Experimental Study of Solar Energy Based Water Purifier (SEBWP) of Single Slope Type by Incorporating N Similar Evacuated Tubular Collectors (ETCs) having Series Connection

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Experimental study of solar energy based water purifier (SEBWP) of single slope type by incorporating N similar evacuated tubular collectors (ETCs) having series connection

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Abstract

This research paper deals with the experimental investigation of solar energy based water purifier (SEBWP) of single slope type by incorporating N similar evacuated tubular collectors (ETCs) having series connection. Experimental investigation has been done for a year from August 2018 to July 2019. MATLAB has been used for evaluating performance parameters of the system followed by the validation of these results with their experimental values. A fair agreement has been found between theoretical and experimental values. Values of correlation coefficients for condensing glass temperature, water temperature and water yield have been found to be 0.9932, 0.9928 and 0.9951 respectively. Further, energy metrics, productivity, cost of producing one kg of fresh water, exergoeconomic and enviroeconomic parameters have been evaluated. Values of energy payback time, per kg cost of producing fresh water and exergy loss per unit Rs. have been evaluated to be 1.72 years, Rs. 0.95/kg and 0.128 kWh/Rs. respectively.

Key words: evacuated tubular collector; solar still; experimental study, exergo-enviro-economic analysis, energy metrics

1. Introduction:

The design, analysis, installation and experimental study of solar energy based water purifier (SEBWP) of single slope type by incorporating N alike evacuated tubular collectors (ETCs) is a pressing need at a time when the world is grappling with the current problem of fresh water scarcity. The purification of dirty water using solar energy is one of the best solutions for providing the fresh water as it is environment friendly and does not need much technical knowledge for its maintenance. The experimental study of solar energy based single slope water purifier (SEBWP) by incorporating flat plate collector was presented by Rai and Tiwari (1983). Since then, a lot of modifications in the design of SEBWP operating in active mode have been reported. Tripathi and Tiwari (2006) have studied SEBWP in active mode for different water depth using solar fraction and concluded that the internal convective heat transfer coefficient decreases with rising water depth due to increases in the sensible heat content of water mass. Dimri et al. (2008) investigated performance of SEBWP in active mode by incorporating material of cover and it was concluded that the production of fresh water (yield) of reported system was higher with copper due to higher thermal conductivity of copper as compared to glass and plastic.

The main drawback of SEBWP in active mode reported by Rai and Tiwari (1983), Tripathi and Tiwari (2006), Dimri et al. (2008) was that SEBWP systems were not self sustainable as the pump was running using conventional source of energy i.e. electrical energy from grid. These systems could be made self sustainable by integrating photovoltaic panel with collector. Based on this concept, Kumar and Tiwari (2009) reported hybrid active SEBWP and compared results with SEBWP in passive mode. They revealed that the lesser production cost of fresh water from passive SEBWP was obtained due to less materials required for the production of passive SEBWP; however, the volume of fresh water production from passive SEBWP was very low and hence could not be commercialized. Further, Dev and Tiwari (2010) reported the thermal modeling of PVT integrated SEBWP in active mode and concluded that the nonlinear characteristic equation is better suited for performance analysis. Singh et al. (2011) studied PVT integrated SEBWP of double slope type experimentally and it was reported that the yield was 1.4 times higher than the similar single slope set up due to better distribution of solar radiation throughout the day in the case of double slope type. El-Sebaii et al. (2011) investigated SEBWP by incorporating shallow solar pond and reported that the fresh wateryield was 68.12%more than the simple SEBWP due to addition of heat by solar pond. Esfahani et al. (2011) have investigated experimentally a special type portable SEBWP consisting of solar collector, thermoelectric cooling device for enhancing condensation, black wool covered wall and concluded that the output was comparable with other types of SEBWP. Arslan (2012) investigated experimentally the different designs of SEBWP in active mode and concluded that the circular box type SEBWP in active mode is most efficient and the highest daily efficiency was obtained as 68.1% due to improvement in the design.

The fresh water yielding of SEBWP in active mode can be improved by replacing flat plate collectors by evacuated tubes as vacuum is present in such tubes which prevent heat loss by convection. Singh et al. (2013) and Kumar et al. (2014) developed thermal model for SEBWP of single slope type by incorporating evacuated tubes in which end points of all pipe were slotted in the basin of solar still in natural as well as forced modes of flow respectively. Sampatkumar et al.

(2013) investigated SEBWP of single slope type integrated with evacuated tubes and it was concluded that the yield of SEBWP was increased by 129% after integrating with evacuated tubes due to additional heat addition by evacuated tubes to basin of SEBWP.

In another study, Hamadou and Abdellatif (2014) investigated SEBWP in active mode of operation for sea water production under optimized condition and concluded that the fresh water production is not the proportion of heat transfer fluid rate. Feilizadeh et al. (2015) investigated experimentally multistage SEBWP in active mode by incorporating solar collectors and concluded that the percentage increase in fresh water production decrease as the collector to basin area ratio is increased because heated water is further heated. Taghvaei et al. (2015) investigated SEBWP in active mode experimentally for five days continuously and concluded that the overall fresh water production and efficiency decreased with the increases in brine depth due to sensible heat absorbed by brine mass at increased brine depth. Sandeep et al. (2015) studied SEBWP of single slope type in which extra condensing surface was provided and concluded that the fresh water production in the improved design was 14.5% higher than the conventional SEBWP of single slope type due to improvement in the condensation as the extra condensation surface was provided. Singh et al (2016) investigated PVT integrated SEBWP of single slope type and concluded that there was a fair conformity between values of theoretical and experimental analyses with coefficient of correlation varying between 0.97 and 0.99.

Issa and Chang (2017) studied SEBWP by integrating with evacuated tube in mixed mode condition and it was concluded that the yield was better than the conventional SEBWP because of heat addition by evacuated tubes in mixed mode connection to basin. Sahota and Tiwari (2017) developed characteristic equation and reported an improvement in fresh water production by 32% with CuO nanofluid over base fluid (water) due to increased absorptivity of nanofluid.

Joshi and Tiwari (2018) investigated SEBWP in active mode of operation by incorporating heat exchanger and reported that the fresh water yield cost was lowest for partially covered flat plate collectors (FPC) with PVT; whereas, SEBWP integrated with fully covered PVT-FPC performed best for electricity generation. Singh and Tiwari (2017), Singh (2018, 2019) and Singh and Al-Helal (2018) performed the analytical study of basin type SEBWP by incorporating N alike evacuated tubular collectors from energy, exergy, cost and energy metrics viewpoints and concluded that SEBWP of double slope type performed better than SEBWP of single slope type due to better distribution of solar energy throughout the day in the case of double slope type.

Kumar et al. (2018) investigated SEBWP operating in active mode experimentally and concluded that the fresh water production from SEBWP operated in active mode was six times more than the SEBWP in passive mode due to addition of more heat by collectors and increased temperature difference between water surface and condensing cover as the condensing cover was cooled. Gupta et al. (2018) developed the distinctive equation for SEBWP of single slope type by incorporating CPC which was fully covered with PV for the same packing factor as that of partially covered and it was reported that the instantaneous efficiency of the system containing CPC with full coverage of PV was better than SEBWP consisting of partially covered PVT-CPC due decreased top loss. Elsheikh et al. (2019) reported the application of artificial neural network for different solar energy devices for optimization and prediction of performance parameters and reviewed the work on solar energy devices. Elbar et al. (2019) investigated SEBWP of single slope type by integrating PV and it was reported that the yield obtained was higher by 31.48%for the PV integrated SEBWP over conventional SEBWP because PV acted as reflector which allows more solar energy into the SEBWP. Feilizadeh et al. (2019) studied thermosyphon SEBWP in active mode with improved condenser and concluded that the increase in the production of fresh water was 46% higher with improved condenser due to the difference of partial vapor pressure between the water surface and condenser surface. Bait (2019) reported the experimental study of SEBWP of double slope type by incorporating tubular solar collector and concluded that the annual production was 35.73% more over the conventional SEBWP due to compact design of collector. Sharshir et al. (2019) conducted an experimental analysis of a pyramid-type SEBWP incorporating evacuated tubes and filled with nanofluid and concluded that the modified system produced 64.5 % more fresh water than the traditional SEBWP due to improved fluid properties.

Essa et al. (2020) studied SEBWP operating in active mode using artificial neural network and reported that Hawks Optimizer – artificial neural network was the most suitable for forecasting the production of fresh water by active mode operated SEBWP. Parsa et al. (2020) reported the effect of variation of water depth on SEBWP powered by photovoltaic and concluded that the fresh water yield was 42.5% more if the depth was raised to 70.23% (from 3871 to 13005) due to increased radiation, decreased atmospheric pressure and ambient air temperature. Hassan (2020) investigated SEBWP experimentally by incorporating parabolic trough collector and concluded that maximum freshwater production increases by about 6% in case of using double slope type than the similar single slope set up. Tiwari et al. (2020) have reported the outcome of condensing cover effect on PVT-CPC integrated conical solar still performance and it was found that the production of fresh water (yield) of active conical SEBWP is higher than conventional SEBWP due to increased condensing cover surface area. Shoeibi et al. (2020) studied SEBWP of double slope type by incorporating thermoelectric cooling and heating and concluded that due to the increased water temperature in the modified solar still, the yield of the modified solar still was 76.4 percent higher than the traditional SEBWP of double slope type. Kumar et al. (2020)

reported the effect of variation of number of collectors on the environmental parameter of SEBWP of single slope type and concluded that due to an increase in the amount of heat added to the SEBWP basin, the value of carbon credit increased with the number of collectors. Further, Singh et al. (2020) examined the impact of mass flow rate variation on the life cycle conversion efficiency of a single slope SEBWP and concluded that as the mass flow rate decreased, the system's life cycle conversion efficiency improved because fluid flowing through collector tubes had more time to consume solar energy. Shehata et al. (2020) investigated ultrasonic humidifier augmented SEBWP with evacuated collector experimentally and concluded that concluded that the ultrasonic humidifier improved the productivity by 44% due to circulation of water between solar still and evacuated collector.

