Pradesh, India. Solar still is made of wood and east and west side of single slope solar still is made of transparent glass to increase the heat input to solar still. Distillate produced from the solar still per day was found to be 2.26 kg/m^2 at 1 cm depth of brackish water on April 20, 2022. Maximum energy and exergy efficiency was found to be 24.51% and 2.8 % respectively. Cost of distilled water per liter and it's payback period was found to be Rs. 2.92 and 290 days respectively. It leads to reduction of 10.7 ton of CO_2 emissions per year during 10 years of its lifetime.

Keywords: Solar still, Ecofriendly, Exergy, Distillate, Enviroeconomic, Exergoeconomic.

Introduction:

Life and sustainability of humanity depend on the availability of clean water. More than a quarter of the population of world gets affected by the availability of pure drinking water by 2025, and about half of the population of the world will be going to face water-stressed circumstances by 2030 [1]. Water distillation for drinkable water has become an increasingly important challenge due to population growth, global level pollution problems, and industrial development. It has become one of the world's greatest challenges to enable water distillation to be more efficient and effective using eco-friendly methods [2]. Due to the present circumstances, solar water desalination systems using solar energy are drawing the attention of everyone in order to solve the water shortage issues while providing a renewable and sustainable solution without leaving any ecological footprint on the earth.

A conventional solar still (CSS) can provide potable water from salt or impure water, which is extremely important in dry and remote areas. It is simple in design, eco-friendly, inexpensive, and reliable device [3-5]. But, due to low pure water production capacity compared with traditional desalination systems makes it very hard to adopt globally [6]. A number of studies have been conducted in order to improve CSS's thermal efficiency and production capacity because of its low performance. For example, use of Phase changing material (PCM) to store latent heat [7,8], wick type solar still [9-13], use of reflectors placed internally as well as externally [14-18], variation in the tilt angle of the glass cover [19-22], use of fins in the solar still [23-27], use of nanomaterials in the solar still [28-31] have been analyzed. The oxide of copper and graphite micro-flakes and cooling water used in a solar distiller enhanced the productivity of a still by improving the cooling rate of the still condenser by employing different configurations of the condenser [32-33]. The results showed an increase in everyday pure water production roughly by 53.9% with graphite micro-flakes and 44.9% with the use of copper oxide. Apart from that, the improvement percentages of the daily pure water production increases to 57.6% and 47.8% respectively due to water cooling of the still cover. Water rises to the surface of the thin layer of material, thereby generating vapor quickly because of capillarity in materials. Therefore, evaporation rates can be further improved by using porous materials having better capillary effect and a large area for evaporation. Thus, to improve the SS (solar still) productivity, application of wick materials have been made in various ways. SS were tested with a variety of absorber shapes (flat, stepped, and stepped with wire mesh) and wick materials (wood pulp paper and coral fleece fabric). They found that wick material coral fleece provided the highest yield, 4.28 kg per day when combined with wire mesh [34].

In recent decades, energy systems have been evaluated and improved by employing exergy analysis [35-37]. By analyzing the exergy from a qualitative perspective, more meaningful data can be extracted that is not possible from energy analysis that are solely quantitative [38]. Based on exergy and energy efficiency, Yousef and Hassan [39] evaluated the performance of the still with PCM on the basis of energy and exergy efficiency. They reported approximately 17.89% and 10% higher energy efficiency per day in contrast to that in CSS with and without the use of fins inside the solar still. In spite of the fact that exergy analysis can be effectively analyzed and optimized through the application of exergy analysis, it still has few limitations as it ignores the environment and economic constraints of engineering processes [40]. This means that, in order to make more better decisions, financial and environmental restrictions must be considered alongside the exergy method. A number of methods have been established for investigating the economic and environmental aspects of energy systems, but methodologies based on exergy, such as exergoeconomic and exergoenvironmental have gained considerable attention in recent years. By identifying structural changes in working conditions that can improve the ecological impact and cost-effectiveness of engineering processes, exergoenvironmental and exergoeconomic approaches can provide valuable insights into improving their environmental impact and cost-effectiveness.

