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# Improving exergo-enviro-economic parameters and annual productivity of double slope solar desalting unit by incorporating concentrator integrated evacuated tubular collectors

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**ABSTRACT**

This paper deals with the improvement of exergo-enviro-economic parameters and productivity of a number (N) of identical compound parabolic concentrator (CPC) evacuated tubular collectors (ETC) integrated double slope solar still (NCPCIETC-DS) for New Delhi climate wherein all kinds of climatic environments in a year have been considered. The system has been analyzed for mass flow rate of 0.012 kg/s and $N = 8$ using computational code developed in MATLAB. Results of NCPCIETC-DS have been compared with results of DS included with NETCs (NETC-DS) for the same mass flow rate, N, geometry, and weather condition. Concludingly, carbon dioxide mitigation is higher by 16.57%, enviro-economic parameter is higher by 16.57%, cost of producing unit kg of freshwater is lower by 36.6%, productivity is higher by 26.82% and exergo-economic parameter (kWh/₹) is higher by 62.5% for NCPCIETC-DS than NETC-DS.

*Keywords:* Exergo-enviro-economic parameters; Production cost of water; Active solar still; Concentrator collector; Performance improvement

## 1. Introduction

The analysis of solar still is the requirement of contemporary time as the world is facing the shortage of freshwater particularly in developing and under-developed countries. Freshwater production using solar still does not affect the environment because this technology works on green energy. The most important part of solar still is that it can be fabricated using locally available material. The work on active solar still was reported by Rai and Tiwari [1] in 1983. Since then, lots of developments on the active solar still have been reported throughout the world. The development of characteristic equations on compound parabolic concentrator (CPC) by incorporating photovoltaic thermal (PVT) was reported by Atheaya et al. [2] and Tripathi et al. [3]. This work on PVTCPC was further extended by Singh and Tiwari [4–6] who integrated PVTCPC with basin type solar still and analyzed from energy metrics viewpoint for knowing the feasibility of the system from energy point of view. The exergo-enviro-economic parameters and different efficiencies were also estimated, and they reported that double slope solar still produced better performance than the similar single slope set-up under optimized condition and 0.14 m of water depth due to better solar energy utilization by double slope set-up. Further, Gupta et al. [7] developed characteristic equations for PVTCPC integrated single slope solar still for the same watt peak as of partially covered PVTCPC integrated solar still and reported an improved performance due to reduced top loss in the case of fully covered PVTCPC integrated solar still.

The performance of active solar still could be improved further by replacing PVTCPC with evacuated tubular

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collector (ETC) because of reduced loss from ETC. The convective loss of heat could be prevented in the case of ETC due to the presence of vacuum. The development of characteristic equation for solar still by incorporating ETCs was investigated by Singh et al. [8] and Singh and Tiwari [9]. The work on ETCs integrated solar still was also investigated by Dev and Tiwari [10] and they reported an improvement in freshwater production by 48% over conventional solar still because of heat addition to the basin. A comprehensive review on active solar still can be witnessed in Sathyamurthy et al. [11].

The performance of solar still by incorporating evacuated tubes was investigated by Singh et al. [12] in natural circulation mode and concluded that the exergy efficacy was in the range of 0.15%–8%. Further, an experimental investigation of solar still by incorporating evacuated tubes was done by Sampathkumar et al. [13] and reported an improvement in freshwater production by 129% over conventional solar still of same geometrical details due to heat addition to basin in the case of active mode. This work was further carried forward by Kumar et al. [14] by inserting pump for enabling the system to work in forced circulation mode and concluded that the performance was better than the similar set-up working in natural circulation mode because of increased effectiveness of heat addition in forced circulation mode. This work was further extended by Mosley et al. [15] in which parabolic trough collector was also incorporated and reported the freshwater production rate of 0.27 kg/m$^2$-h. In another study, Shafii et al. [16] investigated the modified solar still by incorporating evacuated tube and concluded that the freshwater production was highest corresponding to the inclination of tube matching with the latitude of location. A study of hybrid solar still by incorporating humidification and dehumidification concept was done by Sharshir et al. [17] which also included evacuated tube and reported the gain output ratio as 50%. An investigation of double slope solar still by incorporating evacuated tube was done by Bait and Si-Ameur [18] and concluded that the freshwater production and efficacy were higher if evacuated tubes were used in place of flat plate collectors. The carbon dioxide estimation for the system reported by Bait and Si-Ameur [18] was done by Bait [19]. The investigation of solar still by incorporating evacuated tubes in series-parallel arrangement was done by Issa and Chang [20] and reported an improvement in freshwater production by 61.11% over a conventional solar still having similar geometry due to heat addition to basin in the case of active mode of a solar still.

An investigation on basin type solar still by incorporating ETCs under optimized condition was done by Singh and Tiwari [21] and they concluded that the freshwater production in the case of double slope set-up was 15.19% lower than the single slope set-up due to higher freshwater production by double slope set-up than single slope set-up at 0.14 m water depth under optimized condition. This work was further extended by Singh and Al-Helal [22] for comparative energy metrics estimation and they concluded that the life cycle conversion efficiency of double slope set-up was best followed by double slope set-up incorporated with PVTFPCs and PVTCPCs. At the same time, energy metrics analysis for single slope solar still by incorporating PVT collectors was done [23]. Further, exergo-enviro-economic analysis of DS by incorporating ETCs was done by Singh [24] and concluded that the performance of double slope set-up by incorporating ETCs was better than double slope set-up incorporated with PVTCPCs due to the presence of vacuum in the case of ETCs which prevents heat loss by convection.

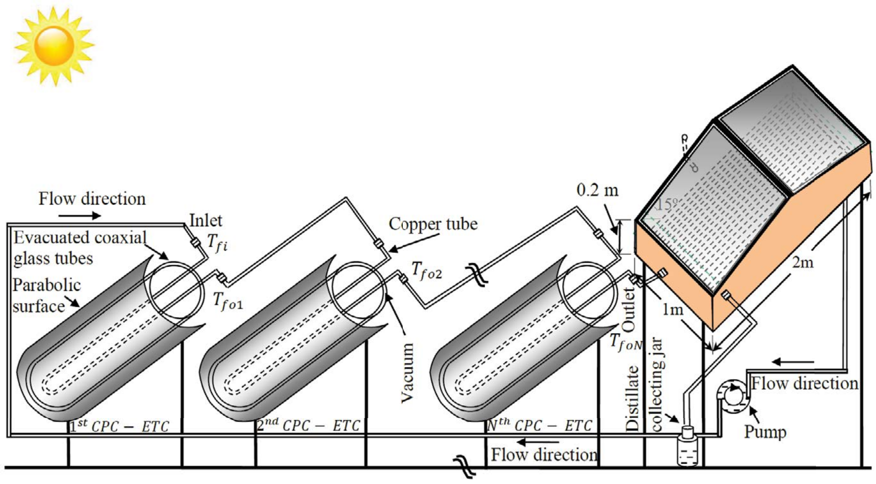
A review on solar desalting units by incorporating evacuated tubular collectors was carried out by Kumar et al. [25]. An investigation on the impact of mass flow rate and number of collectors on the performance of active solar desalting units was carried out. They concluded that values of performance parameters diminish with the increase in mass flow rate and tend to be approximately constant after a certain value of mass flow rate. However, an improvement in performance parameters was seen with the increase in value of the number of collectors [26–33]. Further, sensitivity analysis of active solar desalting units was carried out and it was reported that outcomes of the analysis were very useful for the designer and installer of active solar desalting units because the designer and installers of the systems were having information in advance about which parameter effected more [34–39]. In another study, the effect of variation of water mass in the basin on the performance of solar desalting unit was carried out and reported that the performance was improved with the increase in water mass in the basin for higher water depth. It occurred because sensible heat was contained by water mass during the daytime and the heat of water mass was released during nighttime which resulted in increased evaporation at nighttime [40–42].

