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Production of clean water using ETC integrated solar stills: thermo-enviro-economic assessment

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ABSTRACT

In this communication, a comparative performance study of single basin solar still augmented with evacuated tube collectors under natural (ETC integrated single slope solar still in natural mode) as well as in forced mode (ETC integrated single slope solar still in force mode (EISSF)) has been carried out for the socio-economic viability. Annual yield and life cycle conversion efficiency obtained under forced mode have been found as 1,134.5 kg and 28.8%, while under natural mode as 1,074 kg and 27.3%, respectively. The net ton of carbon dioxide (tCO_2) mitigation under forced and natural mode is estimated as 34.82 and 33.1 tons, respectively. Respective energy and distillate production cost from EISSF system has been obtained as Rs. 0.47 kWh^{-1} and Rs. 0.32 kg^{-1} accounting 30 y life and 2.0% interest rate. With an increase in the selling rate of product from Rs. 2.0 to 6.0 kg^{-1}, the cost payback time decreases significantly and found in the range of 6.4–2.1 y with EISSF, while-in the range 5.7–2.0 y under natural mode. The higher production, efficiency, and environmental reduction of harmful gases under forced mode are advantageous over natural mode and over the other conventional solar distillation systems.

Keywords: Solar still; Evacuated tube collector; Energy and production cost; tCO_2 emission; Payback period

1. Introduction

Energy and water are indispensable resources for the development of a nation. In the current scenario, about 2.1 billion humans worldwide have an inadequacy of potable water and remote arid regions are highly water-stressed (WHO report 2017). The industrialization of societies, population growth, and unsustainable consumption rates have caused the unbalance between the demand and the accessibility of potable water. Various conventional techniques are in use since the past to produce potable water, but these technologies depend on fossil fuels, energy-intensive, and contribute to greenhouse gas emissions (GHGs). The ecological factors relevant to water quality have significant socio-economic dimensions and harmful emissions to the atmosphere, raising the environmental concern globally. There is a relationship between economic growth and tCO_2 mitigation in countries like India, Brazil, and South Africa due to environmental revenue. Among the greenhouse gases, CO_2 (GWP) emission contributes around 57% of global warming. The CO_2 emission per kg freshwater production from the traditional water desalination plants is illustrated in Table 1.

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Table 1
Contribution of CO_2 emissions per kg of water produced [31]

	Multi-stage flash distillation (MSF)	Multi-effect distillation (MED)	Mechanical vapor compression (MVC)	Electrodialysis (ED)	Reverse osmosis (RO)	Solar still (SS)
CO_2 emission (kg)	0.09	0.04	0.051	0.38	0.032	00

Prabhakant and Tiwari [1] reported that greenhouse gases emission contributes to 5.72% worldwide. Kyoto Protocol of 1997 allowed companies in developing nations to reduce CO_2 emissions and earn credits. Indian companies have accumulated about 345 million credits in the past. Solar distillation plays an important role not only in the reduction of greenhouse gases emission but also in energy security and carbon trading. Many attempts have been made globally to enhance the productivity of solar stills due to their beneficial impact on the environment to reduce harmful CO_2 emissions.

Solar energy has many applications, such as desalination of brackish/saline water to produce potable water at an affordable cost in an eco-friendly manner, using a device known as a solar still. However, though the solar still needs more area, it is an attractive consideration, especially in arid and remote areas blessed with plenty of solar energy and inexpensive land and favorable compared to the traditional desalination methods. Swedish engineer Carlos Wilson in 1872 (worked till 1910) in Las Salinas, Chile built a plant of 64 basins (4,459 m^2) of capacity 20,000 L d^{-1}. Various solar distillation methods have been studied since the past to desalinate the impure water. Based on the method of energy fed, solar distillation is broadly classified as passive and active distillation, with various designs reported [2–5]. The single basin solar still is used mostly as a solar distiller under passive mode. However, low productivity (yields a maximum of about 2.0–3.0 kg d^{-1}) from the passive solar design is a barrier to meet the requirement. Tiwari et al. [6] reported higher output from the solar still with a single slope than the double slope during winter, but in summer, vice versa. Rufuss et al. [7] reviewed the work to improve the productivity of solar still using various methods and approaches. They observed that high-temperature distillation can be performed by supplying preheated water through some external source, and most commonly incorporating the solar collector to enhance the output. Rai and Tiwari [8] found academic enhancement of daily output (24%) from flat plate collectors (FPC) integrated solar still using a pump and by 33% in natural circulation mode [9], compared to the passive system. Kumar and Tiwari [10] found maximum yield using FPC coupled solar still with an optimum number of collectors (four) of 8.0 m^2 surface area. Tiwari et al. [11] theoretically investigated that evacuated tube collectors (ETC) heat pipe integrated solar still produce the daily output of 4.24 kg m^{-2}, maximum among other designs.

Further, the experimental work carried out on hybrid (photovoltaic thermal (PVT)) solar still with an enhancement of output by 3.5 folds of passive mode operation [12]. Mishra et al. [13] carried out the performance investigation of PVT-CPC coupled solar still in natural mode and estimated overall energy efficiency of 9.8% from active solar still compared to 24.2% from conventional one. Solar still with black steel wool fibers at 60% preheating produces a distillate yield of 3.534 kg m^{-2} d^{-1} with 38.07% efficiency, which is higher by 51.4% and 38%, respectively, than the conventional design [14]. The effect of inclination of conical shape condensing cover on yield using PVT active solar still was investigated and found optimal at 60° inclination with 0.01 m water depth and 0.01 kg s^{-1} flow rate [15]. Further, a decrease in the yield was reported with increased water depth and mass flow rate. Sharma et al. [16] developed a characteristic equation for dual slope solar still integrated with "*N*" identical PC-ETC and concluded that the average value of instantaneous efficiency is higher by 46.18% than the ETC integrated system. The effect of reducing the size of the droplets was investigated on the solar desalination and found at 70°C temperature, and found the best condition of desalination at the nozzle outlet diameter of 0.0009 m at 0.9 discharge coefficient [17].

The present research indicates a growing trend with ETC because of various advantages associated with the FPC. Better performance using ETC over FPC has been reported when the system operates at high temperature and found an increase in the yield by 32% by coupling single slope solar distiller with ETC under thermosyphon manner [18,19]. Dev and Tiwari [20] observed an annual yield of 630 kg m^{-2} from the solar still coupled with an ETC water heater, which was about 2.0 times higher than the passive mode, with an annual energy efficiency of 21.3% and production cost of \$0.128 kg^{-1}. Singh et al. [21] theoretically predicted that ETC coupled single slope solar still in thermosyphon mode yields 3.8 kg m^{-2} d^{-1} during summer at 0.03 m depth of water and recommended the use of ETC size consisting of 10 tubes in view of efficiency and yield. Xiong et al. [22] experimented ETC connected solar still with folded plates under thermosyphon circulation and found a 64% increase in the yield.