From the extant research study, it has been found that the theoretical study of SEBWP of single slope type coupled with N alike ETCs has been carried out by incorporating different parameters like exergoeconomic, enviroeconomic, energy metrics, productivity and efficacies. However, no researcher in the world has worked on an experimental study of SEBWP integrating ETCs. The system under study is different from the system reported by Singh et al. (2013), Kumar et al. (2014) Sampatkumar et al. (2013) and Issa and Chang (2017) in the sense that they used evacuated tubes; whereas, the ETC in the present study consists of U shaped copper tubes inserted in evacuated tubes. Further, experimental study is a must of any renewable system as it helps in realization of particular technology/system. Hence, experimental study of SEBWP integrated with evacuated tubular collectors has been carried out and reported in this research paper. The main objectives can be stated as follows:

i. Experimental validation of theoretical results with experimental values for SEBWP of single slope type integrated with N alike ETCs for N = 13.

ii. Cost estimation of producing unit kg of fresh water, productivity and exergoeconomic parameter for SEBWP of single slope type integrated with ETCs on the basis of experimental data for N = 13.

iii. Evaluation of energy metrics and enviroeconomic parameter of SEBWP integrated with ETCs taking experimentally collected data as basis.

Fig. 1: Experimental setup of SEBWP of single slope type integrated with evacuated tubular collectors

2. Experimental setup of SEBWP of single slope type integrated with N alike ETCs

The specification of SEBWP of single slope type integrated with N alike ETCs has been revealed as Table 1. Fig. 1 represents the experimental setup of SEBWP of single slope type integrated with evacuated tubular collectors. It consists of series connected evacuated tubular collectors, pump and single slope type SEBWP. The experimental setup incorporates series connected evacuated tubular collectors (13 in number) to SEBWP of single slope type with the help of pump. Pump gets its power from grid for its working. Collectors are connected in series with the help of insulated pipe, the output of last collector is connected to basin through insulated pipe and input to the first collector has also been taken through insulated pipe from pump which takes water from basin through insulated pipe. One collector has a surface area of 0.0864 m^2 hence the total surface area of the sequence of evacuated tubular collectors is 1.1232 m^2. The evacuated tubular collector consists of two concentric cylinders made up of glass and vacuum is provided between these two concentric glass cylinders which prevents heat loss by convection. So, heat loss is lower in this collector in comparison to other collectors like flat plate collector and compound parabolic concentrator collector where heat loss takes place by convection also. The inner glass cover's inner surface is painted black to serve as an absorber. A copper U-tube has been inserted inside the inner glass cylinder. Copper tube has been taken due to its high thermal conductivity property.

The evacuated tubular collectors are connected in series to a single slope type SEBWP basin with 2 m x 1 m (2 m^2) basin area. It was fabricated using galvanized iron (GI) sheet. The inside surface of GI sheet was painted black to absorb solar radiation. The outer surface was covered with glass wool and thermocol. The top surface of single slope type SEBWP was covered with glass having angle of inclination as 15^o as the setup was designed for summer season viewpoint. The glass was fixed with help of iron clamp and rubber placed in between iron frame and glass. The sealing was done using window-putty with an aim to avoid seepage of vapor.

Table 1: Specifications of solar energy based water purifier (SEBWP) of single slope type by incorporating N number of series connected evacuated tubular collectors (ETCs)

SEBWP of single slope type			
Component	Specification	Component	Specification
Length	2 m	Cover material	Glass
Width	1 m	Orientation	South
Inclination of glass cover	15^{o}	Thickness of glass cover	0.004 m
Height of smaller side	0.14 m	K_g	0.816 W/m-K
Material of body	GI Sheet	Thickness of insulation	0.1 m
Material of stand	GI	K_i	0.166 W/m-K
ETC			
Component	Specification	Component	Specification
Type and no. of collectors	ETC , 13	α_p	0.8
DC motor rating	12 V, 24 W	F'	0.968
Radius of inner copper tube	0.0125 m	τ_g	0.95
Thickness of copper tube	0.0005 m	K_g $(Wm^{-1}K^{-1})$	1.09
Outer radius of outer glass tube of evacuated coaxial glass tube	0.024 m	Angle of ETC with horizontal	30^{o}
Inner radius of inner glass tube of evacuated coaxial glass tube	0.0165 m	Length of each copper tube	1.8 m
Thickness of outer/inner glass tube of evacuated coaxial glass tube	0.002 m		

The short wavelength solar radiation reaches the water surface after passing through the condensing cover where a part of energy is reflected by water and the remainder is transmitted to the basin liner after being absorbed by water. The basin liner transmits the absorbed energy to the water as it is insulated from outside, and loss of heat is not possible to outside. The temperature of the water increases and within the solar still the heat transfer from the water surface to condensing cover takes place via convection, radiation and evaporation. Water vapor condenses at the inside surface of the cover after losing latent heat of condensation, and film wise condensation is ensured by careful cleaning of the surface so that condensate can be collected as it will trickle down due to the component of gravity force. Drop wise condensation has negative effect on the performance of solar still as it will not allow the solar radiation to pass through it i.e., it will act as opaque surface to incoming solar radiation. The heat accumulated at the condensing glass surface is dissipated to the surrounding by means of convection and radiation and it strongly depends on the wind speed or water flow rate if additional arrangement is made to dissipate it in the form of water flow over condensing cover over a certain time period. A bottom opening has also been created to allow the sediments to be flushed out after a period of time. Digital thermocouples were used to measure the different temperatures.

3. Instrumentation

Measuring instruments were used for the measurement of different parameters. The velocity of air blowing was measured using the digital anemometer model of LUTRON AM-4201. Solar radiation was assessed on an hourly basis with the aid of a Solarimeter with a minimum count of 20 W/m^2.The various temperatures were measured using digital thermocouple. The calibrated mercury thermometer was used for the measurement of atmospheric temperature. The measurement of distilled water was done using measuring flask.

Table 2: Variation of different parameters of SEBWP of single slope type integrated with evacuated tubular collectors at 0.09 m water depth for 29 April 2019

Time (h)	I_c (W/m^2)	I_s (W/m^2)	V_a (m/s)	T_a (^oC)	T_w (^oC)	T_{gi} (^oC)	Yield (kg/h)
8:00	420	440	3.40	30.0	34.0	32.0	0.000
9:00	600	640	1.50	32.0	39.3	33.5	0.085
10:00	780	820	1.20	33.0	45.6	34.7	0.098
11:00	900	920	2.20	34.6	52.2	40.4	0.380
0:00	960	980	1.70	36.0	60.5	46.5	0.687
13:00	980	1020	0.90	37.5	69.2	56.4	0.982
14:00	960	1000	1.00	39.5	78.2	65.5	1.125
15:00	880	920	1.00	39.0	83.4	73.3	1.458
16:00	760	780	2.10	39.4	89.7	78.5	1.615
17:00	600	600	1.20	37.0	91.4	81.3	1.760
18:00	320	340	1.60	36.8	85.2	77.2	1.268
19:00	0	0	1.30	35.3	80.4	70.3	0.988
20:00	0	0	1.10	35.0	76.7	63.4	0.790
21:00	0	0	0.00	34.0	70.3	58.4	0.578
22:00	0	0	0.90	34.2	68.2	55.5	0.415
23:00	0	0	0.30	28.5	65.4	50.4	0.400
24:00	0	0	0.00	27.2	61.2	48.5	0.320
1:00	0	0	0.80	27.4	60.4	47.2	0.225
2:00	0	0	0.90	26.3	59.4	44.5	0.215
3:00	0	0	1.00	25.4	54.9	42.5	0.200
4:00	0	0	1.20	26.2	52.5	40.3	0.200
5:00	0	0	1.30	26.5	51.6	39.8	0.200
6:00	0	0	2.20	25.6	50.3	37.5	0.115
7:00	0	0	1.80	28.4	48.5	36.5	0.100

4. Methodology

The experiment was carried out on the roof of Galgotias College of Engineering and Technology's Mechanical Block in Greater Noida, Uttar Pradesh, India. The data for the typical day (April 29, 2019) have been presented as Table 2. The basin of single slope type SEBWP was filled with underground water 24 h prior to the starting of the experimentation for establishing a steady state condition prior to the start of the experiment. The experiment began at 8 A.M. local time and lasted until 7 A.M. the next day. Solarimeter was used to measure the solar intensity on the surface of the SEBWP and the evacuated solar collector. The data for the different parameters were collected for 24 h. Different parameters for which data were collected are as follows:

i. Basin water temperature
ii. Inner surface glass temperature
iii. Global radiation falling on the surface of SEBWP and collector
iv. Temperature of blowing air
v. Distillate output on per hour basis

The observation on the hourly basis has been presented as Table 2.