The literature review clearly indicates that the exergo-enviro-economic and productivity analyses of double slope solar still by incorporating concentrator integrated ETCs (NCPCIETC-DS) has not been reported by any researcher worldwide. Hence, the present research work focuses on the estimation of exergo-enviro-economic parameters and productivity for NCPCIETC-DS and comparison of results with results of DS incorporated with ETCs for $N = 8$ and mass flow rate of 0.012 kg/s. The main objective of the research work are as follows:

i. To estimate exergo-enviro-economic parameters, cost of freshwater production and productivity of NCPCIETC-DS.
ii. To compare the performance of NCPCIETC-DS with NETC-DS based on exergo-enviro-economic parameters, cost of freshwater production and productivity.

## 2. Materials and method

The diagrammatic representation of double slope solar still included with compound parabolic concentrator integrated evacuated tubular collectors (NCPCIETC-DS) and cross-sectional view of 1st CPCIETC is displayed as Fig. 1. The particularization of NCPCIETC-DS has been depicted as Table 1. CPCIETCs are a type of solar thermal collector that uses a vacuum-sealed glass tube to trap solar radiation and convert it into heat, which can be used to generate steam or hot water. The double slope active solar desalting unit is a



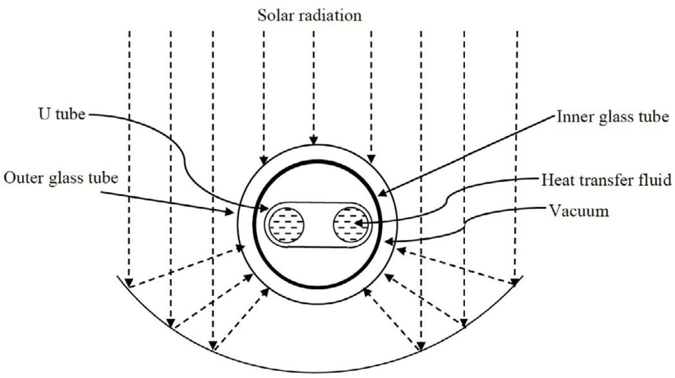




Fig. 1. (a) Schematic diagram of NCPCIETC-DS and (b) elevated view of CPCIETC.

type of solar still that uses the energy from the sun as well as from collectors to purify water. It works by using a transparent cover, which allows sunlight to enter and heat up a basin of water. Basin also receives heat from NCPCIETCs. As the water evaporates, it rises and condenses on a sloping surface, which directs the purified water into a collection container.

Incorporating compound parabolic concentrator integrated evacuated tubular collectors (CPCIETCs) into a double slope solar still can increase the efficiency of the still by concentrating sunlight to the receiver surface of collectors and supplying heat to water in the basin. It results in increasing the temperature of the water and accelerating the evaporation process. The steam generated by the heated water rises and condenses on the sloping surface, where it is directed towards the collection container. The use of CPCIETCs in a double slope solar still reduces the amount of time required for water purification. Overall, the working principle of a double slope solar still with CPCIETCs is based on the same principles as a standard double slope solar still, but with the addition of concentrator reflecting surface to increase the efficiency of the still.

Assumptions for thermal modeling of NCPCIETC-DS are as follows [43]:

i. NCPCIETC-DS is in quasi steady state condition and temperature gradient across insulation thickness as well as condensing cover surface is small.
ii. Heat capacity of condensing cover surface, absorbing surface and insulating materials is negligibly small.
iii. One dimensional heat flow occurs, and all joints are leakproof.
iv. Water mass in the basin is kept constant and stratification does not occur.
v. Film wise condensation is taken by ensuring cleaning of the condensing surface and providing inclination to the condensing surface.

Mathematical equations for different components are as follows:

*2.1. For NCPCIETCs arranged in series*

The expression of the temperature at the outlet of $N$th CPCIETC is written as [44]:

$$T_{\text{foN}} = \frac{(\text{PF}_1)(\alpha\tau)_{\text{eff}}}{\dot{m}_f C_f} \frac{(A_r F_r)(1-K_K^N)}{(1-K_K)} I_b(t) + \frac{(A_r F_r)U_L}{\dot{m}_f C_f} \frac{(1-K_K^N)}{(1-K_K)} T_a + K_K^N T_{\text{fi}} \tag{1}$$

The rate of heat gain for NCPCIETCs is written as:

$$\dot{Q}_{\text{UN}} = \dot{m}_f C_f (T_{\text{foN}} - T_{\text{fi}}) \tag{2}$$

Table 1
Particularization of NCPCIETC-DS and NETC-DS

| Double slope solar desalting unit | | | |
|---|---|---|---|
| Component | Specification | Component | Specification |
| Length | 2 m | Material of cover | Glass |
| Width | 1 m | Orientation | East-west |
| Glass cover inclination | 15° | Glass cover thickness | 0.004 m |
| Smaller side height | 0.2 m | $K_g$ | 0.816 W/m-K |
| Body material | GRP | Insulation thickness | 0.1 m |
| Stand material | GI | $K_i$ | 0.166 W/m-K |
| NCPCIETC | | ETC | |
| Component | Specification | Component | Specification |
| Type and no. of collectors | CPCIETC, N | Type and no. of collectors | ETC, N |
| Rating of DC motor | 12 V, 24 W | Rating of DC motor | 12 V, 24 W |
| Inner copper tube diameter | 0.0125 m | Inner copper tube diameter | 0.0125 m |
| Copper tube thickness | 0.0005 m | Copper tube thickness | 0.0005 m |
| Outer radius of outer glass tube of evacuated coaxial glass tube | 0.024 m | Outer radius of outer glass tube of evacuated coaxial glass tube | 0.024 m |
| Inner radius of inner glass tube of evacuated coaxial glass tube | 0.0165 m | Inner radius of inner glass tube of evacuated coaxial glass tube | 0.0165 m |
| Thickness of outer/inner glass tube of evacuated coaxial glass tube | 0.002 m | Thickness of outer/inner glass tube of evacuated coaxial glass tube | 0.002 m |
| $\alpha_p$ | 0.8 | $\alpha_p$ | 0.8 |
| $F'$ | 0.986 | $F'$ | 0.986 |
| $\tau_g$ | 0.95 | $\tau_g$ | 0.95 |
| $K_g$ (W/m·K) | 1.09 | $K_g$ (W/m·K) | 1.09 |
| Inclination of NCPCIETC | 30° | Angle of ETC with horizontal | 30° |
| Length of each copper tube | 2.0 m | Length of each copper tube | 2.0 m |
| ρ | 0.85 m | Receiver area | 0.27632 m$^2$ |
| Aperture area | 0.82896 m$^2$ | | |
| Receiver area | 0.27632 m$^2$ | | |

| Average monthly wind blow | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
| Velocity (m/s) | 2.77 | 3.13 | 3.46 | 3.87 | 4.02 | 4.11 | 3.39 | 2.91 | 2.85 | 2.16 | 1.83 | 2.40 |

Using Eqs. (1) and (2), rate of heat gain is expressed as:

$$\dot{Q}_{\text{uN}} = \left(\text{PF}_1\right)\left(\alpha\tau\right)_{\text{eff}} \frac{\left(1-K_k^N\right)}{\left(1-K_k\right)} I_b\left(t\right) - \left(A_r F_r\right) U_L \frac{\left(1-K_k^N\right)}{\left(1-K_k\right)} \left(T_{\text{fi}} - T_a\right) \quad (3)$$

One can see all unknown terms of Eqs. (1)–(3) in Appendix A.

After writing equations for different components of double slope solar desalting unit, and solving those equations considering Eq. (2), one can express water temperature and condensing cover temperatures using equations as [45]:

$$T_w = \frac{\bar{f}\left(t\right)}{a}\left(1-e^{-at}\right) + T_{w0}e^{-at} \quad (4)$$

$$T_{\text{giE}} = \frac{A_1 + A_2 T_w}{P} \quad (5)$$

$$T_{\text{giW}} = \frac{B_1 + B_2 T_w}{P} \quad (6)$$

One can see all unknown terms of Eqs. (4)–(6) in Appendix A.