The study carried out by the researchers on ETC integrated solar still in natural mode was extended to the forced mode and optimum results were found at 0.06 kg s^{-1} flow circulation rate [23] with daily output and energy efficiency as 3.9 kg and 33.8%, respectively, on a typical day during summer. Yari et al. [24] carried out work on solar still integrated with ETC under thermosyphon mode and topped with a semi-transparent PV module. They found daily productivity ~2.3 kg m^{-2} maintaining 0.07 m depth of basin water along with 10 tubes while 4.76 kg m^{-2} d^{-1} with 30 tubes. Sinha et al. [25] found less energy production cost from active solar still (Rs. 0.69 kWh^{-1}) than the water heater (Rs. 1.80 kWh^{-1}). Kumar [26] reported energy and potable water generation rates as Rs. 0.85 kWh^{-1} and Rs. 1.42 kg^{-1} for 15 y of life, which was reduced to Rs. 0.93 kg^{-1} accounting for the carbon credit earned at €10/tCO_2.

Patel et al. [27] found a maximum yield of 4.05 kg m^{-2} of ETC coupled stepped solar still with overall efficiency as 28.23% and 2.35 y payback time taking 10 y expected life of the system. Recently, Dubey et al. [28] reported distillate production cost as Rs. 0.32 kg^{-1} based on environment energy cash flow, accounting carbon pricing \$5.0/ tCO_2, and 30 y of life for the ETC coupled dual-slope solar still operating in a forced manner at a low water depth of 0.005 m. Table 2 represents the production cost of distillate reported for some designs of the solar stills.

From the literature survey, it has been found that very few researchers have analyzed the use of ETC with solar still, and no exhaustive comparative analysis of ETC coupled single slope solar distiller in natural and forced mode has been reported under similar climatic conditions and accounting for the environmental-economic due to carbon trading. Hence, the comparative performance investigation of single solar still integrated with identical ETC tubes in a natural and forced manner has been carried out for the first time. The various advantages associated with the forced mode over the natural mode motivated to study the comparative performance of the two arrangements from the thermal, environmental, and economic points of view.

The objective of the present work is to carry out comparative long-term performance study and thermo–enviro-economic analysis of single slope solar still operating in natural as well as in forced mode, to check the comparative socio-economic viability for their use. Further, a comparative assessment in terms of yield, energy efficiency, life cycle conversion efficiency, energy production cost, payback time, etc., has also been analyzed for both the arrangements accounting tCO_2 emission/mitigation.

2. System description

A schematic of ETC integrated single slope solar still in natural mode (EISSN) with a basin size of 1.0 m^2, made of FRP is shown in Fig. 1a. On the top, a glass cover of 0.004 m thickness and 0.76 W m^{-1} K^{-1} thermal conductivity is fixed at 15° inclination with proper sealing to prevent vapor leakage. Evacuated tubes of length 1.4 m and center spacing of 0.07 m are fixed at the bottom of the basin at 45° inclination from due south. After reflection and absorption of some part, the radiations are transmitted through the glass cover and reach the basin water. Some percentiles of the transmitted energy are absorbed by the basin water mass, while some are reflected at the interface, and the remaining reaches the blackened basin liner and gets absorbed. The basin water gets heated and evaporated vapor moves and condenses on the inner glass cover. The condensed water film flowed down due to the inclination of glass and collected in a trough fabricated at the lower end and flows out through a connected pipe in a pot placed outside. Under natural configuration (EISSN), water circulates between the evacuated tubes and solar still in the thermosyphon effect. The solar heat absorbed by the inner ETC tubes moves into water flowing through and finally supplied into the basin with a rise in temperature, where intermixing of water takes place. The system's modified geometry under forced mode (EISSF) operation is shown in Fig. 1b. To meet the uniform flow in each tube, a header with a variable cross-section is used. In forced mode, a DC pump of low mass flow is used to circulate the water between the basin and ETC in a close loop.

The design specification of both the geometries is similar, the only difference being that in EISSF, the circulation of water between basin and ETC is carried out with the help of a small pump in a controlled manner. The design specifications of the complete system are given in Table 3.

3. Thermal analysis

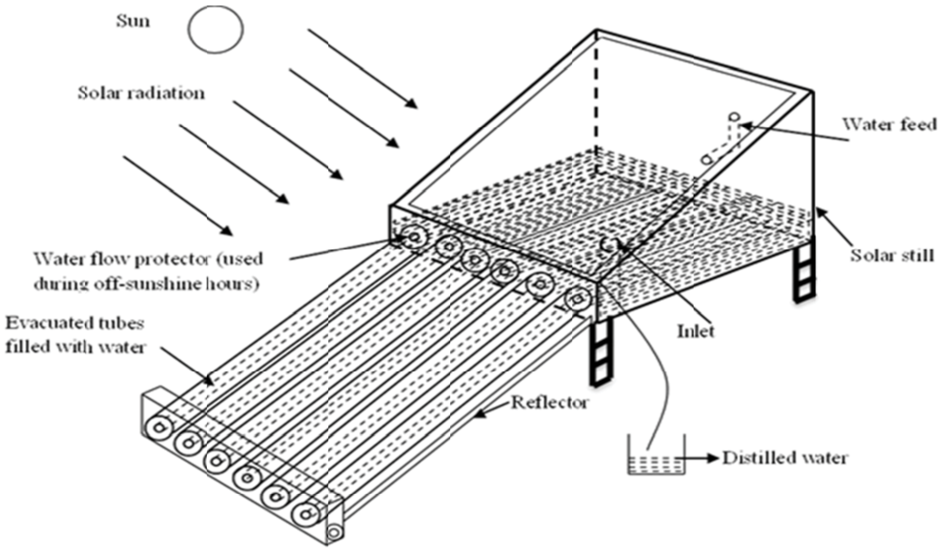
To evaluate the temperatures, output, and energetic performance, and the thermal equations are developed with the help of relations given in Appendix-A. These equations are then solved to estimate the temperature, yield, energy, and other parameters with the following assumptions.

- no vapor leakage from the system as it is sealed by the rubber sealant and window putty from the top,
- negligible heat capacities of basin and glass,
- no temperature drop in the connecting pipe,
- the system operates in a quasi-steady state,
- the water level in the basin is constant.

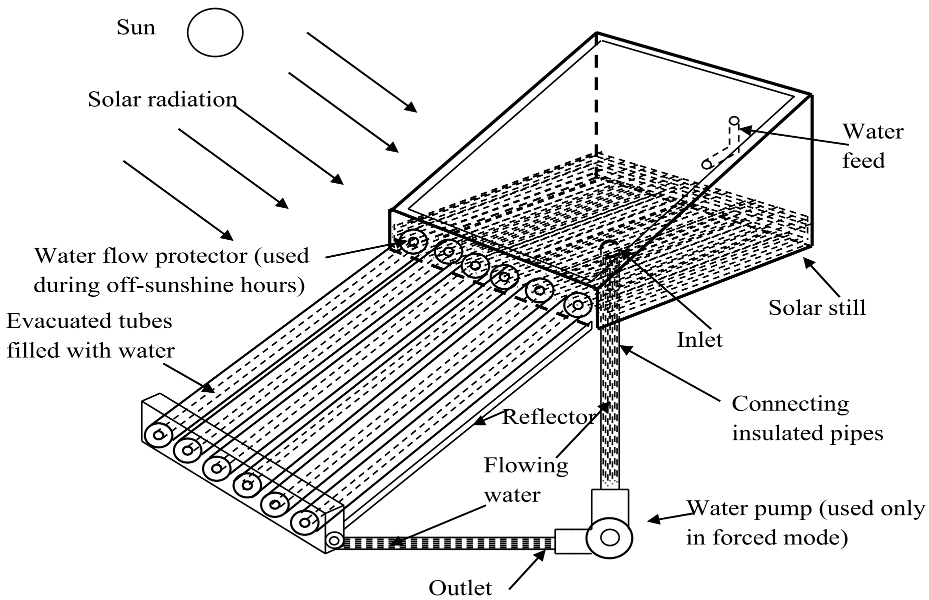
Using the equations reported the linear equations for water temperature attainable within the evacuated tubes and solar still can be expressed as follows.