According to Sahota and Tiwari [41], a solar distillation with double-basin system integrated with different nanofluids yields greater enviro-economic and exergoeconomic gains than a single-basin system. According to the findings, use of oxides of copper, titanium and Aluminum as nanofluids enhanced the yearly distillate production by 5.2%, 10.4%, and 19.1% respectively. Pal et al. [42] made a study of an exergoeconomical and enviroeconomical analysis of solar distiller using cotton and jute wicks. Based on an interest rate of 4% for 50 years, the exergoeconomic parameter for a solar distiller with black cotton and jute wicks observed to be 79.1 W-h/Rs and 62.3 W-h/Rs. In this study, an attempt has been made to fabricate an ecofriendly solar still made of locally available materials. Furthermore, energy, exergy, economic and enviroeconomic analysis has been performed on the ecofriendly solar still in the climate of Azamgarh (latitude 25.75° N, longitude 82.94° E), Uttar Pradesh, India.

Experimental setup

An experimental passive solar still setup has been set up on the roof of Rajkiya Engineering College, Devgaon, Azamgarh (latitude 25.75° N, longitude 82.94° E), Uttar Pradesh, India. Fig. 1 shows the photograph of the passive solar still apparatus used for the experiment.

Fig.1 Photograph of solar still

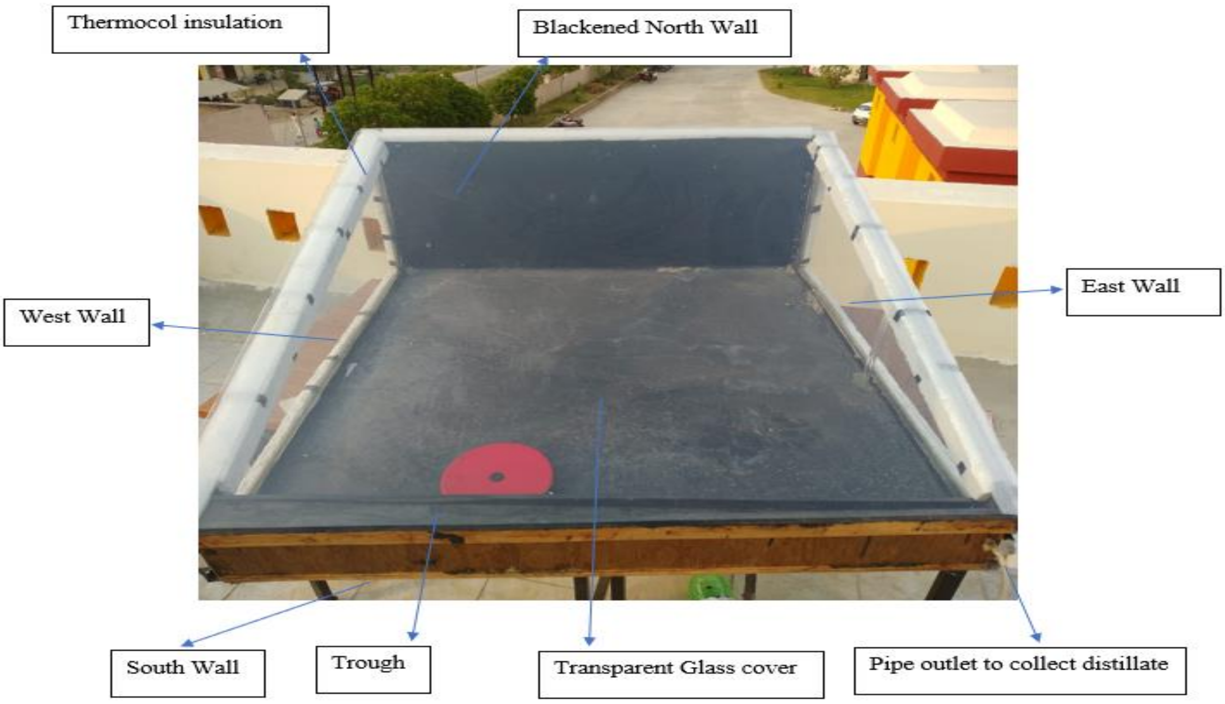

Fig.2 Photograph of solar still with all its parts

The still in use consist of a wooden basin of area 1m^2, wood as the wall material for south and north wall and side walls are made transparent using aluminum frame and glass. All the interior side of the solar still made of wood is painted with water proof black colour paint to absorb maximum solar radiation falling on it. Thermocol of 2 cm thickness is used as an insulating material on the east and west side of the solar still to reduce heat transfer from the solar still. A toughened glass of 4 mm thickness is used as a cover inclined at an angle of 15° and sealed with the use of rubber gasket. All the parts are seal proofed using putty and rubber gasket to stop vapour loss from the solar still to the surrounding. Solar still is oriented in South facing direction to get higher solar radiation on the apparatus. Distillate produced after condensation from the inclined glass trickles down and collected by the trough and pipe provided over the south wall. Table.1 shows the dimension of the ecofriendly solar still.