After knowing values of $T_w$, $T_{\text{giE}}$ and $T_{\text{giW}}$, one can estimate hourly freshwater production as:

$$\dot{m}_{\text{ewh}} = \frac{\left[h_{\text{ewE}}\left(T_w - T_{\text{giE}}\right) + h_{\text{ewW}}\left(T_w - T_{\text{giW}}\right)\right]\left(\frac{A_b}{2}\right)}{L'} \times 3600 \quad (7)$$

Expression for heat transfer coefficients is given in Appendix A.

One can get all fundamental equations for NETC-DS considering $I_b(t) = I(t)$, ρ = 1 and $A_a = A_r$ with the help of Eqs. (1)–(7) and expressions given in Appendix A.

## 3. Analysis

For analyzing NCPCIETC-DS/NETC-DS, four weather conditions per month for the year have been considered in this study. The considered weather conditions can be identified by the number of sunshine hours (SH) in a day and ratio ($r$) of daily diffuse to daily global irradiation at the earth's surface. For type (a), that is, clear day weather condition, value of SH is greater than or equal to 9 h and value of $r$ is less than or equal to 0.25. For type (b), that is, hazy day weather condition, value of SH lies between 7h and 9h, whereas value of $r$ lies between 0.25 and 0.50. For type (c), that is, hazy and cloudy day weather conditions, value of SH lies between 5 h and 7 h, whereas value of $r$ lies between 0.5 and 0.75. For type (d), that is, cloudy day weather condition, value of SH is less than or equal to 5 h and value of $r$ is greater than or equal to 0.75 [46].

### *4.1. Annual freshwater yielding assessment*

The value of hourly freshwater yielding for NCPCIETC-DS and NETC-DS can be assessed using Eq. (7) for weather situation of types a followed by the daily freshwater yielding for NCPCIETC-DS and NETC-DS by adding value of $\dot{m}_{\text{ewh}}$ for 24 h. The multiplication of daily freshwater yielding with the corresponding number of days will give the value of monthly freshwater yielding. Likewise, monthly freshwater yielding for NCPCIETC-DS/NCET-DS for other 3 weather situations can be assessed. The totaling of monthly freshwater yielding for all 4-weather situations will give net monthly freshwater yielding. The addition of monthly freshwater yielding for a year will give annual freshwater yielding ($M_{\text{ewy}}$) for NCPCIETC-DS.

### *4.2. Annual exergy and energy assessment for NCPCIETC-DS/NETC-DS*

The energy output from NCPCIETC-DS/NETC-DS can be estimated using 1st law of thermodynamics as:

$$E_{\text{out}} = \frac{\left(M_{\text{ewy}} \times L\right)}{3600} \tag{8}$$

The amount of exergy on hourly basis for the considered NCPCIETC-DS/NETC-DS can be estimated as [47]:

$$\begin{aligned}\dot{\text{E}}\text{x}_{\text{out},h} = {} & h_{\text{ewgE}} \times \frac{A_b}{2} \times \left[\left(T_w - T_{\text{giE}}\right) - \left(T_a + 273\right) \times \ln\left\{\frac{\left(T_w + 273\right)}{\left(T_{\text{giE}} + 273\right)}\right\}\right] \\ & + h_{\text{ewgW}} \times \frac{A_b}{2} \times \left[\left(T_w - T_{\text{giW}}\right) - \left(T_a + 273\right) \times \ln\left\{\frac{\left(T_w + 273\right)}{\left(T_{\text{giW}} + 273\right)}\right\}\right]\end{aligned} \tag{9}$$

The value of evaporative heat transfer coefficient for east orientation ($h_{\text{ewgE}}$) can be estimated as:

$$h_{\text{ewgE}} = 16.273 \times 10^{-3} h_{\text{cwgE}} \left[\frac{P_w - P_{\text{giE}}}{T_w - T_{\text{giE}}}\right] \tag{10}$$

$$h_{\text{cwgE}} = 0.884 \left[\left(T_w - T_{\text{giE}}\right) + \frac{\left(P_w - P_{\text{giE}}\right) T_w}{268.9 \times 10^3 - P_w}\right]^{\left(\frac{1}{3}\right)} \tag{11}$$

$$P_w = \exp\left[25.317 - \frac{5144}{\left(T_w + 273\right)}\right] \tag{12}$$

$$P_{\text{giE}} = \exp\left[25.317 - \frac{5144}{\left(T_{\text{giE}} + 273\right)}\right] \tag{13}$$

In the similar fashion, value of $h_{\text{ewgW}}$ can be estimated. Here, yearly thermal exergy ($\text{Ex}_{\text{out,annual}}$) can be estimated using Eq. (9). Firstly, hourly thermal exergy from the system for climatic situation of a type has been calculated from Eq. (9). Then, monthly thermal exergy has been assessed as the product of hourly thermal exergy and number of clear days for type a weather situation. Likewise, computation of monthly thermal exergy for other three types of weather situation has been carried out. The value of yearly thermal exergy has been assessed as the summation of monthly thermal exergy for a year.

### *4.3. Exergo-economic parameter assessment for NCPCIETC-DS/NETC-DS*

The exergo-economic parameter relates the exergy with uniform end-of-year annual cost (UEAC). Exergy represents the quality of energy. The value of exergo-economic parameter can be assessed either on the basis of exergy gain or exergy loss. If exergy gain is considered, the objective will be maximization type. If exergy loss is considered, the objective will be minimization type. Here, exergo-economic parameters have been assessed on the basis of exergy gain as the two systems have to be compared. The exergo-economic parameter for NCPCIETC-DS/NETC-DS can be assessed as:

$$\text{Exego – economic parameter based on energy} = \frac{\text{Annual energy gain}}{\text{UEAC}} \tag{14}$$

$$\text{Exego – economic parameter based on exergy} = \frac{\text{Annual exergy gain}}{\text{UEAC}} \tag{15}$$

The value of annual exergy gain can be assessed using the methodology presented in section 4.2 – Annual exergy and energy assessment for NCPCIETC-DS/NETC-DS. The uniform end-of-year annual cost (UEAC) can be assessed using the concept of present value method [48] as:

$$\text{UEAC} = \left(C_p \times \text{CF}\right) + \left(\text{MC} \times \text{CF}\right) - \left(S_V \times \text{SF}\right) \tag{16}$$

where $C_p$ represents total present cost of NCPCIETC-DS/NETCDS, $S_v$ represents salvage value of NCPCIETC-DS/

NETC-DS and MC represents the cost of maintaining the system during the whole life span of NCPCIETC-DS/NETC-DS. The maintenance cost (MC) for NCPCIETC-DS/NETC-DS can be represented as:

$$\text{MC} = C_p \times \text{MCF} \tag{17}$$

where MCF represents maintenance cost factor. The value of MCF has been considered as 0.1.

The expression for CF which is used for converting $C_p$ into a part of UEAC can be written as:

$$\text{CF} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{18}$$

Similarly, SF which is used for converting $S_v$ into a part of UEAC can be written as:

$$\text{SF} = \frac{i}{(1+i)^n - 1} \tag{19}$$

where $i$ stand for interest of the system and $n$ stands for life span of the system.