Table 2
Cost of distillate (1\$ = Rs. 65 in 2019)

Reference	Configuration	Production cost
[32]	Large size solar distillation plant	\$20 m^{-3} ≈ Rs. 1.3 kg^{-1}
[33]	Cluster of 250 passive solar stills	\$16.3 m^{-3} ≈ Rs. 1.06 kg^{-1}
[34]	Pyramid shaped solar still	\$30 m^{-3} ≈ Rs. 1.95 kg^{-1}
[35]	Using porous basin passive solar stills for 50 m^3 d^{-1} production	\$2.4 m^{-3} ≈ Rs. 0.16 kg^{-1}
[12]	Hybrid (PVT) basin type solar still (single slope) for 269 clear day without carbon credit and 30 y life with replacement of FPC after 15 y	Rs. 1.93 kg^{-1}
	Basin type single slope passive solar still for 269 clear day and 30 y life without carbon credit	Rs. 0.70 kg^{-1}
[36]	Double basin ETC connected solar still under natural mode (P_s = Rs. 9,151)	Rs. 0.37 kg^{-1}
[27]	ETC integrated stepped solar still in natural mode (10 y expected life)	Rs. 4.0 kg^{-1}



(a)



(b)

Fig. 1. Schematic of (a) EISSN and (b) EISSF solar still.

Table 3
Specifications of ETC coupled EISSN and EISSF distillation system

Parameters	Value	Parameters	Value
Basin area	1 m^2	Conductivity of glass	0.78 $Wm^{-1} K^{-1}$
Glass area	1.14 m^2	Glass thickness	0.004 m
Thickness of basin	0.005 m	Conductivity of basin	0.351 $Wm^{-1} K^{-1}$
Outer diameter of tube	0.047 m	Tubes No.	10
Tube inner diameter	0.044 m	Water per tube	2.25 kg
Center distance between tubes	0.07 m	Length of tube	1.4 m
		Surface area of tube	0.21 m^2

Pump size for EISSF 12 V, 24 W, variable mass flow, connecting pipe-1/2″ GI

3.1. Evacuated tubes

With the help of energy balance, the linear equation for water mass inside the ETC can be written as [23]:

$$\frac{dT_{cw}}{dt} + a_1 \cdot T_{cw} + b_1 \cdot T_{sw} = g_1(t) \tag{1}$$

where

$$a_1 = \frac{\left(N_c \dot{m} \cdot c_w + a' A_t N_c\right)}{M_{cw} \cdot c_w} b_1 = -\frac{N_c \dot{m}}{M_{cw}} g_1(t) = \frac{A_t N_c \left[I_c(t)\eta_o + a' T_a\right]}{M_{cw} c_w}.$$

3.2. Single slope solar still

The energy balance equation for basin water mass can be expressed as [23]:

$$\frac{dT_{sw}}{dt} + a_2 \cdot T_{cw} + b_2 \cdot T_{sw} = g_2(t) \tag{2}$$

where

$$a_2 = -\frac{\dot{m} \cdot N_c}{M_{sw}}; \quad b_2 = \frac{\dot{m} N_c \cdot c_w + U_L}{M_{sw} \cdot c_w}; \quad g_2(t) = \frac{(\alpha\tau)_{eff} \cdot I_s(t) + U_L \cdot T_a}{M_{sw} \cdot c_w};$$

$$U_L = \frac{h_{bw} \cdot h_{ba}}{h_{bw} + h_{ba}} \cdot A_b + \frac{h_{1w} \cdot h_{go}}{h_{1w} \cdot A_b + h_{go} \cdot A_g} \cdot A_b \cdot A_g + h_s \cdot A_s;$$

$$(\alpha\tau)_{eff} = \alpha'_w \cdot A_b + \frac{h_{bw} \cdot \alpha'_b \cdot A_b}{h_{bw} + h_{ba}} + \frac{h_{1w} \cdot \alpha'_g \cdot A_b \cdot A_g}{h_{1w} \cdot A_b + h_{go} \cdot A_g}.$$

The rate of heat flow within the ETC tube from the circumference may be expressed as [18]:

$$\dot{q} = \frac{\dot{Q}_{u,ETC}}{N_c A_t} = \frac{\left[I_c(t)\eta_o - a'\left(T_{cw} - T_a\right)\right] A_a}{N_c A_t}, \tag{3}$$

$$\text{and } \mathrm{Re} = \frac{4\dot{m}}{\pi d_t \cdot \mu} = 0.192 \left[\frac{\mathrm{Nu} \cdot \mathrm{Gr} \cos\theta}{\mathrm{Pr}} \left(\frac{l_t}{d_t}\right)^{1.2}\right]^{0.4084}$$

Upon further solving, the mass flow rate (kg s^{-1} tube^{-1}) in tube inclined at θ° may be expressed as [18]:

$$\dot{m} = 0.0478 \pi d_t \cdot \mu \left[\frac{\mathrm{Nu} \cdot \mathrm{Gr} \cos\theta}{\mathrm{Pr}} \left(\frac{l_t}{d_t}\right)^{1.2}\right]^{0.4084} \tag{4}$$

where

$$\mathrm{Nu} \cdot \mathrm{Gr} = \frac{g\beta \dot{q} d_t^4}{k\nu^2}, \quad \mathrm{Pr} = \frac{\mu c_w}{k}.$$

Following Kumar [26], the inner (T_{gi}), outer glass cover (T_{go}), and basin liner (T_b) temperature can be estimated as:

$$T_{gi} = \frac{\alpha'_g \cdot I_s(t) \cdot A_g + h_{1w} \cdot A_b \cdot T_{sw} + h_{go} \cdot A_g \cdot T_a}{h_{1w} \cdot A_b + h_{go} \cdot A_g} \tag{5a}$$

$$T_{go} = \frac{h_{kg} \cdot T_{gi} + h_o \cdot T_a}{h_{kg} + h_o} \tag{5b}$$

$$T_b = \frac{\alpha'_b \cdot I_s(t) + h_{bw} \cdot T_{sw} + h_{ba} \cdot T_a}{h_{bw} + h_{ba}} \tag{5c}$$

The value of temperature dependent heat transfer coefficients can be estimated using the expression given in Appendix-A.

On solving the Eqs. (1) and (2) and with the following assumptions, the water temperature at the outlet of ETC and in the solar still can be estimated and expressed by Eqs. (6) and (7).