5. Thermal modeling

The thermal modeling of SEBWP of single slope types by incorporating N alike ETCs involves the writing of equation taking energy balancing as the base for all parts of the system followed by simplification. The objective of simplification of equations obtained from balancing energy is to express the unidentified parameters in terms of known parameters like solar intensity, atmospheric temperature and constants. The water temperature, inner condensing glass cover temperature and fresh water yield on hourly basis are developed as a function of solar intensity, ambient temperature and heat transfer coefficients. When writing energy balance equations, the following assumptions are made to simplify the complex situation:

i. The vapor leakage in SEBWP is neglected.
ii. Solar distiller unit's water depth is constant. The change in distilled water yield is very small when the water depth changes thus change in depth can be neglected.

iii. The brackish water held in the basin does not develop layers.

iv. The heat capacity of the bottom and side insulating material along with condensing glass cover is neglected.

v. The condensation with film type characteristic occurs at inside plane of condensing cover. Careful cleaning of the inner surface of the glass ensures film-wise condensation and by providing small angle to the condensing cover favors it. The component of gravity force along the condensing cover will allow the condensate to trickle down along the surface and finally collected in measuring jar.

vi. All evacuated collectors are identical.

Following Singh et al. (2017), development of expression for the temperature from the last collector and thermal energy addition to the basin water is done by energy balancing for receiver surface and water flowing in the copper tubes.

5.1 For evacuated tubular collectors

5.1.1 For the absorber surface

$$\alpha\tau^2 I(t) 2R dx = \left[F' h_{pf}(T_p - T_f) + U_{tpa}(T_p - T_a)\right] 2R dx \quad (1)$$

Where F' denotes collector efficiency factor.

5.1.2 For fluid flowing through tube

$$\dot{m}_f C_f \frac{dT_f}{dx} dx = F' h_{pf}(T_p - T_f) 2\pi r dx \quad (2)$$

Where r = Radius of copper tube.

Using equations (1) and (2), the water temperature at the first collector's outlet can be expressed as

$$T_{fo1} = \frac{(A\,F_R(\alpha\tau))_1}{\dot{m}_f C_f} I(t) + \frac{(A\,F_R U_L)_1}{\dot{m}_f C_f} T_a + {K_k}^N T_{fi} \quad (3)$$

Where, the value of T_{fi} is equal to T_w.

The temperature at the first collector's outlet will be the same as the temperature at the second collector's inlet, the temperature at the second collector's outlet will be the same as the temperature at the third collector's inlet, and so on. Using this condition, the fluid temperature at the Nth collector's outlet can be calculated as follows:

$$T_{foN} = \frac{(A\,F_R(\alpha\tau))_1}{\dot{m}_f C_f} \frac{(1-{K_k}^N)}{(1-K_k)} I(t) + \frac{(A\,F_R U_L)_1}{\dot{m}_f C_f} \frac{(1-{K_k}^N)}{(1-K_k)} T_a + {K_k}^N T_{fi} \quad (4)$$

The heated fluid (water) available at the outlet of N^{th} collectors allowed to basin of SEBWP of single slope type and hence, $T_{wo} = T_{foN}$.After getting the fluid temperature at the outlet of Nth collector, one can obtain the expression for useful heat gain as

$$\dot{Q}_{uN} = \dot{m}_f C_f \left(T_{foN} - T_{fi}\right) = \frac{(1-{K_k}^N)}{(1-K_k)} (A\,F_R(\alpha\tau))_1 I(t) + \frac{(1-{K_k}^N)}{(1-K_k)} (A\,F_R U_L)_1 (\,T_{fi} - T_a) \quad (5)$$

5.2 For SEBWP of single slope type

5.2.1 For inside surface of condensing glass cover

$$\acute{\alpha}_g I_S(t) A_g \;+\; h_{1w}\left(T_w - T_{gi}\right) A_b \;= \frac{K_g}{L_g}\left(T_{gi} - T_{go}\right) A_g \quad (6)$$

Here,$\acute{\alpha}_g = \left(1 - R_g\right)\alpha_g$denotes the effective absorptivity of glass cover and $h_{1w} = h_{rwg} + h_{cwg} + h_{ewg}$represents the rate of net heat transfer coefficient between water surface and inner surface of the glass cover.

Outer surface of condensing glass cover:

$$\frac{K_g}{L_g}\left(T_{gi} - T_{go}\right) A_g \;=\; h_{1g}\left(T_{go} - T_a\right) A_g \quad (7)$$

Where,$h_{1g} = h_{rg} + h_{cg}$ or $h_{1g} = 5.7 + 3.8V$

Water mass in basin:

$$\dot{Q}_{uN} + \alpha'_w I_S(t) A_b + h_{bw}(T_b - T_w) A_b = h_{1w}(T_w - T_{gi}) A_b + M_w C_w \frac{dT_w}{dt} \qquad (8)$$

Where, $\alpha'_w = (1 - R_g)(1 - \alpha_g)(1 - R_w)\alpha_w$ which denotes the effective absorptivity of water mass and $\dot{Q}_{uN}$ denotes useful heat gain per hour basis from N same evacuated tubular collectors connected in series.

Basin liner:

$$\alpha'_b I_s(t) A_b = h_{bw}(T_b - T_w) A_b + h_{ba}(T_b - T_a) \mathrm{A_b} \qquad (9)$$

Where, $\alpha'_b = (1 - R_g)(1 - \alpha_g)(1 - R_w)(1 - \alpha_w)\alpha_b$ = The fraction of solar flux absorbed by basin liner.

Appendix-A contains the expressions for the different unknown terms used in equations (3) to (6). The first order differential equation of water temperature (T_w) for N-ETC-SS can be obtained using equation (1) and equations (3) to (6) as mentioned:

$$\frac{dT_w}{dt} + a_1 T_w = f_1(t) \qquad (10)$$

Appendix-A contains the expressions for for a_1 and $f_1(t)$ used in equation (7). The solution to differential equation (7) is written as

$$T_w = \frac{\overline{f_1(t)}}{a_1}(1 - e^{-a_1 t}) + T_{w0} e^{-a_1 t} \qquad (11)$$

Where, T_{w0} is the temperature of water at $t = 0$ and during the time interval 0-t, the average value of $f(t)$ can be expressed as $\bar{f}(t)$. After computing the value of T_w with the help of equation (8), one can evaluate values of glass temperature (T_{gi} and T_{go}) using equations (3) and (4) as follows.

$$T_{gi} = \frac{\alpha'_g I_S(t) A_g + h_{1w} T_w A_b + U_{c,ga} T_a A_g}{U_{c,ga} A_g + h_{1w} A_b} \qquad (12)$$

$$T_{go} = \frac{\frac{K_g}{L_g} T_{gi} + h_{1g} T_a}{\frac{K_g}{L_g} + h_{1g}} \tag{13}$$

After estimating parameters namely water temperature (T_w) and glass temperature, the hourly yield ($\dot{m}_{ew}$) can be estimated as:

$$\dot{m}_{ew} = \frac{h_{ewg}\ A_b \left(T_w - T_{gi}\right)}{L} \times 3600 \tag{14}$$

The value of L can be estimated using the relationship provided by Fernandez and Chargoy (1990) and Toyama (1972).

6. Analysis

6.1 Statistical analysis

The rapport between values based on theoretical as well as experimental analyses of different parameters ($T_w, T_g$and potable water production) can be determined by calculating the coefficient of correlation (r_1) and the root mean square percent deviation (e). The value of KARL PEARSON'S coefficient of correlation (r_1) can be estimated as:

$$r_1 = \frac{\sum (x_i - \overline{x})\,(y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2 \sum (y_i - \overline{y})^2}} \tag{15}$$

The value of e can be estimated as:

$$e = \sqrt{\frac{\sum \left[\frac{(x_i - y_i)}{x_i}\right]^2}{N_0}} \tag{16}$$

The coefficient of determination can be evaluated as the square of correlation coefficient (${r_1}^2$). It measures how well the model replicates experiential values (Chapra and Canale 1989, Nakara Chaudhary 2004). Furthermore, the experiment's internal uncertainty has been estimated.

Measurement uncertainty is influenced by both fixed and random errors. The value of standard uncertainty can be computed as (Bell 1999):

$$U_I = \sqrt{\sum_{t=1}^{N_s} \sqrt{\frac{\sigma_t^2}{N_o - 1}}} \tag{17}$$

Here, σ denotes the standard deviation and it can be computed as

$$\sigma = \sum_{t=1}^{N_o} (X_t - \bar{X})^2 \tag{18}$$

N_s denotes the number of sets and N_o denotes the total number of observations. The value of percentage uncertainty can be computed as

$$Percentage\ uncertainity = \frac{U_I}{Average\ of\ total\ number\ of\ observations} \times 100 \tag{19}$$

6.2 Uniform end of year annual cost (UEOYAC), cost of potable water (COPW) and productivity analyses:

6.2.1 UEOYAC analysis

The value of UEOYAC for SEBWP of single slope type integrated with N alike ETCs can be estimated as (Tiwari 2002):

$$UEOYAC = \mathrm{PC} \times \mathrm{CRF} + \mathrm{MC} \times \mathrm{CRF} - \mathrm{SV} \times \mathrm{SFF} \tag{20}$$

Where PC, SV, CRF, SFF and MC stand for present cost, salvage value, capital recovery factor, sinking fund factor and maintenance cost in that order. The value of MC may be estimated as the multiplication of PC with maintenance cost factor that is normally considered as 0.1. The value of CRF which is used for converting PC into UEOYAC and can be expressed as:

$$\mathrm{CRF} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{21}$$

and SFF can be written as

$$\mathrm{SFF} = \frac{i}{(1+i)^n - 1} \tag{22}$$

SFF is applied for converting SV into UEOYAC. In this case, i and n stand for the rate of interest and system life, respectively.