The expression of $P_c$ for 50 y life span of NCPCIETC-DS/NETC-DS can be written as [45]:

$$P_c = \text{IC} + C_p + \frac{C_p}{(1+i)^{10}} + \frac{C_p}{(1+i)^{20}} + \frac{C_p}{(1+i)^{30}} + \frac{C_p}{(1+i)^{40}} \tag{20}$$

where IC represents the initial cost of system and $C_p$ represents cost of the DC motor pump. The life of DC motor pump can be considered as 10 y [49]. It has been assumed that the cost of motor pump assembly at the time of procurement is same as the present cost if inflation takes care of $S_v$. The value of IC of the system NCPCIETC-DS/NETC-DS can be evaluated as:

$$\text{IC} = C_{\text{DS}} + C_{\text{NCPCIETC}} + C_l \tag{21}$$

The first term in Eq. (21) represents present cost of double slope solar still (DS); the second term in Eq. (21) represents

Table 2
Computation of yearly energy output for NCPCIETC-DS and NETC-DS

| Month | Type a weather situation | | | Type b weather situation | | | Type c weather situation | | | Type d weather situation | | | Monthly energy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_a$ | $n_a$ | $m_a$ | $E_b$ | $n_b$ | $m_b$ | $E_c$ | $n_c$ | $m_c$ | $E_d$ | $n_d$ | $m_d$ | |
| NCPCIETC-DS | | | | | | | | | | | | | |
| January | 14.52 | 3 | 43.56 | 13.25 | 8 | 105.97 | 4.02 | 11 | 44.22 | 0.95 | 9 | 8.58 | 202.33 |
| February | 14.22 | 3 | 42.66 | 13.68 | 4 | 54.72 | 4.13 | 12 | 49.52 | 0.80 | 9 | 7.20 | 154.10 |
| March | 15.68 | 5 | 78.40 | 16.51 | 6 | 99.04 | 6.97 | 12 | 83.60 | 3.40 | 8 | 27.20 | 288.24 |
| April | 17.31 | 4 | 69.23 | 17.56 | 7 | 122.92 | 7.92 | 14 | 110.88 | 6.48 | 5 | 32.40 | 335.43 |
| May | 17.37 | 4 | 69.47 | 13.77 | 9 | 123.90 | 9.90 | 12 | 118.80 | 5.67 | 6 | 34.04 | 346.21 |
| June | 16.59 | 3 | 49.76 | 13.92 | 4 | 55.68 | 8.41 | 14 | 117.79 | 3.25 | 9 | 29.28 | 252.51 |
| July | 14.43 | 2 | 28.87 | 11.82 | 3 | 35.46 | 8.41 | 10 | 84.07 | 2.75 | 17 | 46.69 | 195.09 |
| August | 13.99 | 2 | 27.97 | 12.84 | 3 | 38.52 | 6.53 | 7 | 45.69 | 2.87 | 19 | 54.59 | 166.77 |
| September | 17.73 | 7 | 124.09 | 15.37 | 3 | 46.10 | 9.29 | 10 | 92.93 | 3.47 | 10 | 34.67 | 297.79 |
| October | 14.52 | 5 | 72.60 | 10.55 | 10 | 105.53 | 7.55 | 13 | 98.19 | 2.17 | 3 | 6.50 | 282.83 |
| November | 13.05 | 6 | 78.28 | 8.60 | 10 | 86.00 | 2.85 | 12 | 34.24 | 2.37 | 2 | 4.75 | 203.27 |
| December | 12.85 | 3 | 38.56 | 10.93 | 7 | 76.53 | 4.89 | 13 | 63.53 | 0.97 | 8 | 7.79 | 186.41 |
| Annual energy output (kWh) | | | | | | | | | | | | | 2,910.96 |
| NETC-DS | | | | | | | | | | | | | |
| January | 4.07 | 3 | 12.22 | 3.78 | 8 | 30.24 | 1.72 | 11 | 18.92 | 0.82 | 9 | 7.38 | 68.76 |
| February | 4.26 | 3 | 12.78 | 4.46 | 4 | 17.84 | 1.93 | 12 | 23.20 | 0.87 | 9 | 7.86 | 61.68 |
| March | 5.70 | 5 | 28.50 | 6.50 | 6 | 39.00 | 3.39 | 12 | 40.72 | 2.81 | 8 | 22.51 | 130.73 |
| April | 7.67 | 4 | 30.67 | 8.17 | 7 | 57.17 | 4.93 | 14 | 68.97 | 5.10 | 5 | 25.50 | 182.31 |
| May | 8.38 | 4 | 33.52 | 8.35 | 9 | 75.18 | 7.47 | 12 | 89.60 | 5.79 | 6 | 34.76 | 233.06 |
| June | 7.85 | 3 | 23.56 | 8.29 | 4 | 33.17 | 6.67 | 14 | 93.43 | 4.29 | 9 | 38.64 | 188.80 |
| July | 7.15 | 2 | 14.31 | 7.31 | 3 | 21.92 | 5.74 | 10 | 57.40 | 3.87 | 17 | 65.73 | 159.36 |
| August | 6.31 | 2 | 12.63 | 6.91 | 3 | 20.74 | 4.97 | 7 | 34.77 | 3.45 | 19 | 65.49 | 133.62 |
| September | 7.94 | 7 | 55.58 | 7.70 | 3 | 23.10 | 6.09 | 10 | 60.87 | 3.73 | 10 | 37.33 | 176.88 |
| October | 5.57 | 5 | 27.83 | 4.78 | 10 | 47.80 | 3.41 | 13 | 44.29 | 2.13 | 3 | 6.40 | 126.32 |
| November | 4.61 | 6 | 27.68 | 3.44 | 10 | 34.40 | 1.65 | 12 | 19.84 | 1.57 | 2 | 3.15 | 85.07 |
| December | 3.93 | 3 | 11.80 | 3.17 | 7 | 22.21 | 2.00 | 13 | 26.00 | 0.91 | 8 | 7.25 | 67.27 |
| Annual energy output (kWh) | | | | | | | | | | | | | 1,613.85 |

present cost of NCPCIETCs and $C_l$ represents the cost of fabrication for NCPCIETC-DS/NETC-DS. It also includes the cost of piping and labor.

UEAC for NCPCIETC-DS/NETC-DS has been evaluated using Eq. (16) and it has been presented in Table 3. The life span of NCPCIETC-DS/NETC-DS has been taken as 50 y.

*4.4. Computation of production cost of 1 kg of potable water obtained from NCPCIETC-DS/NETC-DS*

Having calculated annual freshwater yielding of potable water from section 4.1 – Annual freshwater yielding assessment and UEAC from section 4.3.1, one can compute the unit cost of producing potable water from NCPCIETC-DS/NETC-DS ($C_{pw}$) as follows:

$$C_{pw} = \frac{\text{UEAC}}{\text{Annual yield}} \tag{22}$$

Values of $C_{pw}$ for NCPCIETC-DS/NETC-DS have been calculated with the help of Eq. (22) and they have been presented in Table 3.

*4.5. Enviro-economic parameter assessment*

The production of freshwater from conventional method using RO system requires electrical energy for its operation. The electrical energy production process emits pollutants which is harmful for the environment. So, freshwater production using solar energy can be used for mitigating the contemporary need of freshwater and it does not emit any pollutants during its operation. The enviro-economic analysis is a way to reduce pollution by providing incentive to diminish the release of polluting elements and motivate to use solar energy technology as solar energy technology does not emit polluting elements. The concept of enviro-economic analysis is based on the price of carbon-di-oxide emission reduction and diminish in carbon-di-oxide emission for the entire life of the system under consideration. The enviro-economic parameter for NCPCIETC-DS/NETC-DS can be estimated as:

$$\begin{aligned}&\text{Enviro}-\text{economic parameter}\\&=\left(\text{Carbon}-\text{di}-\text{oxide emission reduction price}\right)\\&\quad\times\left(\xi_{\text{carbon}-\text{di}-\text{oxide}}\right)\end{aligned} \tag{23}$$

where $\xi_{\text{carbon-di-oxide}}$ is reduction in the emission of carbon-di-oxide for the entire life of the system.