- small time interval
- T_{cwo} and T_{swo} are the initial values of respective temperatures at $t = 0$
- no flow of water through ETC during off-sunshine hours

On simplyfing, water temperature at the outlet of ETC may be obtained as:

$$T_{cw} = \frac{1}{\left(\gamma^+ - \gamma^-\right)} \left[\begin{array}{l} \overline{g_1(t)} \left\{ \frac{\gamma^+ \left(1 - e^{-c^- t}\right)}{c^-} - \frac{\gamma^- \left(1 - e^{-c^+ t}\right)}{c^+} \right\} + \\ \gamma^+ \cdot \gamma^- \overline{g_2(t)} \left\{ \frac{\left(1 - e^{-c^- t}\right)}{c^-} - \frac{\left(1 - e^{-c^+ t}\right)}{c^+} \right\} + \\ T_{cwo}\left(\gamma^+ e^{-c^- t} - \gamma^- e^{-c^+ t}\right) + \gamma^+ \cdot \gamma^- T_{swo}\left(e^{-c^- t} - e^{-c^+ t}\right) \end{array}\right] \tag{6}$$

and water temperature in the solar still may be obtained as:

$$T_{sw} = \frac{1}{\left(\gamma^+ - \gamma^-\right)} \left[\begin{array}{l} \overline{g_1(t)} \left\{ \frac{\left(1 - e^{-c^+ t}\right)}{c^+} - \frac{\left(1 - e^{-c^- t}\right)}{c^-} \right\} + \\ \overline{g_2(t)} \left\{ \frac{\gamma^+ \left(1 - e^{-c^+ t}\right)}{c^+} - \frac{\gamma^- \left(1 - e^{-c^- t}\right)}{c^-} \right\} + \\ T_{cwo}\left(e^{-c^+ t} - e^{-c^- t}\right) + T_{swo}\left(\gamma^+ e^{-c^+ t} - \gamma^- e^{-c^- t}\right) \end{array}\right] \tag{7}$$

where $(a1 + \gamma a_2) = c$; $(b_1 + \gamma b_2) = \gamma c$ and γ^+ and γ^- corresponding values of c^+ and c^-.

Thermal energy supplied by the ETC collector to the solar still can be expressed as:

$$\dot{q}_{uc} = \dot{m}_{uc}\left(T_{cw} - T_{cwo}\right) \times N_c \quad (8)$$

The hourly yield from solar still can be estimated as [12]:

$$m_{ew} = \frac{h_{ew}\left(T_{sw} - T_{gi}\right) \times 3{,}600}{L} \quad (9)$$

4. Performance parameters

Energy conversion and economics of any system determine its effective utilization in life. To check the thermo-economic viability of systems, the following performance parameters are evaluated for the natural (EISSN) and forced mode (EISSF) integrated solar stills.

4.1. Energy efficiency

Solar continue yields during the night because of thermal storage. Higher the thermal storage, the higher the nocturnal yield. Using the first law of thermodynamics, the instant thermal (energy) efficiency of ETC ($\eta_{i,\text{ETC}}$), solar still ($\eta_{i,\text{solar still}}$) and overall efficiencies ($\eta_{i,\text{overall}}$) of the system can be written as [27]:

$$\eta_{i,\text{ETC}} = \left[\eta_o - a'\frac{T_{cwo} - T_a}{I_c(t)}\right] \times 100 \quad (10a)$$

$$\eta_{i,\text{solar still}} = \frac{m_{ew} \cdot L}{\left(\dot{q}_{uc} + I_s(t)A_g\right) \times 3{,}600} \times 100 \quad (10b)$$

$$\eta_{i,\text{overall}} = \frac{m_{ew} \cdot L}{\left(I_c(t) \cdot A_a + I_s(t)A_g\right) \times 3{,}600} \times 100 \quad (10c)$$

Daily yield can be estimated as [8]:

$$\eta_{\text{daily,overall}} = \frac{\sum_1^{24} m_{ew} \cdot L}{\sum_1^{24}\left(I_c(t) \cdot A_a + I_s(t)A_g\right) \times 3{,}600} \times 100 \quad (10d)$$

Hourly and daily energy efficiency may be obtained by taking cumulative values of parameters expressed in Eqs. (10). The energy payback time (EPBT), energy production factor (EPF), and energy life cycle conversion efficiency (LCCE) of the integrated solar still can be written as [26]:

$$\text{EPBT} = \frac{\text{Emergy}}{\text{The annual output of energy}} = \frac{E_{in}}{E_{out}} \quad (11)$$

$$\text{EPF} = \frac{E_{out} \times n}{E_{in}} \quad (12)$$

$$\text{LCCE} = \frac{E_{out} \times n - E_{in}}{E_{in,solar} \times n} \times 100 \quad (13)$$

The value of EPF is always less than one. However, if EPF $\rightarrow$ 1, the system is considered the best technology in view of energy conversion.

4.2. Energy production cost

This is an investment to produce unit energy from the system and expressed as [26]:

$$E_{pc} = \frac{\text{Net annualized cost}}{\text{Annual energy}} = \frac{\text{UA}_{net}}{E_{out}} \quad (14)$$

4.3. Annualized cost

The net annualized cost of EISSN and EISSF can be written as [12]:

$$\text{UA}_{net} = P_s \cdot F_{CR,in} + P_s \cdot M_s \cdot F_{CR,in} - S_s \cdot F_{SR,in} \quad (15)$$

where

$$F_{CR,i,n} = \frac{i(1+i)^n}{\left(1+i\right)^n - 1} \text{ and } F_{SR,i,n} = \frac{i}{(1+i)^n - 1}$$

In India, financial assistance under loan facility is available at an interest rate 2.0%–5.0% on solar equipment, depends on the type of users. Further, to promote the use of solar equipment, the Government of India provides a 30%–90% subsidy on benchmark capital cost in the following category.

The pump cost has been considered along with the system's total cost (P_s) in forced mode arrangement. The pump's life is taken as 10 y and can be replaced by an adjustment of its salvage value at the end of 10 y. Generally, 10% maintenance cost (M_s) is taken of the net present cost. The principal cost under forced mode for 30 y life span can be estimated as [12]:

$$P_s = P + \left[\frac{P_p}{\left(1+i\right)^{10}}\right] + \left[\frac{P_p}{\left(1+i\right)^{20}}\right] \quad (16)$$

The cost of various components of ETC integrated system considering mass production at the commercial level is given in Table 4. Emergy (embodied energy) has been estimated as 881.0 and 997.0 kWh, for the EISSN and EISSF system, respectively.

The cost of distilled water per liter can be estimated as [12]:

$$\text{CPL} = \frac{\text{UA}_{net}}{\text{Annual Yield}} \quad (17)$$

4.4. Carbon credit earned

Carbon credit is a financial earning for tCO_2 removed or reduced from the atmosphere. The average carbon dioxide equivalent intensity for electricity generation from the coal accounting transmission, distribution, and domestic appliances losses reaches ~1.58–2.0 kg kWh^{-1} of CO_2 emission. When fabricating the solar unit, some amount of carbon dioxide (tCO_2) is emitted and can be estimated using the emergy used during fabrication. Following Nordhaus [29], annual CO_2 emission/mitigation from the system can be written as:

$$\text{Annual } CO_2 \text{ emission (kg)} = \frac{E_{\text{in}} \times 1.58}{n} \tag{18}$$

$$\text{Annual } CO_2 \text{ mitigation (kg)} = E_{\text{out}} \times 1.58 \tag{19}$$

Net tCO_2 mitigation in a lifetime can be evaluated as:

$$\text{Net } CO_2 \text{ mitigation (tons)} = \frac{\left(E_{\text{out}} \times n - E_{\text{in}}\right)}{1{,}000} \times 1.58 \tag{20}$$