Table. 1 Details of the solar still parts and dimensions.

S.No.	Details of Solar still parts	Dimensions
1.	North wall	39 cm × 100 cm
2.	South wall	12 cm × 100 cm
3.	Area of East wall	6450 cm^2
4.	Area of West wall	6450 cm^2
5.	Inclination angle of glass cover	15°
6.	Transparent Glass Sheet thickness	4 mm
7.	Thickness of wood used as trough	1.8 cm
8.	Transmissivity of glass cover	0.9

Experimental procedure

The solar still has been cleaned and filled with normal tap water up to 1 cm height in the basin. The solar still has been placed such that inclined glass cover is in south facing direction. The solar radiation on all parts of solar still, water and ambient temperature and distillate produced from still has been measured every hour from 07:00 h to 18:00 h. A stop watch was also used to measure the time precisely during experiment. The experiments on the solar still are performed on a clear day of the month of April 20, 2022 in the climatic conditions of Azamgarh (latitude 25.75° N, longitude 82.94° E), Uttar Pradesh, India.

Thermal modelling

Energy efficiency:

Performance of a solar still can be determined by its energy efficiency. It is based on the first law of thermodynamics. Energy efficiency can be calculated using the output energy and input energy of the solar still. Output energy can be calculated by evaporation energy ($m_w \times h_{fg}$) and input energy can be calculated by using the solar energy falling into the solar still ($I(t) \times A$) where, m_w is the mass of water condensed and collected from the solar still, h_{fg} is the latent heat of vaporization of water (can be considered as 2325 kJ/kg [43]), $I(t)$ is the solar radiation falling on solar still walls per hour and "A" is the area on which solar radiation is falling.

Instantaneous energy efficiency (η_i)can be given as

$$\eta_i = \frac{m_w \times h_{fg}}{\sum[I(t) \times A] \times 3600} \qquad (1)$$

And, energy efficiency per day (η_d) can be given as

$$\eta_d = \frac{\sum m_w \times h_{fg}}{\sum[I(t) \times A] \times 3600} \qquad (2)$$

Exergy efficiency:

The exergy efficiency may be defined as the ratio of output exergy in terms of water evaporated to the input exergy in terms of input solar radiation and can be represented by [44, 45]-

$$\eta_x = \frac{Exergy\ out}{Exergy\ In} = \frac{E_{x,evap}}{E_{x,input}} \qquad (3)$$

In the experiment, some of the condensed water droplets on the transparent inclined glass cover return to the basin, so the experimental sample's actual performance may be lower than the theoretical one. Hourly performance of the exergy can be measured by [46]

$$E_{x,output} = E_{x,evap} = \frac{m_w \times h_{fg} \times \left(1-\frac{T_a}{T_w}\right)}{3600} \qquad (4)$$

Where, T_a and T_w are the temperatures of ambient and water, respectively.

The exergy input to solar still due to radiation can be expressed as a function of radiation exergy as stated by Petela model [47]-

$$E_{x,\,input} = A_s \times I(t)\left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_s}\right)^4\right] \quad (5)$$

Where, T_s is the temperature of surface of the sun (6000K) and A_s is the total basin area in m^2.

Economic Analysis:

For economic analysis of solar still, different parameters will be required like capital cost (C), salvage value per year (SVY), Sinking fund factor (SFF), Maintenance and operational cost per year (MCY), and interest rate per year (i, taken as 12%) [48,49]. The capital recovery factor (CRF) can be represented in terms of per year interest rate and the lifetime years (n) of the solar still as [49]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

Annual fixed cost (AFC) can be represented by [47]:

$$AFC = CRF \times C \quad (7)$$

Where C is the capital cost which includes cost of materials used like glass, aluminium frame, wood, black paint, rubber gasket, foam, thermocol insulation etc. Table 2. Shows the total cost incurred in fabrication of the solar still.