The value of PC for a SEBWP of single slope type integrated with ETCs with a 30-year life span can be calculated as

$$\mathrm{PC} = PI + P_{\mathrm{u}} + \frac{P_u}{(1+i)^{10}} + \frac{P_{\mathrm{u}}}{(1+i)^{20}} \tag{23}$$

Where, PI = $Cost\ of\ solar\ still + Cost\ of\ ETCs + Fabrication\ cost$ (24)

The cost of fabrication also involves piping and labor. Values of UEOYAC have been evaluated using equation (20) and they have been presented in Table 5. The required capital investment has been presented as Table 4.

6.2.2 COPW analysis

The cost of obtaining per kg of fresh water from SEBWP of single slope type integrated with ETCs can be written as

$$COPW = \frac{UEOYAC}{Annual\ yield} \tag{25}$$

Values of COPW have been estimated using equation (25) and they have been presented in Table 5.

.6.2.3 Productivity analysis

Productivity gives the relation between output and input and it is different from efficiency in the sense that the value of productivity should always be more than 100% whereas the value of efficiency should be less than 100%. Higher the pruductivity better will be the living standard of persons because higher productivity means more products are available for use. It is also expressed as the rtio of effectiveness and efficiency. The value of annual productivity for SEBWPof single slope type integrated with ETCs can be estimated as (Ashcroft 1950, Benson 1952, Cox 1951, International Labor Office 1979):

$$Productivity = \frac{Output\ from\ SEBWP\ integrated\ wit\ ETCs}{Input\ provided\ toSEBWP\ integrated\ wit\ ETCs} \times 100 \tag{26}$$

Here, output from SEBWPof single slope type integrated with ETCs represents the annual fresh water produced from the system. This output can be expresse in terms of rupees by multiplying the amount of annual fresh water in kg with unit cost (Rs./kg) of fresh water sold in the market. Hence, output from SEBWP of single slope type integrated with ETCs in terms of Rs. can be written as

$$Output\ from\ SEBWP\ integrated\ with\ ETCs = (Annual\ yield) \times (Selling\ price) \tag{27}$$

Input provided to SEBWPof single slope type integrated with ETCs will be UEOYAC and it can be estimated using equation (20). The productivity has been evaluated using equation (26) and has been presnted in Table 5.

6.3 Energy metrics analysis

The energy metrics analysis is an essential part of solar energy technology because the application of solar energy technology is not justifiable if energy produced by solar energy based system during the entire life span is less than the value of embodied energy of the solar system. It involve the calculation of energy payback time (T_{EPB}), life cycle conversion efficiency (η_{LCC}) & energy production factor (F_{EP}). Energy metrics offers the performance of the system over a longer period of time. The embodied energy encompasses both energy as well exergy; however, the exergy part is much higher than the energy part. Embodied energy is one of the most important parameters for the calculation of T_{EPB}. Economics of renewable energy system involves the selection of low embodied energy for the selected system. It is essential to focus on the energy densities of all the materials involves in the fabrication of the renewable energy assisted system to calculate the total embodied energy. Embodied energy of the different components has been determined by the product of mass of the component with the energy density of that material. Total embodied energy is calculated by sum of embodied energy for individual components.

6.3.1 T_{EPB} analysis

The term T_{EPB} for SEBWPof single slope type integrated with ETCs is the time span required to recover embodied energy which is known as the energy needed for the production of SEBWP of single slope type integrated with ETCs. The value of T_{EPB} can be calculated taking energy or exergy as the basis; however, the value of T_{EPB}on the basis of energy is far lower than the exergy based T_{EPB} because exergy means quality of energy and the amount of exergy produced by the system is much lower than the energy obtained from the system. A comparatively poorer value of T_{EPB} is expected as lower value of T_{EPB} means the energy or exergy based breakeven point will be obtained in lesser time and higher amount of energy will be produced which results in higher amount of carbon credit. $T_{EPB}$for SEBWP of single slope type integrated with ETCs on the basis of energy as well as exergy can be expressed as:

$$T_{EPB,energy} = \frac{Embodiedenrgy\ of\ SEBWP\ integrated\ with\ ETCs(E_{in})}{Annualenergyoutput\ obtained\ from\ SEBWP\ integrated\ with\ ETCs\ (E_{out})} \quad (28)$$

$$T_{EPB,exergy} = \frac{Embodiedenergy\ of\ SEBWP\ integrated\ with\ ETCs(E_{in})}{Annualexergyoutput\ obtained\ from\ SEBWP\ integrated\ with\ ETCs\ (E_{out})} \tag{29}$$

The value of hourly exergy rate can be estimated as follows:

$$Hourly\ exgy = h_{ewg} \times A \times \left[(T_w - T_{gi}) + (T_a + 273)ln\left\{\frac{(T_w+273)}{(T_{gi}+273)}\right\}\right] \tag{30}$$

6.3.2 $\boldsymbol{F_{EP}}$ analysis

The term $\boldsymbol{F_{EP}}$ for SEBWPof single slope type integrated with ETCs is defined as the ratio of Annual energy output obtained from SEBWP of single slope type integrated with ETCs to energy needed for the production of SEBWP of single slope type integrated with ETCs. Thus, F_{EP} is the reciprocal of term T_{EPB}that represents the overall performance of the system. The ideal value on annual basis is 1. Values of EPFF_{EP} for EBWP integrated with ETCs on the basis of energy as well as exergy can be estimated as:

$$\boldsymbol{F_{EP}}_{,energy} = \frac{Annualenergyoutput\ obtained\ from\ SEBWP\ integrated\ with\ ETCs\ (E_{out})}{Embodiedenergy\ of\ SEBWP\ integrated\ with\ ETCs(E_{in})} \tag{31}$$

$$\boldsymbol{F_{EP}}_{,exergy} = \frac{Annualenergyoutput\ obtained\ from\ SEBWP\ integrated\ with\ ETCs\ (E_{out})}{Embodiedexergy\ of\ SEBWP\ integrated\ with\ ETCs(E_{in})} \tag{32}$$

6.3.3 $\boldsymbol{\eta_{LCC}}$ analysis

The term η_{LCC} gives an idea about net output of SEBWP of single slope type integrated with ETCs with regard to solar energy impinging the surface of the system for the whole life span of the system. The ideal value of LCCE for SEBWP of single slope type integrated with ETCs is one. The system is considered performing better in the value of η_{LCC} is higher. Value of $\eta_{LCC}$for SEBWP of single slope type integrated with ETCs on the basis of energy and exergy can be estimated as

$$\eta_{LCC,exergy} = \frac{(Annual\ energy \times n) - E_{in}}{(Annual\ solar\ exergy) \times n} \tag{33}$$

$$\eta_{LCC,exergy} = \frac{(Annual\ exergy \times n) - E_{in}}{(Annual\ solar\ exergy) \times n} \tag{34}$$

The variation of monthly solar energy falling on the surface of system has been presented in Fig. 6. By adding monthly exergy for twelve months, value annual solar energy impinging on the surface can be estimated. Values of $\eta_{LCC,}$have been estimated using equations (32) and (33) and they have been presented in Table 6.

6.4 Exergoeconimic and enviroeconomic analyses of SEBWP of single slope type integrated with ETCs:

6.4.1Exergoeconimic analysis of SEBWP of single slope type integrated with ETCs:

The value of exergoeconomic parameter has been estimated using first and second laws of thermodynamics. This relationship means that the system is constructed in such a way that it achieves an overall optimum design by efficiently balancing the exergy and economic parameters. The exergoeconimic parameter relates either exergy loss or exergy gain with UEOYAC. In the case of exergy gain, the objective is maximization type, whereas, in the case of exergy loss, the objective is minimization type. The parameter exergoeconomic can be estimated as:

$$Exergoeconomic\ parameter = \frac{Annual\ exergy\ loss\ for\ SEBWP\ integarted\ with\ ETCs\ \ (L_{ex,annual})}{UEOYAC} \tag{35}$$

Here, rate of exergy loss for SEBWP can be estimated as

$$L_{ex,annual} = \left[(h_{cwc} + h_{rwc})\left\{(T_w - T_{gi}) + (T_a + 273)\ln\left\{\frac{(T_w+273)}{(T_{gi}+273)}\right\}\right\}\right] + \left[(M_w C_w)\left\{(T_{wf} - T_{wi}) + (T_a + 273)\ln\left\{\frac{(T_{wf}+273)}{(T_{wi}+273)}\right\}\right\}\right] \quad (36)$$

Here, h_{cwc} *and* h_{rwc} represent convective and radiative heat transfer coefficients from water surface to inside surface of condensing cover. M_w stands for mass of water in basin, T_{wf} is the final temperature of water and T_{wi} is the initial temperature of water.

6.4.2 Enviroeconomic analysis of SEBWP of single slope type integrated with ETCs:

It provides economic incentive for controlling environmental pollution so that the emission of pollutants can be reduced and motivates individual to apply renewable energy technology which does not affects the environment. It can be estimated as:

$$Enviroeconmic\ parameter = ((Annual\ energy\ out) \times n - Emb\text{odied energy})(0.002)(\text{CRP}) \quad (37)$$

8. Results and discussion

The data for one year from August 2018 to July 2019 was noted after installation of SEBWP of single slope type integrated with ETCs. These values of all relevant equations have been made input to programming code written in MATLAB. This MATLAB code has been used to estimate the values of water temperature, glass temperature and yield. These values have been plotted as shown in Fig. 3 and values of r and e were estimated using equations (15) and (16) respectively. The various performance parameters based on the output of MATLAB code have presented in Figs. 2-5 and Table 4 to Table 8.