The market rates of carbon credit due to tCO_2 mitigation are fluctuating and about half of the emissions covered by carbon pricing initiatives are priced below \$10/tCO_2 [30]. Considering the carbon credit at \$5.0/tCO_2 (i.e., 1\$ = Rs. 65 in 2019), financial incentive received due to carbon trading during completed life span can be estimated as:

$$\text{CC}_n = \frac{\left(E_{\text{out}} \times n - E_{\text{in}}\right)}{1{,}000} \times 1.58 \times 5 \times 65 \tag{21a}$$

Cash flow/kg of distillate accounting carbon pricing

$$\text{(Rs./kg)} = \frac{\text{CC}_n}{n \cdot M_Y} \tag{21b}$$

The payback period (n_p) can be expressed as [12]:

$$n_p = \frac{\ln\left[\dfrac{\text{CF}}{\text{CF} - P_s \times i}\right]}{\ln\left[1 + i\right]} \tag{22}$$

where

$$\text{CF} = M_Y \times S_p - P_u \times 3.0 + \text{CC}_Y \tag{23}$$

Out of annual cash flow, annually P_u unit power (Rs. 3.0 kWh^{-1}) is utilized to operate the pump in EISSF system.

5. Results and discussion

Equations formulated from (1)–(9) have been simulated in MATLAB R2018a program to estimate the temperatures of basin water, glass surfaces, at the outlet of ETC, hourly yield, etc., using the measured experimental climatic data recorded. The value of the temperature obtained at the end of each hour, becomes the input for the next round. The performance parameters have been evaluated using Eqs. (10)–(22), including life cycle assessment of EISSN and EISSF solar stills, respectively. Basin water mass of 30 kg (depth 0.03 m) has been considered as storage in the basin for the comparative performance, using mass circulation rate as 0.06 kg s^{-1} through the pump while estimating the performance of EISSF.

Fig. 2 shows the trends of measured values of the climatic parameters such as solar intensity on solar still and collector and ambient air temperature of a typical day. By using the design and climatic parameters, the water (T_{sw}) and inner glass cover (T_{gi}) have been estimated and illustrated for both the designs of solar stills. It has been observed that temperatures attainable during the forced mode of operation is higher than the natural mode and the difference of 2.0°C–3.0°C occurs during the peak, due to the faster heat extraction and avoidance of intermixing within the ETC tubes under forced circulation. The hourly variation of yield and heat transfer coefficients are depicted in Fig. 3. The maximum hourly yield has been found to be 0.658 kg at 14:00 h with EISSF, marginally higher than the EISSN. The heat transferred by the three modes increases with water temperature. The maximum value of evaporative heat transfer coefficient has been estimated as 97.0 W m^{-2} K^{-1} at 15:00 h and found marginally higher under forced mode due to higher water temperature obtainable under the forced mode, which leads to higher output.

Fig. 4 shows the variation of hourly instantaneous energy efficiency of ETC, solar still, and the overall efficiency of both designs of solar still. The overall efficiency has been observed in the range of 0.0%–64.0%, which reaches more than 100% at 16:00 h. This is due to the availability of low solar flux during evening hours, which results in a sudden drop in the value of the quantity in the denominator of Eq. (10). On the other hand, the distillate production rate does not drop significantly, because of the time lag between evaporation and condensation in the basin solar still as well as the drop in ambient temperature. A similar trend has also been observed with EISSF, with a marginal increase in efficiency during peak hours. The decrease in collector efficiency after 15:00 h during low solar flux time has been due to higher energy associated with the re-circulating hot water, which reveals that the use of ETC during evening time (low sunshine period) is not much beneficial. Further, a sessional variation of yield on typical days is reported in Fig. 5. Better productivity has been obtained between spring to autumn sessions. The maximum and minimum yields have been found with EISSF geometry as 4.6 and 1.95 kg during August and December, respectively. Averaging the yields obtained from each month and further multiplying by 300 d (clear d y^{-1}), the respective annual yields from EISSN and EISSF have been found as 1,074 and 1,134.5 kg. It has been found that accounting per unit area of solar collection, the natural mode of operation yields ~535.1 kg m^{-2}, while under the forced mode, the system yields ~567.3 kg m^{-2}, annually. The annual energy output from EISSF has been estimated as 768.0 kWh, higher than the EISSN (725.0 kWh). The daily energy efficiencies evaluated using Eq. (10d) are also depicted in Fig. 6, and found to be higher under forced mode. The maximum energy efficiency has been found as 34.3% in April using EISSF. From the results, it has been found that EISSF solar still performs better compared to the EISSN in terms of yield and efficiency, due to controlled mass flow rate and faster removal of heat from the ETC tubes.

To check the economic viability of the systems for commercial purposes should be determined by its economics. Table 5 shows the capital (P_s), salvage (S_s), maintenance (M_s) costs, etc., of the solar distillation unit, considering Government subsidy in India. Net uniform annual cost (UA_{net}) has been estimated as Rs. 1,163.9 and 1,323.3 for EISSN and EISSF, respectively, at 2.0% interest rate and 15 y of life span. The net uniform annual cost (UA_{net}) has been found highly dependent on capital investment, the interest rate as well as expected life span. The higher the investment, the more net uniform annual cost (UA_{net}), which increases linearly with an increase in interest rate (2.0%–5.0%). The UA_{net} has been decreased by 44%–30% with an increase in system life from 15 to 30 y at fixed interest rate. The net uniform annual cost (UA_{net}) has been found to be decreased as Rs. 295.6 and 365.1 for EISSN and EISSF, respectively considering 30 y of life and accounting annual environmental revenue generated due to carbon credit. The effect of interest rate and expected life of the system on EPF, EPBT, and LCCE have been estimated and illustrated in Table 6. The net output of annual energy from EISSN and EISSF units is 725.0 and 768.0 kWh, respectively. The EPFs are found as 12.3 and 11.5 for EISSN and EISSF, respectively, for 15 y life period and increases about two times considering 30 y of life and worthwhile. The system having higher EPF, may yield less compared to the system having less EPF. However, it depends upon the radiation and climatic conditions, and a higher value of EPF is preferable for economic effectiveness. Further, the EPBT of EISSN and EISSF systems has been estimated as 1.2 and 1.3 y, respectively. Life cycle conversion efficiency of EISSF has been found as 28.8%, higher than EISSN (27.3%), considering 30 y of expected life. The net tCO_2 mitigation by EISSF for the life of 30 y has been evaluated as 34.82 tons, higher than EISSN, with net carbon credit of Rs. 377.3 y^{-1} if traded at $5.0/$tCO_2$.