Table.2 Total cost of fabrication of solar still

Details of Materials and components of solar still	**Cost (Rs)**
Wood	3000
Transparent Glass	1500
Stand	1000
Frame for side glass	750
Paint and pipe	850
Rubber gasket and thermocol insulation	200
Fabrication and Labor cost	1700
Total cost	**Rs. 9000**

The salvage value (S) of the solar still can be represented by [47]:

$$S = 0.2 \times C \quad (8)$$

SFF and SVY can be found by using the equation [47]:

$$SFF = \frac{i}{(1+i)^n - 1} \quad (9)$$

$$SVY = SFF \times S = \text{SFF} \times 0.2 \times C \quad (10)$$

The maintenance and operational cost per year of the solar still per year (MCY) is assumed to be 10% of the Annual fixed cost (AFC) [47].

Thus, total cost per year (TAC) can be calculated by [44,50]:

$$TAC = AFC + MCY - SVY \quad (11)$$

Also, cost of pure water per liter produced from solar still can be determined by [50]:

$$CPL = \frac{TAC}{Y_A} \quad (12)$$

Where, Y_A is the average distillate produced per year by the solar still.

Also, payback period can be calculated by

$$PP = \frac{C \times No. of\ clear\ days\ in\ a\ year}{Y_A \times Market\ cost\ of\ distilled\ water} \quad (13)$$

Exergoeconomic analysis:

The exergoeconomic approach is a method of assessing and enhancing system performance based on exergy. By appropriately balancing the economic and exergy factors, this technique aims to reach the overall optimal design. Overall exergy output can be represented as the ratio of exergy output per year and total annual cost [41] and given as:

$$E_g = \frac{Exergy\ output}{Total\ Annual\ Cost} \quad (14)$$

Where, E_g is the exergoeconomic parameter.

Environmental analysis:

Desalination systems powered by the sun are environmentally friendly, as they reduce carbon dioxide emissions into the atmosphere. CO_2 emissions from coal-fired power plants are around 980 gramme CO_2/kW h, but when losses due to electricity transmission and distribution are factored in, the figure rises to around 2 kg CO_2/kW h [51,52]. Thus, emissions of carbon di oxide per year in tons from solar stills can be given by [52]:

$$\emptyset_{CO_2} = \frac{E_{out} \times n \times 2}{1000} \qquad (15)$$

Where, $\emptyset_{CO_2}$ is the environmental parameter and E_{out} is the output energy from the solar still per year.

The emissions of carbon di oxide annually in tons considering exergy approach from the solar stills can be given by [52]:

$$\emptyset_{ex,CO_2} = \frac{E_{ex,out} \times n \times 2}{1000} \qquad (16)$$

Where, $\emptyset_{ex,CO_2}$ is the exergoenvironmental parameter and $E_{ex,out}$ is the total exergy output from the solar still per year.

Enviroeconomic analysis

An enviroeconomic analysis of a solar still can be performed on the basis of price of CO_2 emitted over the lifespan of the solar still and can be represented by [52]:

$$\beta_{CO_2} = \gamma_{CO_2} \times \emptyset_{CO_2} \qquad (17)$$

Where, β_{CO_2} is the enviroeconomic parameter, γ_{CO_2} is the international market price of carbon that can be taken as 14.5 $ [53].

Whereas, exergoenviroeconomic parameter (β_{ex,CO_2}) can be represented as [52]:

$$\beta_{ex,CO_2} = \gamma_{CO_2} \times \emptyset_{ex,CO_2} \qquad (18)$$

Results and Discussions

Experiments were conducted on 20/04/2022 at Rajkiya Engineering College, Azamgarh, U.P, 276201, India and solar radiation on east, west and glass cover have been measured along with the temperature of water and ambient air per hour from 7 am to 6 pm. Depth of brackish water was 2 cm and the apparatus is placed such that the inclined glass cover was south facing to allow maximum solar radiation inside the still. The intensity of solar radiation remains more or less same throughout the month and one typical day of April month is taken for experiment.

The variation of solar radiation available on inclined top glass cover, east and west wall with time has been shown in Fig. 3 and it shows that the solar radiation is maximum during 11am to 1 pm. Maximum solar radiation measured by the solarimeter was 1035 W/m^2 at 01:00 pm.