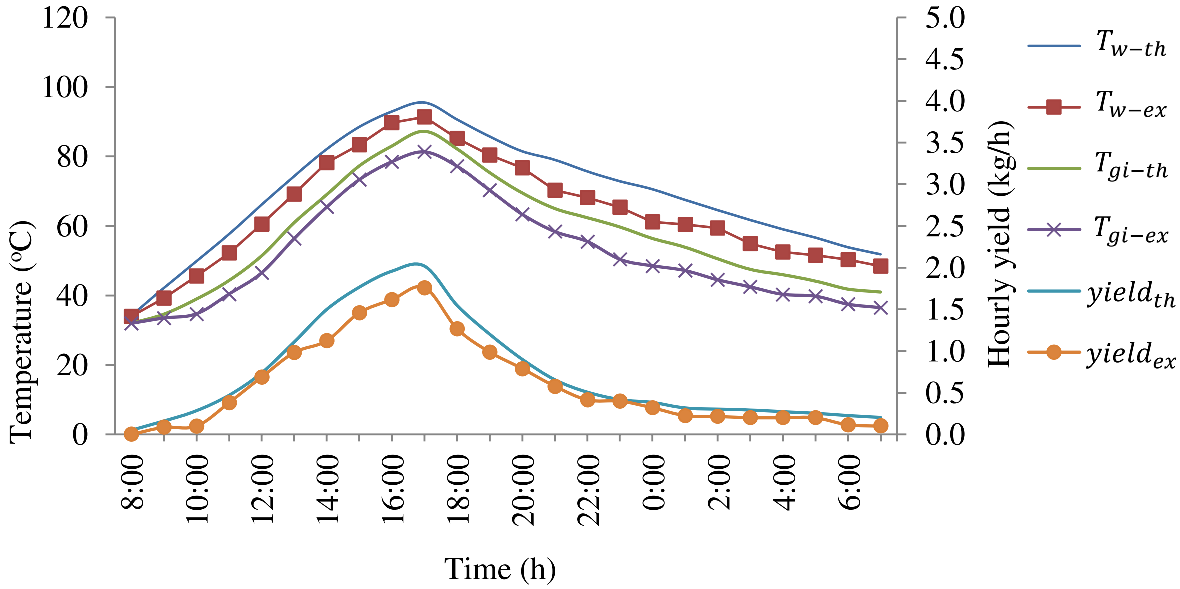

Fig. 2: Validation of values of T_w, T_{gi} and hourly yield on April 29, 2019 for SEBWP of single slope type integrated with evacuated tubular collectors

Table 3: Calculation for annual production of potable water for SEBWP of single slope type integrated with evacuated tubular collectors

Typical day of month	**Number of clear days (day)**	**Daily yield (Kg)**	**Monthly yield (Kg)**
02-08-18	18	8.95	161.14
28-09-18	19	8.90	169.19
11-10-18	27	9.70	261.98
07-11-18	24	3.54	84.94
16-12-18	29	1.79	51.92
03-01-19	17	2.40	40.80
03-02-19	13	3.15	40.91
19-03-19	29	5.53	160.37
29-04-19	28	14.20	397.71
19-05-19	30	10.16	304.89
08-06-19	24	11.15	267.55
02-07-19	16	10.07	161.12
Annual yield (Kg)			**2102.53**

Fig. 2 represents the validation of values of T_w, T_{gi} and hourly yield on April 29, 2019 for SEBWP of single slope type integrated with ETCs. Values of r and e for T_w, T_{gi} and hourly yield have been estimated using equations (15) and (16) respectively. It has been found that values of r varies from 0.9928 to 0.9951 and that of e varies from 8.2 % to 28.53% which show that there is a fair agreement between theoretically calculated vales and experimentally collected values for T_w, T_{gi} and hourly yield. Table 3 represents the evaluation of annual yield for SEBWP of single slope type integrated with ETCs based on experimentally collected values for typical day of each month.

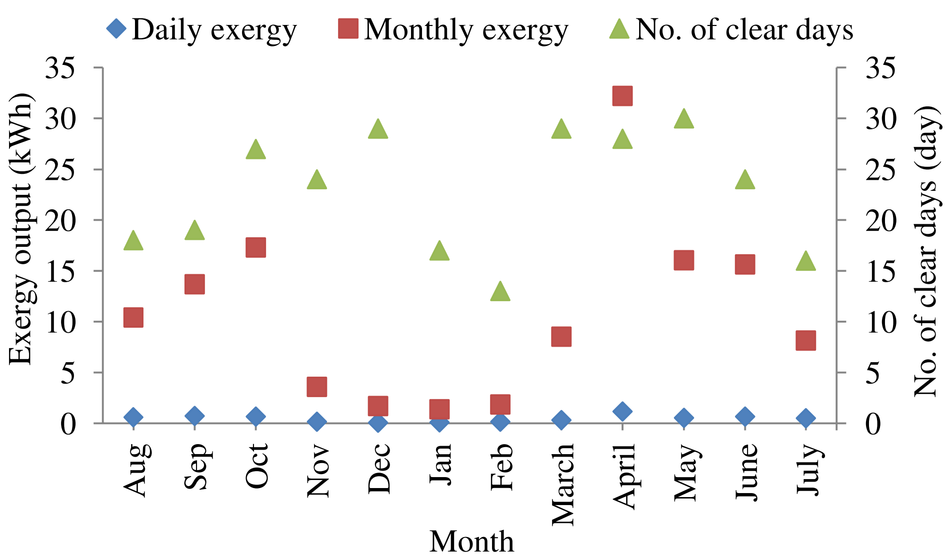

Fig. 3: Variation of monthly exergy output for SEBWP of single slope type integrated with evacuated tubular collectors

Fig. 3 represents the variation of monthly exergy output for SEBWP of single slope type integrated with evacuated tubular collectors. The hourly exergy output has been estimated using equation (30) followed by the estimation of daily exergy by summing hourly exergy for 24 h. The monthly exergy has been estimated by multiplying daily exergy with number of clear days in that month. It has been found that monthly exergy is maximum for April because of better solar intensity received in the month of April. Further, the value of monthly exergy depends on daily exergy and number of clear days.

Table 4: Capital investment for SEBWP of single slope type integrated with evacuated tubular collectors

S.N.	**Parameter**	**cost**
1	Solar still	12000
2	Copper tube @ 280 per meter	14924
3	Evacuated tube @500each	6500
4	Aluminum stand	3000
5	Iron stand for solar still	1000
6	Motor and pump	2000
7	Fabrication cost	5000
8	Salvage value of the system after 30 years taking inflation rate is 4%	13755.46

Table 5: Calculation of UEOYAC production cost and productivity for SEBWP of single slope type integrated with evacuated tubular collectors

Evaluation of UEOYAC								
S.N.	n (Year)	i (%)	PC Rs.	M Rs.	SV Rs.	$F_{CR,i,n}$ (Fraction)	$F_{SR,i,n}$ (Fraction)	UEOYAC Rs.
1	30	2	47410.64	4741.06	13755.46	0.045	0.025	2002.94
2	30	5	46405.61	4640.56	13755.46	0.065	0.015	3111.67
3	30	10	45492.37	4549.24	13755.46	0.106	0.006	5221.88
Evaluation of COPW and Productivity								
S.N.	n (Year)	i (%)	UEOYAC Rs.	AY (kg)	COPW (Rs./kg)	SP Rs.	RE Rs.	Productivity (%)
1	30	2	2002.94	2102.53	0.95	5	10512.65	524.86
2	30	5	3111.67	2102.53	1.48	5	10512.65	337.85
3	30	10	5221.88	2102.53	2.48	5	10512.65	201.32

The investment in installing SEBWP of single slope type integrated with ETCs has been presented in Table 4. The cost of different components is the price of products as per local market. Also, the salvage value has been estimated as per the local market price. UEOYAC for SEBWP of single slope type has been estimated using equation (20) and they have been presented in Table 5. The life span of SEBWP integrated with ETCs has been taken as 30 years except motor and pump. The life of pump with motor has been taken as 10 years and it has been assumed that the inflation after 10 years can be adjusted with its salvage value. The rate of interest has been considered as 2%, 5% and 10%. The value of UEOYAC is minimum for 2% rate of interest as 2% rate of interest is minimum. Values of COPW and annual productivity for SEBWP of single slope type integrated with ETCs has been estimated using equations (25) and 26 respectively and they have been presented in Table 5. It is found that the value of COPW is minimum for 2% rate of interest because UEOYAC is minimum for 2% rate of interest. Further, the value of productivity is maximum for 2% rate of interest as UEOYAC value is minimum for 2% rate of interest. Also, productivity is inversely proportional to UEOYAC as evident from equation (26). It has also been observed that the value of productivity is more than 100% for all interest rates under consideration. It means that the system is feasible.