Table 7 illustrates the energy and distillate production cost, accounting for carbon trading. Production cost depends on the interest rate, expected life, and tCO_2 mitigation. The respective minimum energy production cost from EISSN and EISSF has obtained ~Rs. 0.90 and 0.97 kWh^{-1} at 2.0% interest rate. However, the respective energy production cost decreases to Rs. 0.40 and 0.47 kWh^{-1} accounting carbon revenue generated. The respective distillate production cost has been evaluated as Rs. 0.27 and 0.32 kg^{-1} and found insignificantly higher using the EISSF system. It has been observed that with the enhancement of expected life from 15 to 30 y, distillate production costs decrease by 43.0% (at i = 2%) and 31.0% (at i = 5%) without carbon credit, while 62% (at i = 2%) and 42.0% (at i = 5.0%) accounting carbon credit. The production cost decreases linearly with an increase in life span, due to a linear decrease in the capital recovery and sinking fund factor at a fixed interest rate and the variation is shown in Fig. 7. The payback period has been found as second-order polynomial function of the selling price. The payback periods from EISSN and EISSF have been estimated as 5.7 and 6.4 y, respectively, at a 2.0% interest rate, 30 y life, and Rs. 2.0 kg^{-1} selling rate in the market. With an increase in selling price from Rs. 2.0 to 6.0 kg^{-1}, the payback time decreased to ~2.0 y for both the system, irrespective of the interest rate and expected

Table 4
Capital investment and emergy of EISSN and EISSF system accounting Government subsidy [12,26,37]

Sl. No.	Component	Value
1	Cost of solar still (Rs.)	3,500
2	Cost of collector (Rs.)	10,000
3	Cost of water pump (Rs.)	1,000
4	Cost of fabrication (Rs.)	2,000
5	Solar still emergy (kWh)	459
6	Collector emergy (kWh)	422
7	Pump emergy (kWh)	0.86
8	G I pipe emergy (kWh)	116
9	Annual power cost at Rs. 3 kWh^{-1}	251.7
10	Principal cost of EISSN (Rs.)	15,500
11	Principal cost of EISSF (Rs.)	16,500
12	Residual value after 15 y (Rs.)	2,500
13	Residual value after 30 y (Rs.)	4,000

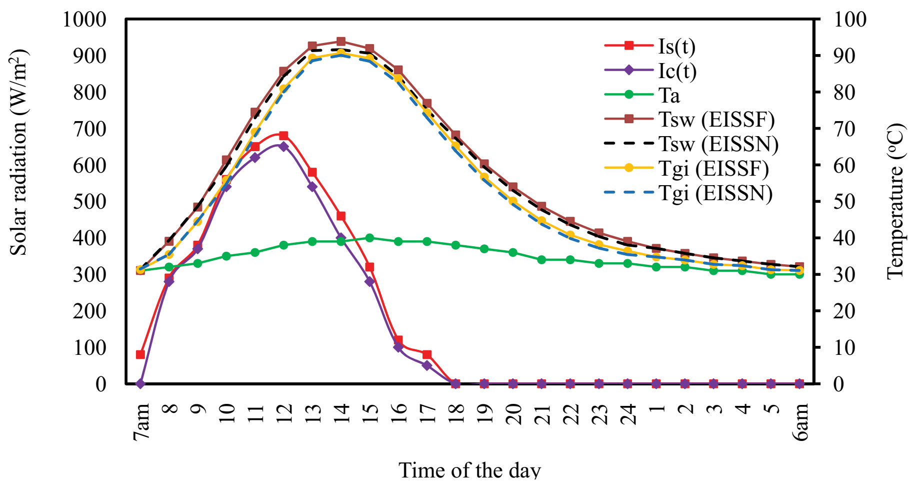


Fig. 2. Variation of solar radiation and temperatures on typical day.

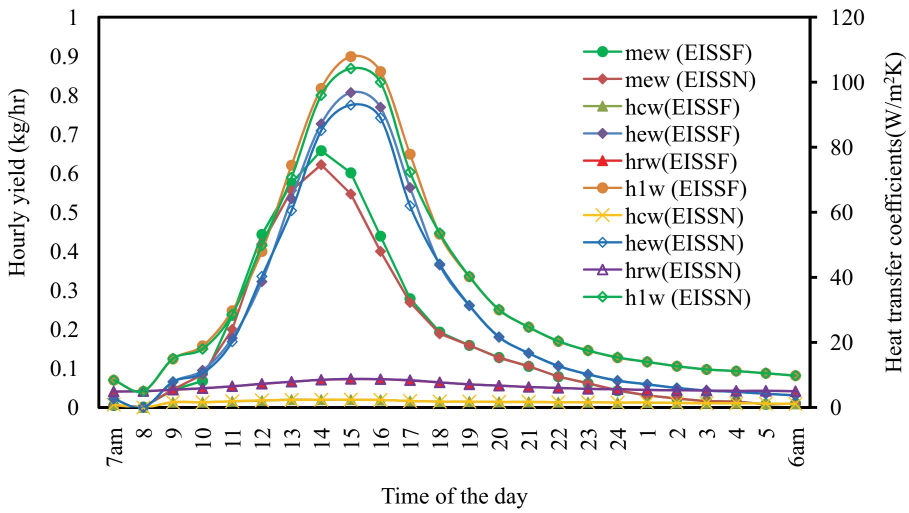


Fig. 3. Variation of yield and heat transfer coefficients from EISSN and EISSF.

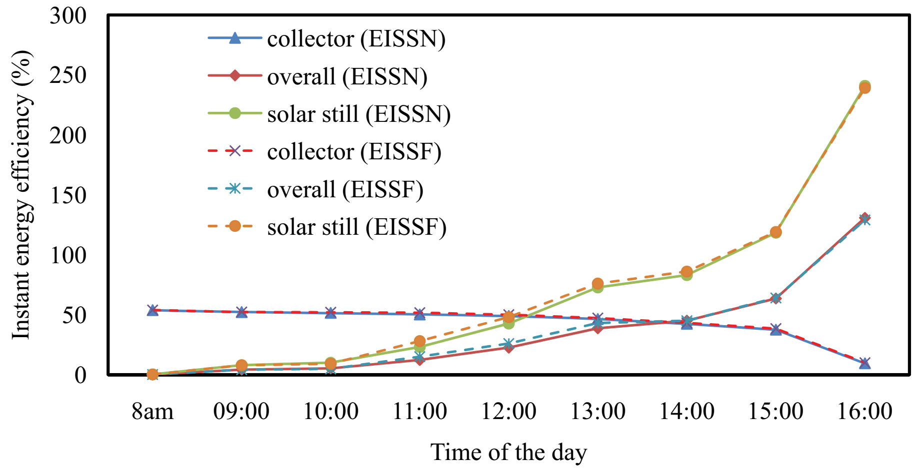


Fig. 4. Variation of instant energy efficiency of EISSN and EISSF.

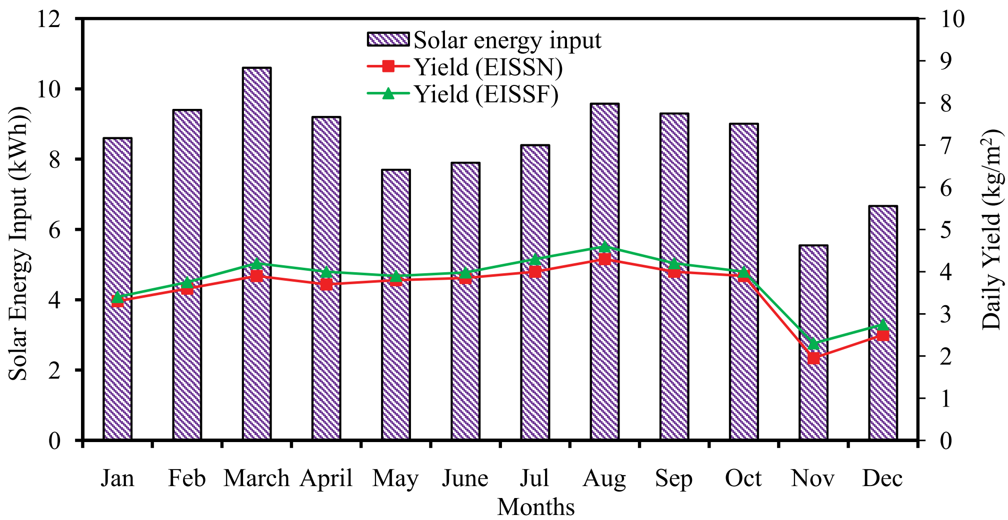


Fig. 5. Seasonal effect on daily yield on typical day in different months.