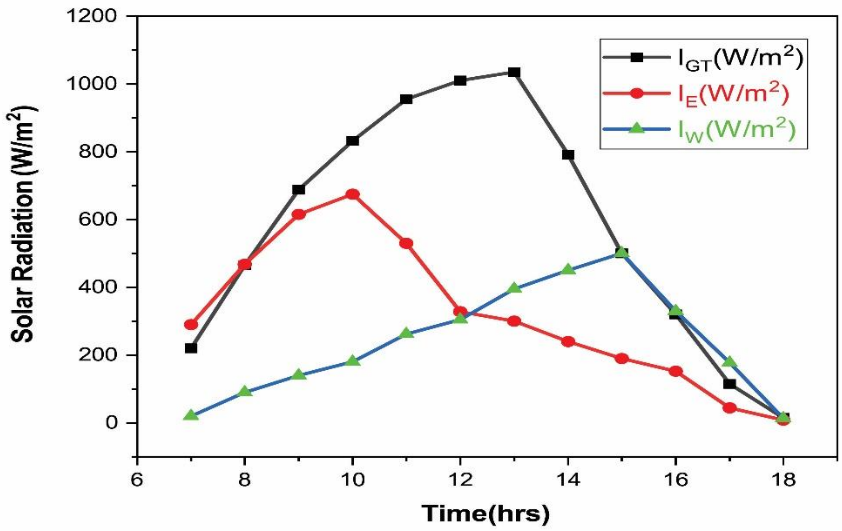

Fig. 3 Variation of Solar radiation on Top glass cover (I_{GT}), east (I_E) and west wall (I_W)of solar still with time in hrs.

Fig. 4 shows the variation of water temperature and total global solar radiation with respect to time. The water temperature increases till 13:00 h due to increase in the intensity of solar radiation and afterward decreases due to decrease in the intensity of solar radiation. The maximum temperature of water was found to be 63°C at 13:00 h.

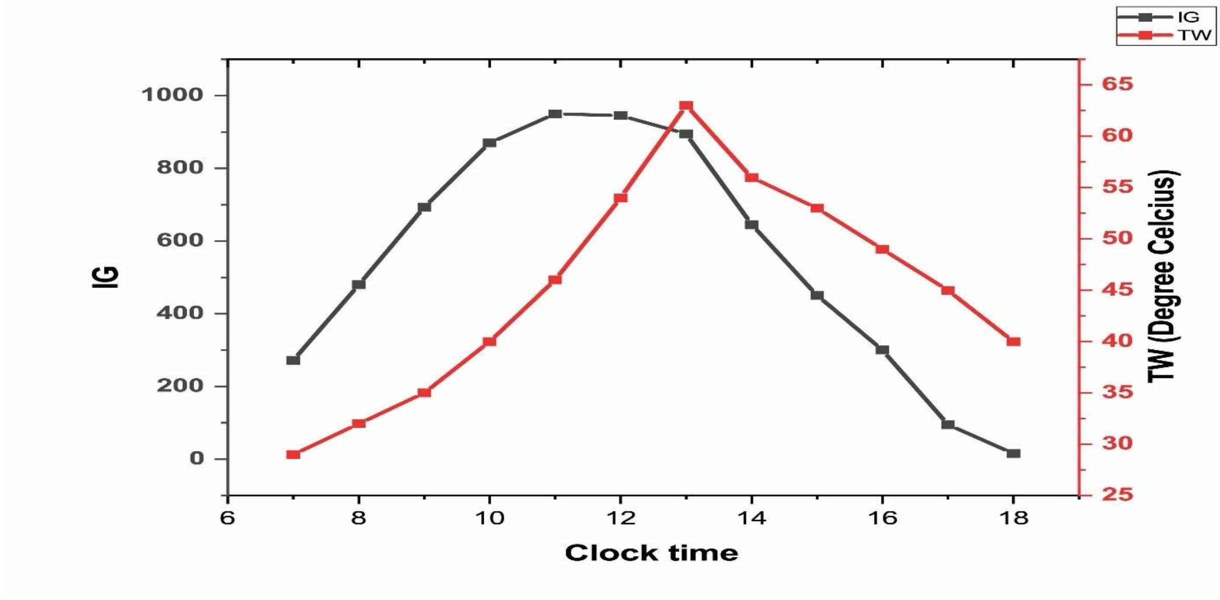

Fig. 4 Variation of Global Solar radiation (I_G) and water temperature (T_W) with time.