Table 6 presents the calculation of embodied energy (E_{in}), energy payback time (T_{EPB}), energy production factor (F_{EP})and $\eta_{LCC}$for SEBWP of single slope type integrated with ETCs. Fig. 4 presents the variation of monthly solar energy falling on the surface of SEBWP of single slope type integrated with ETCs. The value of embodied energy has been estimated as the product of energy density (kWh/kg) and mass (kg). The mass of different components has been calculated as the product of density (kg/m^3) and volume (m^3). Values of $T_{EPB,energy}$ and $T_{EPB,exergy}$ has been found to be 1.72 year and 25.9 year respectively. The value of $T_{EPB,energy}$ is lower than $T_{EPB,exergy}$ because exergy represents the quality of energy (high grade energy) and hence lower value of exergy is obtained from SEBWP of single slope type integrated with ETCs. Values of $F_{EP,energy}$ and $F_{EP,exergy}$have been found to be 0.58 and 0.039. The value of $F_{EP,energy}$ is higher as F_{EP} is the reciprocal of T_{EPB} as evident from equations (31) to (34). Values of

$\eta_{LCC,energy}$ is higher than $\eta_{LCC,exergy}$ because exergy is lower than energy as exergy represents the quality of energy.

Table 6: Calculation of embodied energy (E_{in}), energy payback time (T_{EPB}), energy production factor (F_{EP}) and life cycle conversion efficiency ($\boldsymbol{\eta_{LCC}}$) for SEBWP of single slope type integrated with evacuated tubular collectors

Name of component	**Solar energy based water purifier of single slope type integrated with ETCs**
	Embodied energy (kWh)
Solar still	706.99
ETC (N=13)	1287.43
Others	20
Single slope PVT-FPC active solar distillation system	
Annual yield = 2102.53 kg	
Total embodied energy = 2014.42 kWh	
Net annual energy available from SEBWP of single slope type integrated with ETCs = 1170.95 kWh	
Net annual exergy available from SEBWP of single slope type integrated with ETCs = 77.76 kWh	
Life of the system(Year) = 30	
The value of T_{EPB} for SEBWP of single slope type integrated with ETCs based on energy (year) = 1.72	
The value of T_{EPB} for SEBWP of single slope type integrated with ETCs based on exergy (year) = 25.90	
The value of F_{EP} for SEBWP of single slope type integrated with ETCs based on energy (per year) = 0.58	
The value of F_{EP} for SEBWP of single slope type integrated with ETCs based on exergy (per year) = 0.039	
Solar energy for life time (E_{sol}) in kWh= 144770.23	
Solar exergy for life time (E_{sol}) in kWh= 134636.31	
The value of $\boldsymbol{\eta_{LCC}}$ for SEBWP of single slope type integrated with ETCs based on energy (fraction) = 0.23	
The value of $\boldsymbol{\eta_{LCC}}$ for SEBWP of single slope type integrated with ETCs based on exergy (fraction) = 0.0024	

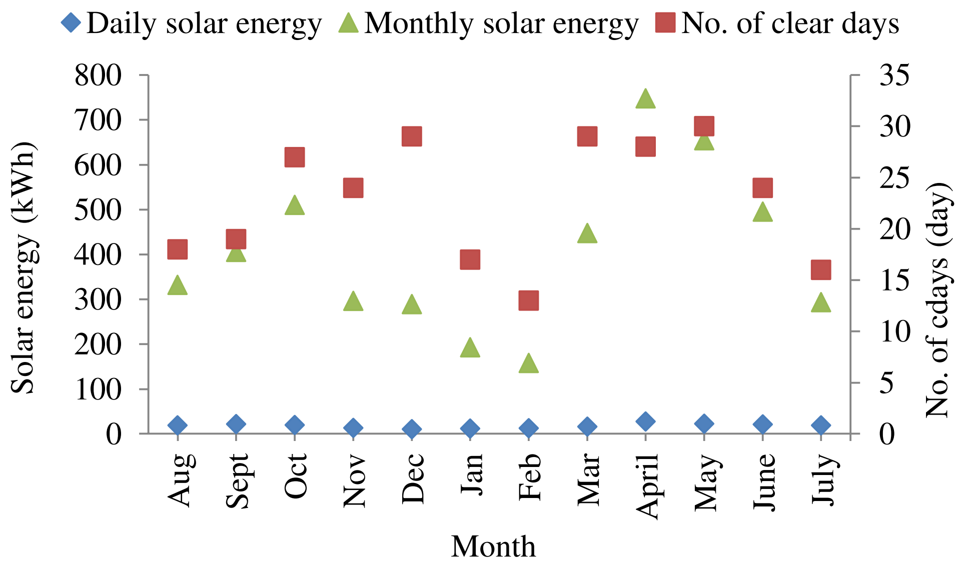

Fig. 4: Variation of monthly solar energy falling on the surface of SEBWP of single slope type integrated with evacuated tubular collectors

Table 7: Evaluation of exergoeconomic parameter for SEBWP of single slope type integrated with evacuated tubular collectors

S.N.	n (Year)	i (%)	UEOYAC (Rs.)	Annual Exergy loss (kWh)	Exergoeconomic parameter (kWh/Rs.)
1	30	2	2002.94	669.1278	0.334
2	30	5	3111.669	669.1278	0.215
3	30	10	5221.878	669.1278	0.1281

Table 8: Evaluation of enviroeconomic parameter for SEBWP of single slope type integrated with evacuated tubular collectors

	Single slope active solar still
Life (year)	30
Embodied energy (kWh)	2014.42
Net annual energy available (kWh)	1170.95
Net energy available (kWh) for life time	35128.50
CO_2 credit (t)	66.22
Environmental cost (Enviroeconomic parameter) ($)	960.31

Table 7 presents the estimation of exergoeconomic parameter for SEBWP of single slope type integrated with ETCs and Fig. 5 presents the variation of monthly exergy loss for SEBWP of single slope type integrated with ETCs. The value of exergoeconomic parameter has been found to be minimum for 10% rate of interest because UEOYAC is highest for this interest rate. Table 8 presents the evaluation of enviroeconomic parameter for SEBWP of single slope type integrated with ETCs. The carbon credit has been estimated as 66.22 t and the corresponding enviroeconimic parameter has been found to be 960.31$.

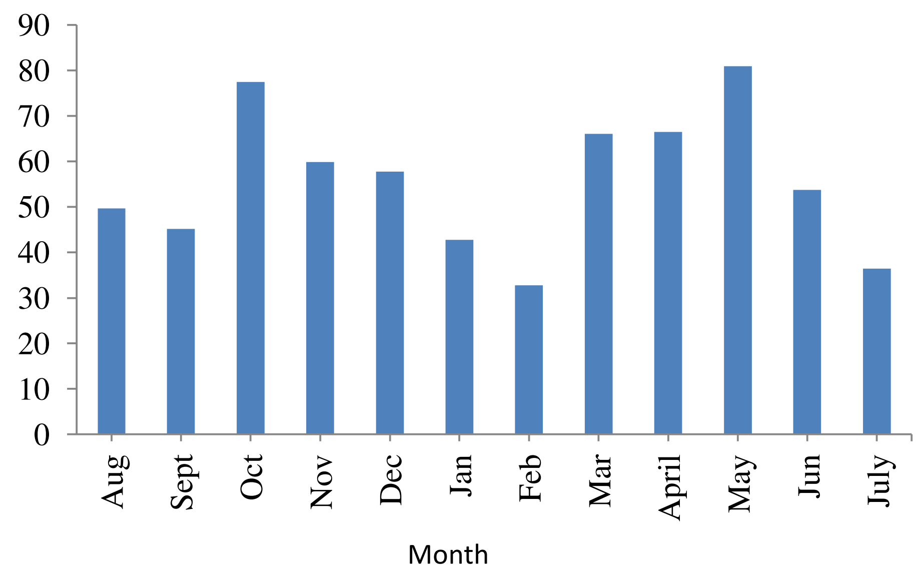

Fig. 5: Variation of monthly exergy loss for SEBWP of single slope type integrated with evacuated tubular collectors

8. Conclusions

The experimental study of SEBWP of single slope type integrated with ETCs has been carried out and based on the findings of this research; the following conclusions have been drawn:

i. A fair agreement has been found between experimental and theoretical values of T_w, T_{gi} and yield with correlation coefficient varying between 0.9928 and 0.9951.

ii. COPW values have been found to range from Rs. 0.95 to Rs. 2.48 as interest rates range from 2% to 10%.Values of productivity have been found to be more than 100% which represent that the system is feasible.

iii. Values of $T_{EPB,energy}$ and $T_{EPB,exergy}$ have been found to be 1.72 years and 25.90 years respectively; values of $F_{EP,energy}$ and $F_{EP,exergy}$ have been found to be 0.58 per year and 0.039 per year respectively; whereas, values of $\boldsymbol{\eta_{LCC,energy}}$ and $\boldsymbol{\eta_{LCC,exergy}}$ have been found to be 0.23 and 0.0024 respectively.

iv. The value of exergy loss (kWh) per unit UEOYAC (Rs.) has been found to vary between 0.13 and 0.33.

v. The value of enviroeconomic parameter has been found to be 960.31 $ for the system.