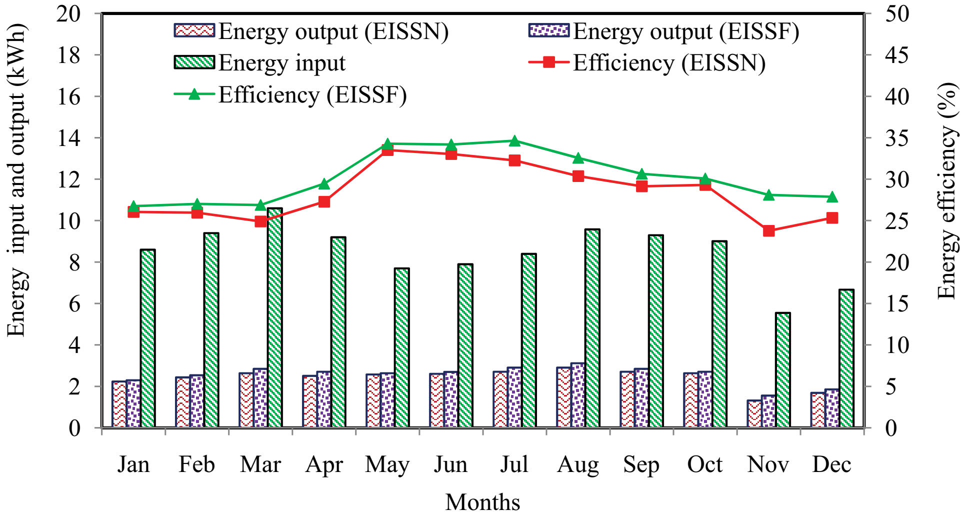


Fig. 6. Comparative daily energy input/output and energy efficiencies of ESSN and EISSF.

Table 5
Capital cost, salvage value, annualized cost, etc., for EISSN and EISSF solar stills

Type of solar still	n	i (%)	P_s (Rs.)	M_s (Rs.)	S_s (Rs.)	$F_{CR,i,n}$	$F_{SR,i,n}$	UA_{net} (Rs.) WOCC	UA_{net} (Rs.) WCC
EISSN	15	2	15,500	1,550	2,500	0.0778	0.0578	1,163.9	825.7
		5	15,500	1,550	2,500	0.0963	0.0463	1,515.1	1,173.2
	30	2	15,500	1,550	4,000	0.0446	0.0246	652.8	295.6
		5	15,500	1,550	4,000	0.0650	0.0150	1,042.9	685.7
EISSF	15	2	16,500	1,650	2,500	0.0778	0.0578	1,323.7	963.5
		5	16,500	1,650	2,500	0.0963	0.0463	1,686.2	1,325.2
	30	2	16,500	1,650	4,000	0.0446	0.0246	742.3	365.1
		5	16,500	1,650	4,000	0.0650	0.0150	1,158.4	781.6

Table 7
Energy and distillate production cost accounting carbon credit earned

Type of solar still	Life (y)	Interest rate (%)	Energy production cost (Rs. kWh^{-1})		Cost per kg of distillate (Rs. kg^{-1})	
			WOCC	WCC	WOCC	WCC
EISSN	15	2	1.6	1.10	1.09	0.77
		5	2.1	1.62	1.41	1.1
	30	2	0.9	0.40	0.61	0.27
		5	1.4	0.94	0.97	0.64
EISSF	15	2	1.7	1.25	1.17	0.85
		5	2.2	1.73	1.49	1.17
	30	2	0.97	0.47	0.65	0.32
		5	1.5	1.02	1.02	0.69

life. The distillate may also be sold at the rate the produced rate of distillate (CPL) to the rural community. However, the payback period would get increased significantly.

The payback periods are expected to decrease further, if operated in a higher solar flux area or if the distillate is sold at a higher selling price in the Indian market. The comparative environmental – economics of some designs of the solar stills is represented in Table 8. It has been observed that though the hybrid (PV/T) solar still yields more than the ETC coupled single slope solar still but required the larger

Table 8
Comparative assessment with some designs of solar stills

References	Annual yield (kg)	Net tCO_2 mitigation y^{-1} at 1.58 kg kWh^{-1} for 30 y	Enviro-energy cash flow (Rs. y^{-1}) at \$5/tCO_2	Energy payback time (y)	CPL (Rs. kg^{-1})
[39]	504	16.17	175	1.6	0.34
[26]	1,389	33	352	5	0.76
[40]	1,496	36.5	489	–	2.08*
[28]	1,627	51	557	1.2	0.32
EISSN	1,074	33.01	335	1.2	0.27
EISSF	1,134	34.82	377	1.3	0.32

*Considering 10 y life time of the system.

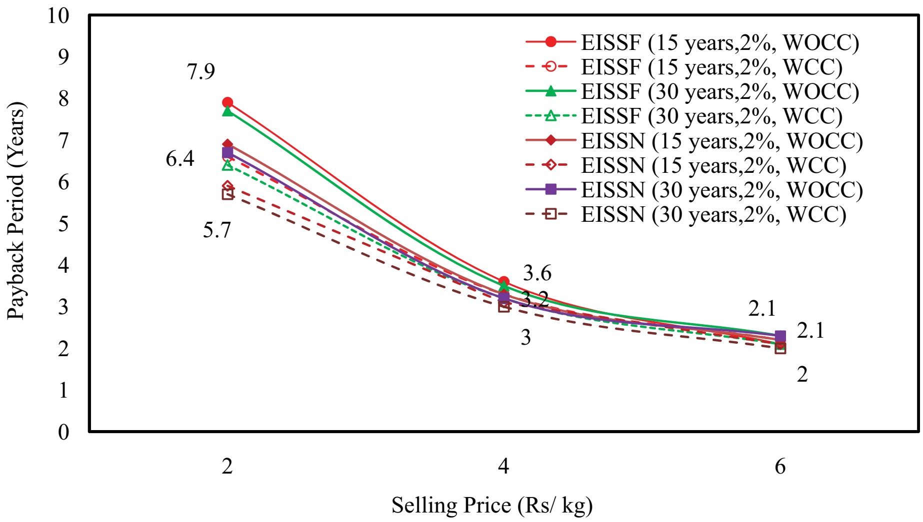


Fig. 7. Effect of selling price and life of system on the payback period.

size of the collector area (6 m²). The EISSF solar still yields higher than EISSN and gives more economic return due to higher tCO_2 mitigation compared to the other designs. The energy payback period and production cost of distillate using EISSF have been found insignificantly higher than EISSN due to the application of a recirculation water pump besides, however, significantly lower than the traditional solar still. The cash flow per kg of distillate due to environmental credit is in the range of Rs. 0.33–0.35, irrespective of the design of solar still if traded at \$5.0/tCO_2 mitigation.