If a consumer makes use of unit electrical power, loss during distribution and transmission amounts to 40% and the domestics appliance loss due to its poor condition is 20%, power required to be generated in power plant = 1/(1–0.2)(1–0.4) = 2.08 units. The mean value of carbon-di-oxide emission for unit kWh at source is about 0.96 kg if electrical energy is produced from coal [50]. In this way, the value of carbon-di-oxide emission corresponding to 1 kWh electrical power consumption comes out to be 2.08 × 0.96 = 2 kg. The value of reduction in the amount of carbon-di-oxide for the entire life of NCPCIETC-DS/NETC-DS in terms of ton of carbon-di-oxide can be estimated as:

Table 3
Computation of UEAC for NCPCIETC-DS and NETC-DS

| Investment for NCPCIETC-DS and NETC-DS | | | |
|---|---|---|---|
| S.N. | Parameter | Cost of NCPCIETC-DS (Rs.) | Cost of NETC-DS (Rs.) |
| 1 | Solar desalting unit | 19,183 | 19,183 |
| 2 | NCPCIETC ($N$ = 8) | 28,858 | 15,060 |
| 3 | DC motor and pump | 2,000 | 2,000 |
| 4 | Fabrication | 8,000 | 6,000 |
| 5 | Salvage value of the system after 50 y, if inflation remains @ 4% in India, (using present value of scrap material sold in Indian market) | 34,141 | 24,335 |

| Computation of UEAC | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $n$ | $i$ | $P_s$ | $M$ | $S_s$ | $F_{CR,i,n}$ | $F_{SR,i,n}$ | UNEC | $M_w$ | $C_{wp}$ |
| Yr. | % | Rs. | @10% | Rs. | Fraction | Fraction | Rs. | kg | Rs./kg |
| NCPCIETC-DS | | | | | | | | | |
| 50 | 2 | 63,037.56 | 6,303.76 | 34,141 | 0.031823 | 0.01182 | 1,803.10 | 4,366.34 | 0.41 |
| 50 | 5 | 61,182.32 | 6,118.23 | 34,141 | 0.054777 | 0.00478 | 3,523.33 | 4,366.34 | 0.81 |
| 50 | 10 | 59,268.18 | 5,926.82 | 34,141 | 0.100859 | 0.00086 | 6,546.14 | 4,366.34 | 1.50 |
| NETC-DS | | | | | | | | | |
| 50 | 2 | 47,239.56 | 4,723.96 | 24,335 | 0.031823 | 0.01182 | 1,365.99 | 2,420.64 | 0.56 |
| 50 | 5 | 44,971.45 | 4,497.14 | 24,335 | 0.054777 | 0.00478 | 2,593.42 | 2,420.64 | 1.07 |
| 50 | 10 | 43,470.18 | 4,347.02 | 24,335 | 0.100859 | 0.00086 | 4,801.87 | 2,420.64 | 1.98 |

$$\left(\xi_{\text{carbon-di-oxide}}\right)_{\text{energy}} = \left[\begin{array}{c}(\text{Annual energy output})(\text{life of system}) \\ -\text{embodied energy}\end{array}\right] \times (0.002) \tag{24}$$

$$\left(\xi_{\text{carbon-di-oxide}}\right)_{\text{exergy}} = \left[\begin{array}{c}(\text{Annual exergy output})(\text{life of system}) \\ -\text{embodied energy}\end{array}\right] \times (0.002) \tag{25}$$

*4.6. Annual productivity assessment for NCPCIETC-DS/NETC-DS*

The productivty stands for the deep relationship that exists between output and input. The main objective of productivity estimation is to enhance value of output as high as possible while keeping input as low as possible. International Labour Office [51] defines the term productivity as effectiveness divided by efficiency. The annual productivity for NCPCIETC-DS/NETC-DS can be defined as [51]:

$$\eta_{p,\text{annual}} = \frac{\begin{array}{c}(\text{Annual freshwater output}) \\ \times(\text{Selling price of freshwater})\end{array}}{\text{UEAC}} \times 100 \tag{26}$$

## 5. Methodology

The methodology for computing different parameters for NCPCIETC-DS/NETC-DS can be expressed as follows:

*Step I*

The input data namely solar intensity, number of clear days and ambient temperature for NCPCIETC-DS/NETC-DS have been accessed from Indian Meteorological Department (IMD), Pune, India. Liu and Jordan formula has been employed for the assessment of intensity on the inclined surface using code written in MATLAB.

*Step II*

The value of $\dot{Q}_{\text{UN}}$ has been assessed using Eq. (3). Further, values of $T_w$, $T_{\text{giE}}$ and $T_{\text{giW}}$ have been assessed using Eqs. (4)–(6) in that order.

*Step III*

The value of hourly freshwater yielding for NCPCIETC-DS/NETC-DS has been done using Eq. (13) followed by the evaluation of annual yield with the help of method presented in section 4.1 – Annual freshwater yielding assessment. Likewise, annual exergy and energy for NCPCIETC-DS/NETC-DS have been assessed using Eqs. (8) and (9), respectively.

*Step IV*

The values of exergo-economic parameters based on energy and exergy have been assessed using Eqs. (15) and (16) in that order.

*Step V*

Values of enviro-economic parameter and productivity have been assessed using Eqs. (23) and (26) in that order.

## 6. Results and discussion

The input data required for numeric computation consisting of ambient air temperature, solar radiation striking a horizontal surface and number of days for the four weather conditions were obtained from the Indian Meteorological Department (IMD), Pune, India. For surface inclined at 30° north latitude, solar radiation can be calculated by using the formula proposed by Liu and Jordan encoded in MATLAB. After dining all relevant data to computational code in MATLAB, different outputs have been obtained and they have been presented as Figs. 2–3 and Tables 2–5.

The comparative monthly freshwater yielding for NCPCIETC-DS and NETC-DS at $N$ = 8 and $\dot{m}_{\text{fr}}$ = 0.012 kg/s has been displayed as Fig. 2. As seen in Fig. 2, value of monthly freshwater yielding is higher for NCPCIETC-DS than the freshwater yielding of NETC-DS in each month of year because more heat is made available to basin water by NCPCIETC than NETC due to the presence of concentrator in the case of NCPCIETC. Likewise, the comparative monthly exergy for NCPCIETC-DS and NETC-DS at $N$ = 8

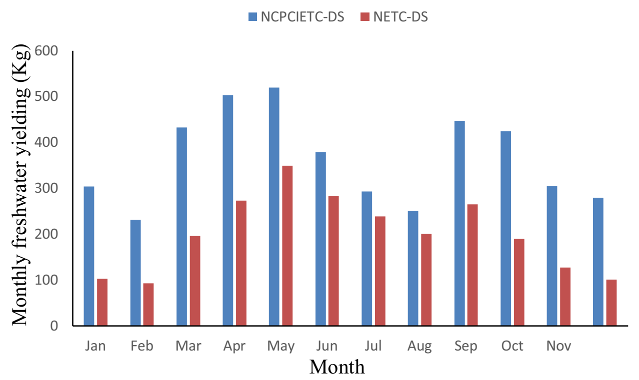



Fig. 2. Dissimilarity of monthly freshwater yielding of NCPCIETC-DS and NETC-DS.

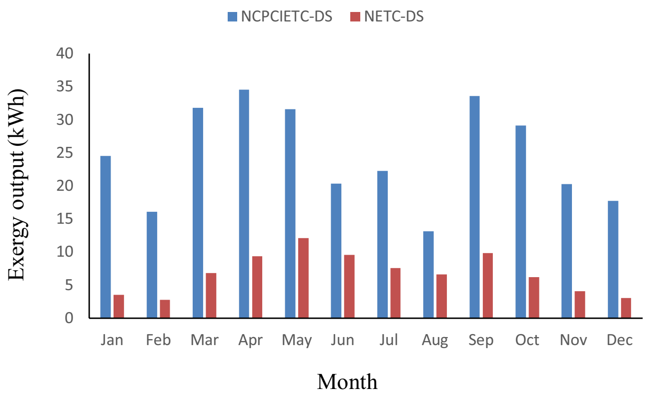



Fig. 3. Dissimilarity of monthly exergy output of NCPCIETC-DS and NETC-DS.