Appendix

$(AF_R(\alpha\tau))_1 = PF_1\alpha\tau^2 A_R F_R$; $\quad (A\,F_R U_L)_1 = (1 - K_k)\dot{m}_f c_f$;

$PF_1 = \frac{h_{pf}}{F' h_{pf} + U_{tpa}}$; $\quad U_L = \frac{U_{t,pa} \cdot h_{pf}}{F' h_{pf} + U_{t,pa}}$;

$$F_R = \frac{\dot{m}_f C_f}{U_L A_R}\left[1 - \exp\left(-\frac{2\pi r' L' U_L}{\dot{m}_f c_f}\right)\right] ;$$

$$K_K = \left(1 - \frac{A_R F_R U_L}{\dot{m}_f c_f}\right)$$

$$h_{pf} = 100\, W m^2 K^{-1}$$

$$U_{t,pa} = \left[\frac{Ro_2}{R_{o1} h_i} + \frac{R_{o2}\ln(\frac{Ri_2}{Ri_1})}{K_g} + \frac{1}{C_{ev}} + \frac{R_{o2}\ln(\frac{Ro_2}{Ro_1})}{K_g} + \frac{1}{h_o}\right]^{-1}$$

$$a_1 = \frac{1}{M_w C_w}\left[\dot{m}_f C_f (1 - K_k^N) + U_s A_b\right] ;$$

$$\overline{f_1}(t) = \frac{1}{M_w C_w}\left[\alpha'_{eff} A_b \overline{I_s}(t) + \frac{(1-K_k{}^N)}{(1-K_k)}(AF_R(\alpha\tau))_1 \overline{I_c}(t) + \left(\frac{(1-K_k{}^N)}{(1-K_k)}(AF_R U_L)_1 + U_s A_b\right)\overline{T}_a\right] ;$$

$$\alpha'_{eff} = \alpha'_w + h_1 \alpha'_b + h'_1 \alpha'_g \ ; h_1 = \frac{h_{bw}}{h_{bw} + h_{ba}} ;$$

$$h_1' = \frac{h_{1w}A_g}{U_{c,ga}A_g + h_{1w}A_b} \ ; h_{1w} = h_{rwg} + h_{cwg} + h_{ewg} \ ;$$

$$h_{ewg} = 16.273 \times 10^{-3} h_{cwg} \left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right] \ ;$$

$$h_{cwg} = 0.884 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}} ;$$

$$P_w = exp\left[25.317 - \frac{5144}{T_w + 273}\right] \ ; P_{gi} = exp\left[25.317 - \frac{5144}{T_{gi} + 273}\right] \ ;$$

$$h_{rwg} = (0.82 \times 5.67 \times 10^{-8})\left[(T_w + 273)^2 + (T_{gi} + 273)^2\right]\left[T_w + T_{gi} + 546\right] \ ;$$

$$U_s = U_t + U_b \ ; U_b = \frac{h_{ba}h_{bw}}{h_{bw} + h_{ba}} \ ; U_t = \frac{h_{1w}U_{c,ga}A_g}{U_{c,ga}A_g + h_{1w}A_b} \ ;$$

$$U_{c,ga} = \frac{\frac{K_g}{l_g}h_{1g}}{\frac{K_g}{l_g} + h_{1g}} \ ; h_{ba} = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb} + h_{rb}}\right]^{-1} \ ;$$

$$h_{cb} + h_{rb} = 5.7 \ Wm^{-2}K^{-1} \ , \ \ h_{bw} = 250 \ Wm^{-2}K^{-1} \ ;$$

Nomenclatures

SEBWP	solar energy based water purifier
ETCs	evacuated tubular collectors
N	number of evacuated tubular collectors
GI	galvanized iron
I(t)	solar intensity falling on the surface of collector, W/m^2
I_s(t)	solar intensity falling on the surface of SEBWP, W/m^2
R	outer radius of glass tube, m
F’	collector efficiency factor, fraction
h_{pf}	heat transfer coefficient from plate to fluid, W/m^2-K
T_p	temperature of absorber plate, ^{o}C
T_f	temperature of fluid/water, ^{o}C

T_a atmospheric temperature, ^oC

U_{tpa} overall heat transfer coefficient from plate to environment, W/m^2-K

$\dot{m}_f$ mass flow rate, kg/s

C_f specific heat capacity of fluid/water, kJ/kg-K

r radius of copper tube, m

T_{fo1} temperature of fluid at the outlet of first collector, ^oC

T_{fi} temperature of fluid at the inlet of first collector, ^oC

T_{foN} temperature of fluid at the outlet of Nth collector, ^oC

$\dot{Q}_{uN}$ rate of useful heat gain, kWh

A_g area of glass cover, m^2

h_{1w} total heat transfer coefficient from water surface to glass cover, W/m^2-K

T_w temperature of water, ^oC

T_{gi} temperature at inside surface of glass, ^oC

T_{go} temperature at outside surface of glass, ^oC

A_b area of basin liner, m^2

K_g thermal conductivity of glass, W/m-K

L_g thickness of glass cover, m

h_{1g} total heat transfer coefficient from glass surface to ambient, W/m^2-K

h_{bw} heat transfer coefficient from basin liner to water, W/m^2-K

T_b temperature of basin liner, ^oC

M_w mass of water in basin, kg

h_{ba} heat transfer coefficient between basin liner and ambient, W/m^2-K

$\dot{m}_{ew}$ hourly water yield, kg/h

r_1 coefficient of correlation, fraction

e	root mean square percent deviation, %
${r_1}^2$	coefficient of determination, fraction
U_I	standard uncertainty
σ	standard deviation
UEOYAC	uniform end of year annual cost, Rs.
COPW	cost of potable water, Rs./kg
PC	present cost, Rs.
CRF	capital recovery factor, fraction
MC	maintenance cost, Rs.
SFF	sinking fund factor, fraction
i	interest rate, %
n	life of system, year
SV	salvage value, Rs.
P_u	cost of pump, Rs.
T_{EPB}	energy payback time, Year
F_{EP}	energy production factor, per year
η_{LCC}	life cycle conversion efficiency, fraction
E_{in}	embodied energy, kWh
h_{cwc}	convective heat transfer coefficients from water surface to inside surface of condensing cover, W/m^2-K
h_{rwc}	radiative heat transfer coefficients from water surface to inside surface of condensing cover, W/m^2-K
T_{wf}	final temperature of water, ^oC
T_{wf}	initial temperature of water, ^oC

CRP carbon dioxide reduction price, $

R_{i1} inner radius of inner cylindrical glass tube, m

R_{i2} outer radius of inner cylindrical glass tube, m

R_{o1} inner radius of outer cylindrical glass tube, m

Ro_2 outer radius of outer cylindrical glass tube, m

α absorptivity

τ transmissivity

$\acute{\alpha}_g$ effective absorptivity of glass

$\acute{\alpha}_w$ effective absorptivity of water

$\acute{\alpha}_b$ effective absorptivity of basin liner

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Declaration of competing Interest

The authors declare that there is no competing interest

Availability of data and materials

All data are given in the manuscript

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Sanjeev Kumar Sharma - Writing-review & editing

Ashis Mallick – Writing, Formal analysis,

Desh Bandhu Singh- Data curation, Project administration, Software, review & editing

Gopal Nath Tiwari - Review & editing

Figures

Figure 1

Experimental setup of SEBWP of single slope type integrated with evacuated tubular collectors

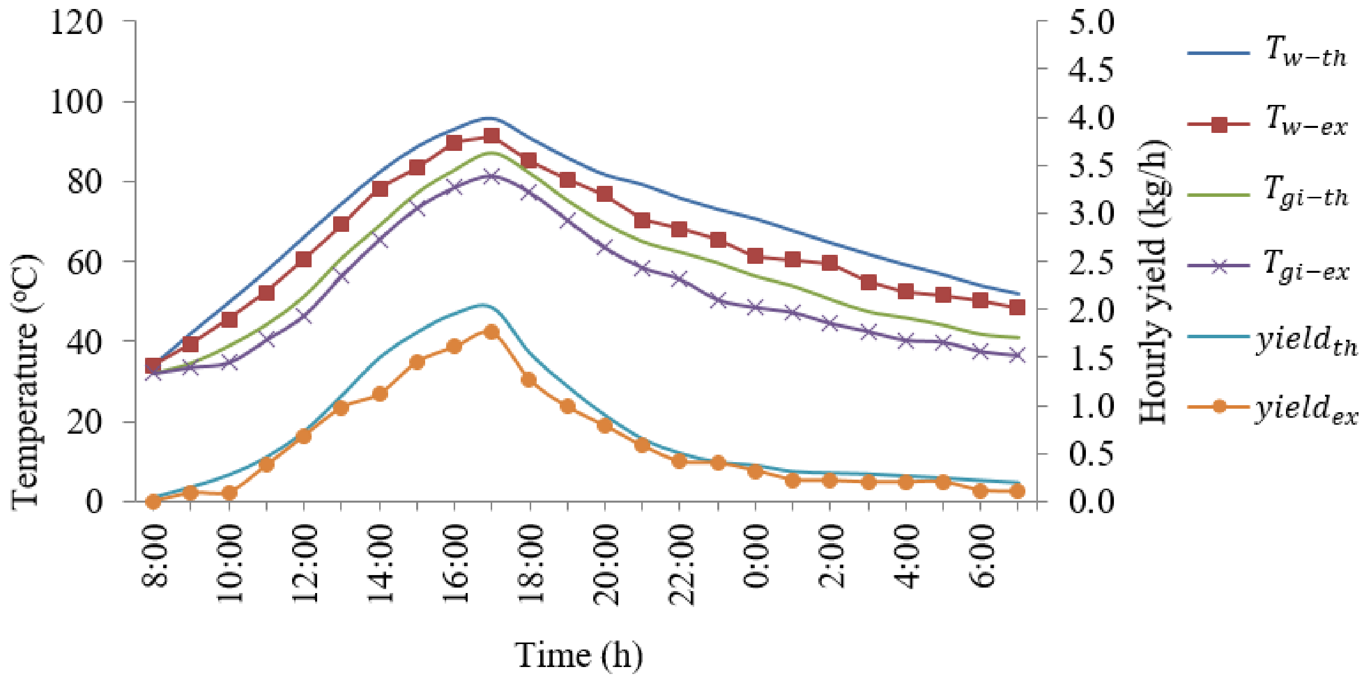

Figure 2

Validation of values of Tw, Tgi and hourly yield on April 29, 2019 for SEBWP of single slope type integrated with evacuated tubular collectors