6. Conclusions

Comparative performance of single slope solar still coupled with ETC under natural as well as under forced mode has been carried out using identical data and a similar meteorological environment. The following conclusions are drawn.

- The higher production, efficiency, and environmental reduction of harmful gases under forced mode are advantageous over natural mode. Annual yield and life cycle conversion efficiency obtained using EISSF have been found as 1,134.5 kg and 28.8%, While with EISSN as 1,074 kg and 27.3%, respectively. The net tCO_2 mitigation by EISSF during the entire life of 30 y has been evaluated as 34.82 tons with environmental credit ~Rs. 377.3 y^{-1} and found significantly higher than EISSN.
- The energy payback period of EISSF and EISSN has been obtained as 1.2 and 1.3 y, respectively, and found worthwhile for both the designs. Energy and distillate production costs from EISSF have been estimated as Rs. 0.47 kWh^{-1} and Rs. 0.32 kg^{-1}, respectively, insignificantly higher than EISSN.
- At selling rate of Rs. 6.0 kg^{-1} of distillate, the cost payback periods of EISSF and EISSN have been found as 2.1 and 2.0 y, respectively, which will be reduced further with an increase in the selling price of distillate.

The work can be extended for future studies on the following:

- The experimental study of both designs can be performed under similar conditions at higher latitudes to estimate the performance in field conditions.
- Systems performance can be studied in a regenerative mode as well as an accounting shadowing effect.

Symbols

a' — ETC efficiency coefficient, 0.824 Wm^{-2} K
A_a — Collector aperture area, 1.0 m^2
A_b — Basin area, 1.0 m^2
A_g — Area of glass surface, m^2
A_t — Tube circumferential area, 0.21 m^2
CC_Y — Carbon credit, Rs.
CPL — Production cost, Rs. kg^{-1}
c_w — Specific heat of water, Jkg^{-1} K^{-1}
d_t — Tube outer diameter, 0.047 m
EPF — Energy production factor
E_{in} — Emergy, kWh
$E_{in, solar}$ — Energy input on solar still, kWh
E_{out} — Energy output from the solar still, kWh
Gr — Grashof number
h_{ba} — Overall heat transfer coefficient from basin to ambient, 5.7 Wm^{-2} K^{-1}
h_{bw} — Convective heat transfer coefficient basin to water, 100 Wm^{-2} K^{-1}
h_{1w} — Total internal heat transfer coefficient from water to glass surface, Wm^{-2} K^{-1}
h_{kg} — Conductive h.t.c., glass, 0.78 Wm^{-2} K^{-1}
h_{cw} — Internal convective heat transfer coefficient, Wm^{-2} K^{-1}
h_{ew} — Internal evaporative heat transfer coefficient, Wm^{-2} K^{-1}
h_{rw} — Internal radiative heat transfer coefficient, Wm^{-2} K^{-1}
h_{go} — Overall h.t.c., inner glass surface to ambient, Wm^{-2} K^{-1}
i — Interest rate, %
I_c(t) — Solar flux fall over ETC, Wm^{-2}
I_s(t) — Solar flux fall over the solar still surface, Wm^{-2}
k — Thermal conductivity, Wm^{-1} K^{-1}
l_t — Tube length, 1.4 m
LCCE — Life cycle conversion efficiency, %
M_Y — Annual yield, kg
$\dot{m}$ — Circulation rate per tube, kg s^{-1} $tube^{-1}$
m_{ew} — Hourly distillate yield, kg
M_{sw} — Water mass, basin, kg
M_{cw} — Water mass, each tubes, kg
n — Solar still life, years
N_c — No. of ETC tubes
Nu — Nusselt number
p_{gi} — Vapour pressure at the inner surface of glass, N m^{-2}
p_w — Vapour pressure at surface of basin water, N m^{-2}
Pr — Prandtl number
P_u — Yearly power consumed to run the pump, kWh
$\dot{q}$ — Circumferential heat, W m^{-2}
Re — Reynold's Number
S_p — Selling rate, Rs. kg^{-1}
t — Time, s
T_a — Ambient temperature, °C
T_b — Liner temperature, °C
T_{cw} — Water temperature in tube, °C
T_{gi} — Inner glass surface temperature, °C
T_{go} — Temperature, outer glass surface, °C
T_{sw} — Temperature, basin water, °C
V_a — Wind velocity, m s^{-1}
WOCC — Without carbon credit
WCC — With carbon credit

Greek

α'_b — Fractional absorptivity by basin liner, 0.30–0.80
α'_g — Fractional absorptivity by glass cover, 0.05
β — Thermal expansion coefficient, K^{-1}
μ — Viscosity, dynamic, Pa s
ν — Viscosity, kinematic, m^2 s^{-1}
ρ — Density, water, kg m^{-3}
ρ_g — Reflectivity, glass, 0.05
ρ_w — Reflectivity, water, 0.05

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Appendix-A

Thermo physical properties can be estimated as [21]:

$$c_w = 4,226 - 3.224T + 0.057T^2 - 0.0002656T^3 \tag{A1}$$

$$L = 2.506\times10^6 - 3.639\times10^3 T + 0.2678T^2 - 8.103\times10^{-3}T^3 - 2.079\times10^{-5}T^4 \tag{A2}$$

$$\rho = 1,001 - 0.08832T - 0.003417T^2 \tag{A3}$$

$$K = 0.557 + 0.002198T - 0.00000578T^2 \tag{A4}$$

$$\mu = 4.2844\times10^{-5} + (0.517(T+64.993)^2 - 91.296)^{-1} \tag{A5}$$

$$\beta = \left(0.3 + 0.116T - 0.0004T^2\right)\times10^{-4} \tag{A6}$$

$$p_{\text{gi}} = \exp\left(25.317 - \frac{5,144}{T_{\text{gi}} + 273}\right) \tag{A7}$$

$$p_{\text{sw}} = \exp\left(25.317 - \frac{5,144}{T_{\text{sw}} + 273}\right) \tag{A8}$$

Internal heat transfer co-efficient can be estimated as [38]:

$$h_{\text{cw}} = 0.884\left[\left(T_{\text{sw}} - T_{\text{gi}}\right) + \frac{\left(P_{\text{sw}} - P_{\text{gi}}\right)\left(T_{\text{sw}} + 273\right)}{268.9\times10^3 - P_{\text{sw}}}\right]^{\frac{1}{3}} \tag{A9}$$

$$h_{\text{ew}} = 0.016273\times h_{\text{cw}}\times\frac{\left(P_{\text{sw}} - P_{\text{gi}}\right)}{\left(T_{\text{sw}} - T_{\text{gi}}\right)} \tag{A10}$$

$$h_{\text{rw}} = \varepsilon_{\text{eff}}.\sigma\left[\left(T_{\text{sw}} + 273\right)^2 + \left(T_{\text{gi}} + 273\right)^2\right]\left[T_{\text{sw}} + T_{\text{gi}} + 546\right] \tag{A11}$$

$$h_{ba} = \left[\frac{L_b}{K_b} + \frac{1}{5.7}\right]^{-1},\ h_{\text{kg}} = \frac{k_g}{l_g},\ h_b = \frac{k_b}{l_b},\ \varepsilon_{\text{eff}} = \left[\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right]^{-1} \tag{A12}$$

$$h_{1g} = h_{1g} = 5.7 + 3.8V_a \tag{A13}$$