Fig. 5 shows the hourly variation of distillate produced from the solar still with respect to time. The depth of brackish water in the solar still was 1 cm. The distillate produced from the still increases from 09;00 to 13:00 h due to increase in the total solar radiation input to the still and starts decreasing afterward due to reduction in the intensity of solar radiation. The maximum distillate obtained from the solar still was 0.367 kg/m^2 at 13:00 h. The Cumulative distillate produced from the solar still was 2.26 kg/m^2.

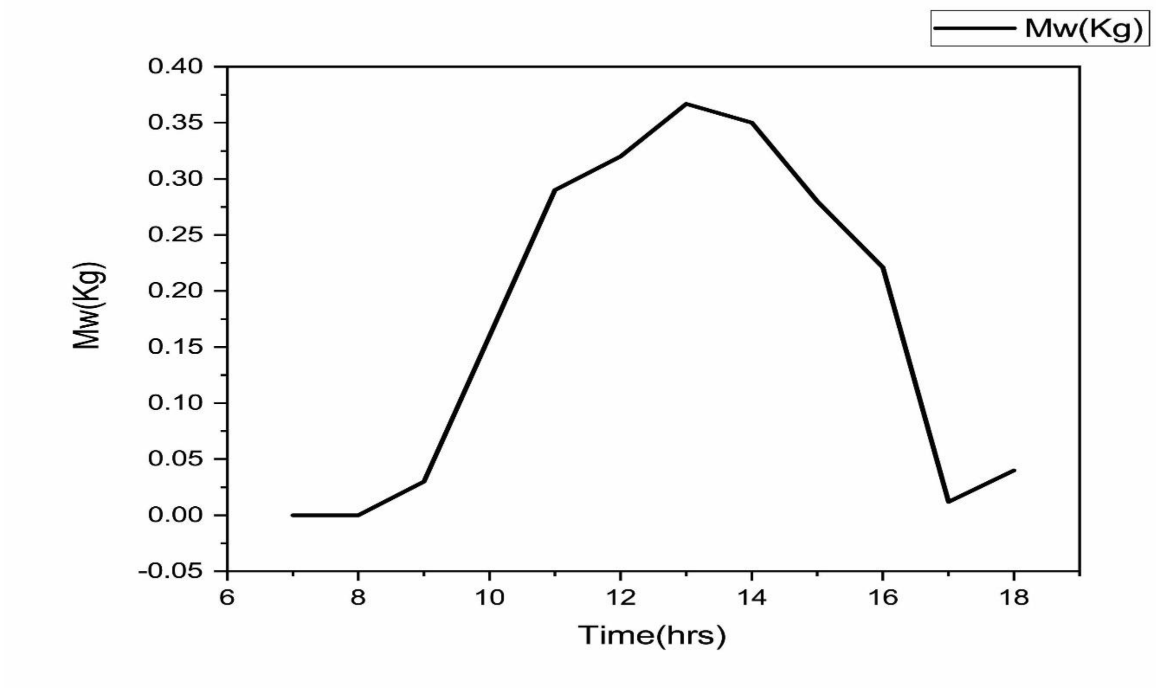

Fig. 5 Variation of mass of distillate produced (M_W) with time.

Fig. 6 shows the variation of instantaneous energy efficiency (%) and instantaneous exergy efficiency (%) with respect to time (h). The instantaneous energy efficiency increases with time from 09:00 to 16:00 h and maximum instantaneous energy efficiency was 24.51% at 16:00 h. The instantaneous exergy efficiency increases from 09:00 to 13:00 h and then decreases from 14:00 to 15:00 h. It again increases at 16:00 h due to decreased amount of solar radiation and fall in ambient temperature. The maximum instantaneous exergy efficiency was 2.8 % at 13:00 h. The value of exergy efficiency is very low in comparison to energy efficiency due to rich exergy value of the input solar radiation because of the temperature of surface of the Sun. The daily energy efficiency of solar still was found to be 12.78%.