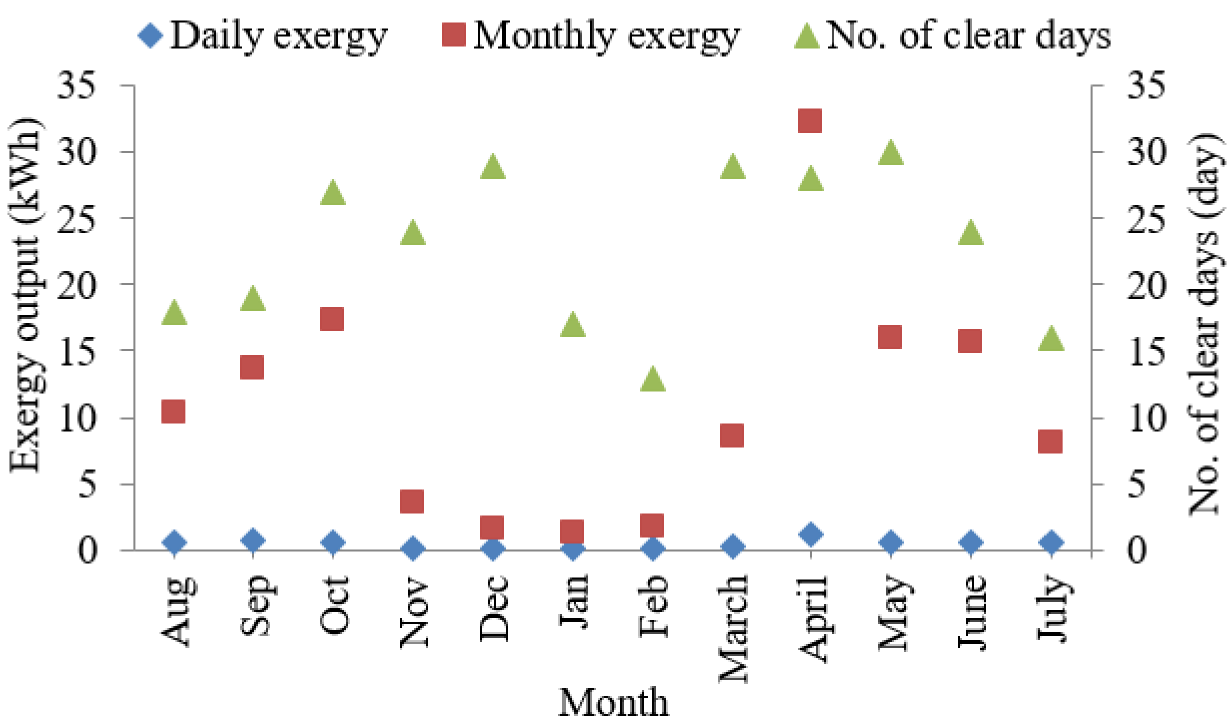

Figure 3

Variation of monthly exergy output for SEBWP of single slope type integrated with evacuated tubular collectors

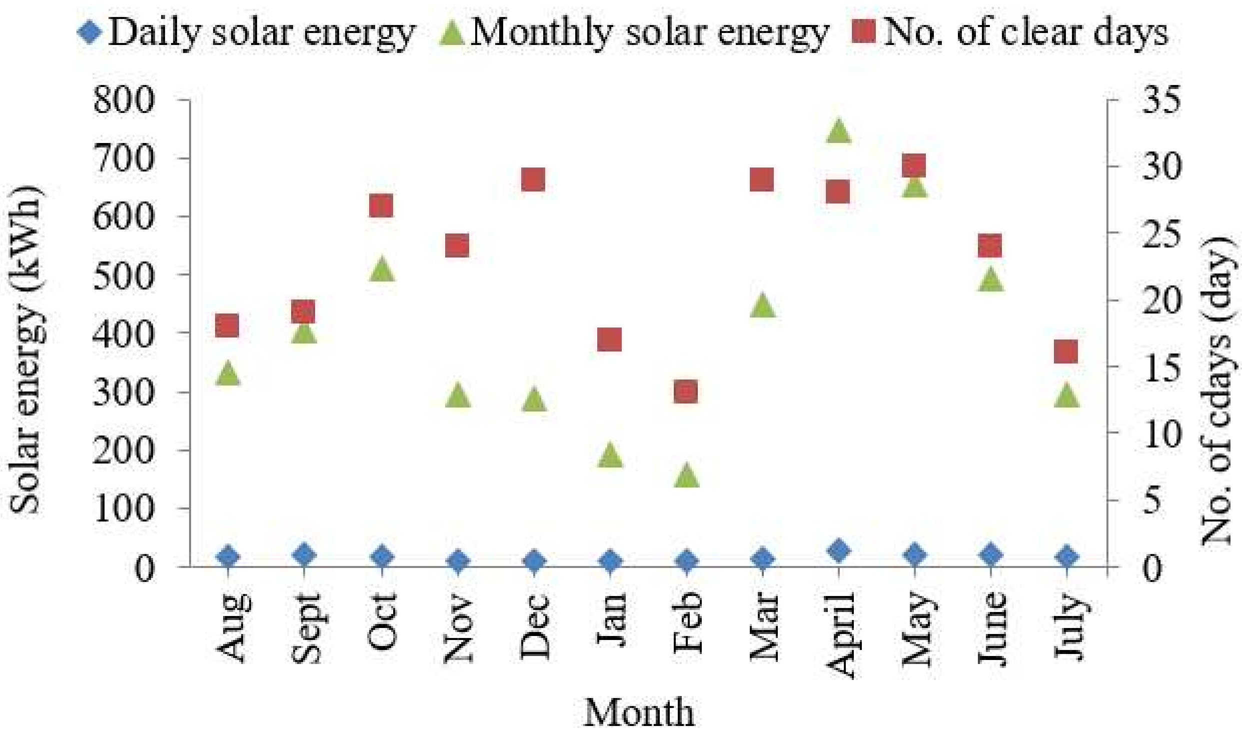

Figure 4

Variation of monthly solar energy falling on the surface of SEBWP of single slope type integrated with evacuated tubular collectors

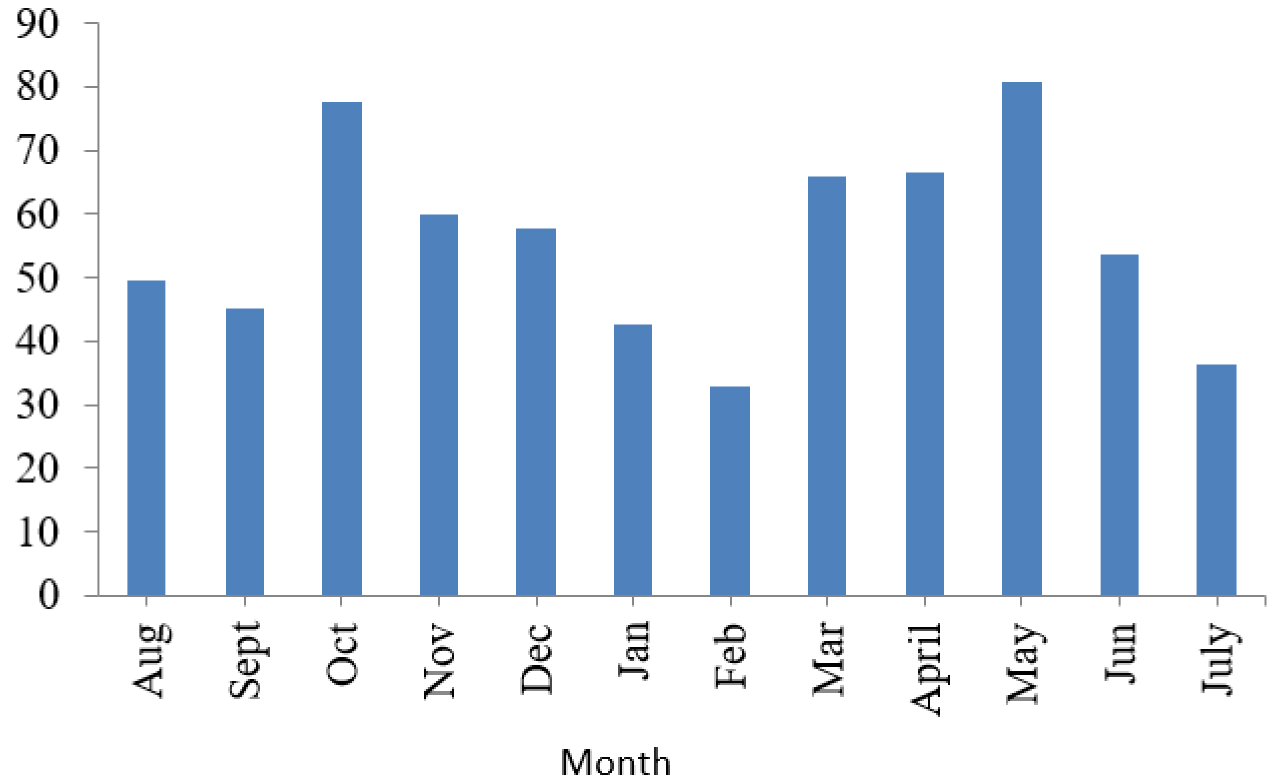

Figure 5

Variation of monthly exergy loss for SEBWP of single slope type integrated with evacuated tubular collectors