Table 4
Estimation of exergo-economic parameter as well as annual productivity

| Estimation of exergo-economic parameter | | | | Estimation of productivity | | |
|---|---|---|---|---|---|---|
| Rate of interest | UEAC | Annual exergy | Exergo-economic parameter | Annual yield | Selling price of freshwater | Productivity |
| (%) | (Rs.) | (kWh) | (kWh/Rs.) | kg | (Rs.) | (%) |
| NCPCIETC-DS | | | | | | |
| 2 | 1,803.1 | 294.73 | 0.16 | 4,366.44 | 5 | 1,210.81 |
| 5 | 3,523.33 | 294.73 | 0.08 | 4,366.44 | 5 | 619.65 |
| 10 | 6,546.14 | 294.73 | 0.05 | 4,366.44 | 5 | 333.51 |
| NETC-DS | | | | | | |
| 2 | 1,365.99 | 81.25 | 0.06 | 2,420.77 | 5 | 886.09 |
| 5 | 2,593.42 | 81.25 | 0.03 | 2,420.77 | 5 | 466.71 |
| 10 | 4,801.87 | 81.25 | 0.02 | 2,420.77 | 5 | 252.07 |

Table 5
Computation of carbon dioxide mitigation and enviro-economic parameter

| Component | NCPCIETC-DS | NETC-DS |
|---|---|---|
| | EBE (kWh) | EBE (kWh) |
| DS | 1,483.90 | 1,483.90 |
| Collectors ($N$ = 8) | 3,084.30 | 880.29 |
| Others | 23 | 20 |
| NCPCIETC-DS | | |
| EBE | | 4,591.20 |
| Annual energy output (kWh) | | 2,910.96 |
| Life span (y) | | 50.00 |
| Carbon dioxide mitigation (ton) | | 281.91 |
| Enviro-economic parameter ($) | | 4,087.75 |
| NETC-DS | | |
| EBE | | 2,384.19 |
| Annual energy output (kWh) | | 1,613.85 |
| Life span (y) | | 50 |
| Carbon dioxide mitigation (ton) | | 235.19 |
| Enviro-economic parameter ($) | | 3,410.27 |

and $\dot{m}_{fr}$ = 0.012 kg/s has been displayed as Fig. 3. As seen in Fig. 3, the value of annual freshwater yielding is higher for NCPCIETC-DS than the freshwater yielding of NETC-DS in each month of the year. The higher value of monthly exergy in the case of NCPCIETC-DS has been obtained due to more heat supplied to basin water by NCPCIETC due to the presence of concentrator in the case of NCPCIETC.

The comparative assessment of annual energy of NCPCIETC-DS and NETC-DS at $N$ = 8 and $\dot{m}_{fr}$ = 0.012 kg/s has been displayed as Table 2. As seen in Table 2, the annual energy output is higher for NCPCIETC-DS because monthly energy output is higher for NCPCIETC-DS in each month of year. The value of monthly energy output is higher for NCPCIETC-DS because more solar energy is captured by NCPCIETC-DS than NETC-DS. Due to the higher solar energy collection area, difference of temperature of water and condensing cover is higher in the case of NCPCIETC-DS which results in the production of higher energy output by NCPCIETC-DS.

The comparative assessment of UEAC and unit cost of freshwater yielding for NCPCIETC-DS and NETC-DS at $N$ = 8 and $\dot{m}_{fr}$ = 0.012 kg/s has been displayed as Table 3. The rate of interest has been considered as 2%, 5% and 10%. The life of both systems has been considered as 50 y. As seen in Table 3, the production cost of unit freshwater yielding is lower by 32.10% for NCPCIETC-DS than NETC-DS at 5% interest rate. The reason for the lower freshwater yielding cost may be attributed to 44.56% higher freshwater yielding for NCPCIETC-DS than NETC-DS. The comparative assessment of exergo-economic parameter and productivity for NCPCIETC-DS and NETC-DS at $N$ = 8 and $\dot{m}_{fr}$ = 0.012 kg/s has been displayed as Table 4. The exergo-economic parameter at 5% rate of interest is 62.5% higher for NCPCIETC-DS than NETC-DS. The reason may be attributed to the fact that the exergy output and UEAC are 72.43% and 26.39% higher for NCPCIETC-DS than NETC-DS. In fact, the increase in exergy output dominates the increase in UEAC for NCPCIETC-DS than NETC-DS. Further, the annual productivity is 24.68% higher for NCPCIETC-DS than NETC-DS at 5% rate of interest. The reason for higher annual productivity for NCPCIETC-DS may be attributed to 44.56% higher freshwater yielding and hence 44.56% higher revenue earned for NCPCIETC-DS than NETC-DS. Also, the value of UEAC for NCPCIETC-DS is 26.39% higher than NETC-DS. However, the increase in the value of annual revenue dominates the increase in the value of UEAC.

The comparative assessment of carbon dioxide mitigation and enviro-economic parameter for NCPCIETC-DS and NETC-DS at $N$ = 8 and $\dot{m}_{fr}$ = 0.012 kg/s has been displayed as Table 5. The carbon-dioxide emission reduction price has been considered as $14.5 per $tCO_2$. The value of enviro-economic parameter for NCPCIETC-DS is higher by 16.57% for NCPCIETC-DS than NETC-DS. The reason for the higher value of enviro-economic parameter for NCPCIETC-DS may be attributed to the higher energy output for NCPCIETC-DS than NETC-Ds as evident from Table 2.

## 5. Conclusions

The comparative exergo-enviro-economic parameters and annual productivity of NCPCIETC-DS and NETC-DS have been assessed at $N$ = 8, $\dot{m}_{fr}$ = 0.012 kg/s and water depth = 0.14 m. On the basis of current research study, the following conclusions have been made:

i. The value of kWh per unit cost based on exergo-economic parameter has been assessed to be 62.5% higher for NCPCIETC-DS than NETC-DS at 5% rate of interest.
ii. Values of carbon dioxide mitigation and enviro-economic parameter for NCPCIETC-DS have been assessed to be higher for NCPCIETC-DS than NETC-DS.
iii. The value of annual productivity for NCPCIETC-DS has been assessed to be higher than NETC-DS at all rates of interest under consideration. At 5% rate of interest, the value of annual productivity for NCPCIETC-DS has been assessed to be 24.68% than NETC-DS.
iv. The production cost of unit freshwater yielding for NCPCIETC-DS has been assessed to be 32.10% lower than NETC-DS.