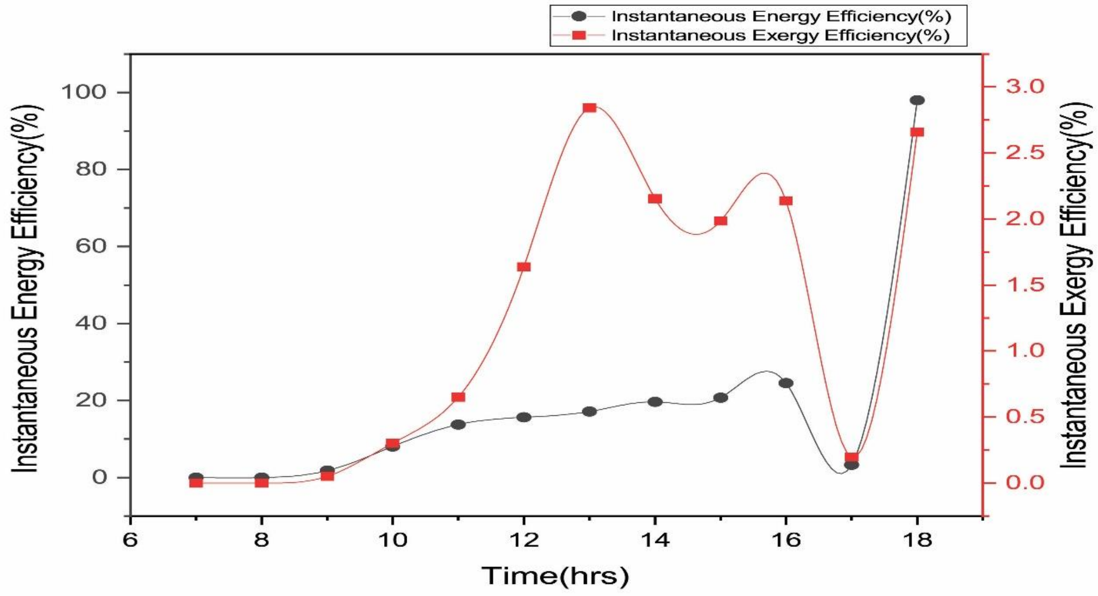

Fig. 6 Variation of instantaneous energy and exergy efficiency with time.

Economic evaluation of the solar still shows that for 10 years of lifetime and 12% interest rate, cost of distilled water per liter in a year comes to be Rs. 2.92. Also, payback period of the solar still was calculated to be 290 days. Table 3. shows the economic analysis of the ecofriendly solar still.

Table 3. Economic analysis of an ecofriendly solar still

Types of cost	Value
Total cost of solar still (C)	Rs. 9000
Salvage value (S)	Rs. 1800
Salvage value per year (SVY)	Rs 113.21
Maintenance and operational cost per year (MCY)	Rs. 175.47
Annual fixed cost (AFC)	Rs. 1754.7
Sinking fund factor (SFF)	0.063
Capital recovery factor (CRF)	0.195
Total cost per year (TAC)	Rs. 1816.98
Cost of pure water per liter (CPL) in a year	Rs. 2.92
Payback period (PP)	290 days

Exergoeconomic, Environmental and Enviroeconomic evaluation is represented by Table 4.

Table 4. Exergoeconomic, Environmental and Enviroeconomic evaluation analysis of ecofriendly solar still

Parameters	Value
Exergoeconomic parameter (kWh/Rs)	0.085
Environmental parameter (ton of CO_2/ year)	10.7
Exergoenvironmental parameter (ton of CO_2/ year)	0.3
Enviroeconomic parameter (Rate $ /year)	155.5
Exergoenviroeconomic parameter (Rate $/year)	4.5

Conclusions:

From the experimental and economic and enviroeconomic analysis of proposed ecofriendly solar still, following conclusions have been drawn:

1. The maximum solar radiation falling on the solar still was measured on top inclined glass cover and found to be 1035 W/m^2 at 13:00 h.

2. The maximum distillate produced was 0.367 kg/m^2 at 13:00 h while the total distillate obtained in a day was 2.26 kg/m^2.

3. The maximum instantaneous energy and exergy efficiency was found to be 24.51% at 16:00 h and 2.8% at 13:00 h respectively. The overall energy efficiency in a day was 12.78%.

4. The cost of pure water per liter and payback period was found to be Rs. 2.92 and 290 days respectively.

5. The value of exergoeconomic and environmental parameter was 0.085 kWh/Rs and 10.7 ton of CO_2/year.

5. The value of exergoenvironmental, enviroeconomic and exergoenviroeconomic parameter were found to be 0.3 ton of CO_2/year, 155.5 $/year and 4.5 $/year respectively.

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