## Symbols

| | |
|---|---|
| $A_b$ | — Area of basin, $m^2$ |
| $A_{gE}$ | — Area of east glass cover, $m^2$ |
| $A_{gW}$ | — Area of west glass cover, $m^2$ |
| $C_f/C_w$ | — Specific heat capacity, J/kg-K |
| $C_p$ | — Total present cost of N-CPC-ETC-DS/NETCDS |
| $C_l$ | — Cost of fabrication for N-CPC-ETC-DS/NETCDS |
| $C_{NCPCIETC}$ | — Present cost of NCPCIETCs |
| $C_{DS}$ | — Present cost of DS |
| CF | — Capital recovery factor |
| $C_{pw}$ | — Unit cost of producing potable water from N-CPC-ETC-DS/NETCDS |
| DS | — Double slope solar still |
| $\dot{E}x_{out}$ | — Hourly exergy output, kWh |
| ETC | — Evacuated tubular collector |
| $\dot{E}_{out}$ | — Hourly energy output |
| $F'$ | — Collector efficiency factor, dimensionless |
| HC | — Heat transfer coefficient, $W/m^2$-K |
| $h_{cw}$ | — Convective heat transfer coefficient from water to inner surface of glass cover, $W/m^2$-K |
| $h_{ewE}$ | — Evaporative heat transfer coefficient from water surface to inner surface of east glass cover, $W/m^2$-K |
| $h_{ewW}$ | — Evaporative heat transfer coefficient from water surface to inner surface of west glass cover, $W/m^2$-K |
| $h_c$ | — Convective heat transfer coefficient, $W/m^2$-K |
| $h_{ba}$ | — Heat transfer coefficient from blackened surface to ambient, $W/m^2$-K |
| $h_{bw}$ | — Heat transfer coefficient from blackened surface to water mass, $W/m^2$-K |
| $h$ | — Heat transfer coefficient, $W/m^2$-K |
| $h_{rw}$ | — Radiative heat transfer coefficient from water to inner surface of glass cover, $W/m^2$-K |
| $h_r$ | — Radiative heat transfer coefficient, $W/m^2$-K |
| $h_{1w}$ | — Total heat transfer coefficient from water surface to inner glass cover, $W/m^2$-K |
| $h_{1g}$ | — Total heat transfer coefficient from water surface to inner glass cover, $W/m^2$-K |
| $h_{EW}$ | — Radiative heat transfer coefficient from inner surface of east glass cover to inner surface of west glass cover |
| $I(t)$ | — Total solar flux, $W/m^2$ |
| $I_b(t)$ | — Beam radiation on collector, $W/m^2$ |
| IC | — Initial cost of system |
| $i$ | — Rate of interest |
| $I_{SE}(t)$ | — Solar intensity on east glass cover, $W/m^2$ |
| $I_{SW}(t)$ | — Solar intensity on west glass cover, $W/m^2$ |
| $K$ | — Thermal conductivity, W/m-K |
| $L_g$ | — Thickness of glass cover, m |
| $L'$ | — Latent heat, J/kg |
| $L$ | — Length, m |
| $\dot{m}_f$ | — Mass flow rate of fuid/water, kg/s |
| $\dot{m}_{ew}$ | — Mass of distillate from double slope solar still, kg |
| MC | — Maintenance cost |
| MCF | — Maintenance cost factor |
| $N$ | — Number of parabolic concentrator integrated evacuated tubular collector |
| NCPCIETC-DS | — Double slope solar still included with N identical parabolic concentrator integrated evacuated tubular collectors |
| SH | — Number of sunshine hours |
| $n$ | — Number of days |
| NETC-DS | — Double slope solar still coupled with N alikel ETCs |
| CPCIETC | — Compound parabolic concentrator integrated evacuated tubular collectors |
| $PF_1$ | — Penalty factor first, dimensionless |
| $\dot{Q}_{UN}$ | — Useful energy gain for N identical collector connected in series, kWh |
| $R_{o1}$ | — Inner radius of outer glass tube of evacuated coaxial glass tube, m |
| $R_{i1}$ | — Inner radius of inner glass tube of evacuated coaxial glass tube, m |
| $R_{i2}$ | — Outer radius of inner glass tube of evacuated coaxial glass tube, m |
| $R_{o2}$ | — Outer radius of outer glass tube of evacuated coaxial glass tube, m |
| CR | — Concentration ratio |
| $r$ | — Radius of copper tube in ETC |
| $S_v$ | — Salvage value of system N-CPC-ETC-DS/NETCDS |
| SF | — Sinking fund factor |
| ρ | — Reflectivity |
| $T_{foN}$ | — Outlet water temperature at the exit of Nth PCETC, °C |
| $T_a$ | — Ambient temperature, °C |
| $T_{giE}$ | — Temperature at inside plane of condensing cover oriented towards east, °C |

$T_{giW}$ — Temperature at inside plane of condensing cover oriented towards west, °C
$T$ — Time, h
$T_{wo}$ — Water temperature at $t = 0$, °C
$T_w$ — Water temperature, °C
UEAC — Uniform end-of-year annual cost
$U_L$ — Overall heat transfer coefficient
$V$ — Velocity of air, m/s

## Subscript

$b$ — Basin liner
$P$ — Plate
$E$ — East
eff — Effective
$f$ — Fluid
$g$ — Glass
in — Incoming
out — Outgoing
$w$ — Water
$W$ — West

## Greek letters

$\alpha$ — Absorptivity (fraction)
$\eta$ — Efficiency, %
$(\alpha\tau)_{eff}$ — Product of effective absorptivity and transmittivity
$\sigma$ — Stefan–Boltzmann constant, W/m²-K⁴
$\tau$ — Transmissivity

## References


[1] S.N. Rai, G.N. Tiwari, Single basin solar still coupled with flat plate collector, Energy Convers. Manage., 23 (1983) 145–149.
[2] D. Atheaya, A. Tiwari, G.N. Tiwari, I.M. Al-Helal, Analytical characteristic equation for partially covered photovoltaic thermal (PVT) compound parabolic concentrator (CPC), Sol. Energy, 111 (2015) 176–185.
[3] R. Tripathi, G.N. Tiwari, I.M. Al-Helal, Thermal modelling of N partially covered photovoltaic thermal (PVT) – compound parabolic concentrator (CPC) collectors connected in series, Sol. Energy, 123 (2016) 174–184.
[4] D.B. Singh, G.N. Tiwari, Effect of energy matrices on life cycle cost analysis of partially covered photovoltaic compound parabolic concentrator collector active solar distillation system, Desalination, 397 (2017) 75–91.
[5] D.B. Singh, G.N. Tiwari, Exergoeconomic, enviroeconomic and productivity analyses of basin type solar stills by incorporating N identical PVT compound parabolic concentrator collectors: a comparative study, Energy Convers. Manage., 135 (2017) 129–147.
[6] D.B. Singh, G.N. Tiwari, Performance analysis of basin type solar stills integrated with N identical photovoltaic thermal (PVT) compound parabolic concentrator (CPC) collectors: a comparative study, Sol. Energy, 142 (2017) 144–158.
[7] V.S. Gupta, D.B. Singh, R.K. Mishra, S.K. Sharma, G.N. Tiwari, Development of characteristic equations for PVT-CPC active solar distillation system, Desalination, 445 (2018) 266–279.
[8] D.B. Singh, V.K. Dwivedi, G.N. Tiwari, N. Kumar, Analytical characteristic equation of N identical evacuated tubular collectors integrated single slope solar still, Desal. Water Treat., 88 (2017) 41–51.
[9] D.B. Singh, G.N. Tiwari, Analytical characteristic equation of N identical evacuated tubular collectors integrated double slope solar still, J. Sol. Energy Eng., 135 (2017) 051003 (11 pages).
[10] R. Dev, G.N. Tiwari, Annual performance of evacuated tubular collector integrated solar still, Desal. Water Treat., 41 (2012) 204–223.
[11] R. Sathyamurthy, S.A. El-Agouz, P.K. Nagarajan, J. Subramani, T. Arunkumar, D. Mageshbabu, B. Madhu, R. Bharathwaaj, N. Prakash, A review of integrating solar collectors to solar still, Renewable Sustainable Energy Rev., 77 (2017) 1069–1097.
[12] R.V. Singh, S. Kumar, M.M. Hasan, M.E. Khan, G.N. Tiwari, Performance of a solar still integrated with evacuated tube collector in natural mode, Desalination, 318 (2013) 25–33.
[13] K. Sampathkumar, T.V. Arjunan, P. Senthilkumar, The experimental investigation of a solar still coupled with an evacuated tube collector, Energy Sources Part A, 35 (2013) 261–270.
[14] S. Kumar, A. Dubey, G.N. Tiwari, A solar still augmented with an evacuated tube collector in forced mode, Desalination, 347 (2014) 15–24.
[15] H.J. Mosleh, S.J. Mamouri, M.B. Shafii, A.H. Sima, A new desalination system using a combination of heat pipe, evacuated tube and parabolic through collector, Energy Convers. Manage., 99 (2015) 141–150.
[16] M.B. Shafii, S.J. Mamouri, M.M. Lotfi, H.J. Mosleh, A modified solar desalination system using evacuated tube collector, Desalination, 396 (2016) 30–38.
[17] S.W. Sharshir, G. Peng, N. Yang, M.A. Eltawil, M.K.A. Ali, A.E. Kabeel, A hybrid desalination system using humidification–dehumidification and solar stills integrated with evacuated solar water heater, Energy Convers. Manage., 124 (2016) 287–296.
[18] O. Bait, M. Si-Ameur, Tubular solar-energy collector integration: performance enhancement of classical distillation unit, Energy, 141 (2017) 818–838.
[19] O. Bait, Exergy, environ–economic and economic analyses of a tubular solar water heater assisted solar still, J. Cleaner Prod., 212 (2019) 630–646.
[20] R.J. Issa, B. Chang, Performance study on evacuated tubular collector coupled solar still in west Texas climate, Int. J. Green Energy, 14 (2017) 793–800.
[21] D.B. Singh, G.N. Tiwari, Energy, exergy and cost analyses of N identical evacuated tubular collectors integrated basin type solar stills: a comparative study, Sol. Energy, 155 (2017) 829–846.
[22] D.B. Singh, I.M. Al-Helal, Energy metrics analysis of N identical evacuated tubular collectors integrated double slope solar still, Desalination, 432 (2018) 10–22.
[23] D.B. Singh, Improving the performance of single slope solar still by including N identical PVT collectors, Appl. Therm. Eng., 131 (2018) 167–179.
[24] D.B. Singh, Exergo-economic, enviro-economic and productivity analyses of N identical evacuated tubular collectors integrated double slope solar still, Appl. Therm. Eng., 148 (2019) 96–104.
[25] R. Kumar, D.B. Singh, A. Dewangan, V.K. Singh, N. Kumar, Performance of evacuated tube solar collector integrated solar desalination unit — a review, Desal. Water Treat., 230 (2021) 92–115.
[26] D.B. Singh, D. Kumar, R.Kumar Yadav, S.K. Sharma, Y. Chaturbedi, N. Kumar, V.K. Dwivedi, An investigation of effect of mass flow rate variation on productivity, exergoeconomic and enviroeconomic parameters of N similar PVTCPCs included with double slope solar still, Desal. Water Treat., 243 (2021) 1–17.
[27] D.B. Singh, R.K. Yadav, Y. Chaturvedi, M. Kumar, G.K. Sharma, N. Kumar, Study on effect of dissimilarity of mass flow rate on energy metrics of solar energy-based double slope water purifier by incorporating N alike PVT compound parabolic concentrator collectors, Desal. Water Treat., 231 (2021) 27–43.
[28] A. Raturi, K. Bharti, R. Kumar, D.B. Singh, Effect of the variation of N on productivity of solar energy based single slope water purifier integrated with N alike partly covered compound parabolic concentrating solar collectors, Mater. Today Proc., 46 (2021) 10824–10830.

[29] V. Singh, R. Kumar, D.B. Singh, An investigation on effect of dissimilarity of mass flow rate on hourly, daily and annual efficiencies of double slope type solar still included with N similar PVT compound parabolic concentrators, Desal. Water Treat., 246 (2022) 36–53.
[30] D. Kumar, R.K. Sharma, D.B. Singh, Effect of the variation of a mass-flowrate and a number of collectors on the performance of an active solar still, Desal. Water Treat., 248 (2022) 1–17.
[31] V. Singh, R. Kumar, R.K. Sharma, S.P. Singh, H. Sinhmar, D.B. Singh, An investigation on effect of variation of mass flow rate and number of collectors on yearly efficiency of single slope solar still by incorporating N similar photovoltaic thermal flat plate collectors, Water Supply, 22 (2022) 5126–5148.
[32] G.K. Sharma, A. Mallick, R.K. Sharma, R. Dobriyal, N. Kumar, D.B. Singh, An investigation on dissimilarity of mass flow rate and N on exergo-enviro-economic parameters for solar still of single slope type integrated with N similar PVT flat plate collectors having series connection, Environ. Sci. Pollut. Res., 29 (2022) 65842–65859.
[33] G.K. Sharma, A. Mallick, R.K. Sharma, N. Kumar, D.B. Singh, A comprehensive study on the effect of variation of flow rate of fluid and N on energy metrics of N similar photovoltaic thermal flat plate collectors integrated single slope solar still, Desal. Water Treat., 283 (2023) 97–108.
[34] A. Raturi, R. Dobriyal, R.K. Sharma, A Dwivedi, S.P. Singh, D.B. Singha, Sensitivity investigation for solar still of double slope type included with N similar CPC integrated ETC by incorporating yield and efficiency, Desal. Water Treat., 244 (2021) 12–26.
[35] A. Raturi, D.B. Singh, P.P. Patil, A.K. Sharma, Sensitivity analysis of a solar still of a single slope type included with N similar evacuated tubular collectors having series connection, Desal. Water Treat., 234 (2021) 309–323.
[36] D.B. Singh, G. Bansal, H. Prasad, A. Mallick, N. Kumar, S.K. Sharma, Sensitivity analysis of N undistinguishable photovoltaic thermal compound-parabolic-concentrator collectors (partly covered, 50%) integrated single-slope solar distiller unit, ASME J. Sol. Energy Eng., 143 (2021) 021003 (11 pages), doi: 10.1115/1.4048012.
[37] D.B. Singh, Sensitivity analysis of N identical evacuated tubular collectors integrated double slope solar distiller unit by incorporating the effect of exergy, Int. J. Exergy, 34 (2021) 424–447.
[38] K. Bharti, S. Manwal, C. Kishore, R.K. Yadav, P. Tiwari, D.B. Singh, Sensitivity analysis of N alike partly covered PVT flat plate collectors integrated double slope solar distiller unit, Desal. Water Treat., 211 (2021) 45–59.
[39] A.R. Singh, A.B. Agarwal, D.B. Singh, Sensitivity analysis of double slope solar still having compound parabolic concentrator integrated ETCs by incorporating heat transfer coefficients, exergy gain and exergy efficiency, Desal. Water Treat., 276 (2022) 13–27.
[40] D. Kumar, R.K. Sharma, D.B. Singh, Effects of dissimilarity of water depth on energy and exergy efficiencies and productivity of single slope solar still coupled to evacuated tubular collectors, Desal. Water Treat., 278 (2022) 301–310.
[41] D. Kumar, R.K. Sharma, S.K. Sharma, V.K. Dwivedi, S. Tiwari, D.B. Singh, Influence of dissimilarity of water depth on performance of N alike photovoltaic thermal flat plate collectors included with double slope solar still: a comparative study, Desal. Water Treat., 273 (2022) 13–33.
[42] R.K. Yadav, M. Kumar, J. Singh, D.B. Singh, N. Kumar, Effects of the dissimilarity of water depth on energy and exergy efficiencies and productivity of solar energy, Int. J. Exergy, 38 (2022) 333–345.
[43] D.B. Singh, J.K. Yadav, V.K. Dwivedi, S. Kumar, G.N. Tiwari, I.M. Al-Helal, Experimental studies of active solar still integrated with two hybrid PVT collectors, Sol. Energy, 130 (2016) 207–223.
[44] R.K. Mishra, V. Garg, G.N. Tiwari, Energy matrices of U-shaped evacuated tubular collector (ETC) integrated with compound parabolic concentrator (CPC), Sol. Energy, 153 (2017) 531–539.
[45] S.K. Sharma, A. Mallick, S.K. Gupta, N. Kumar, D.B. Singh, G.N. Tiwari, Characteristic equation development for double slope solar distiller unit augmented with N identical parabolic concentrator integrated evacuated tubular collectors, Desal. Water Treat., 187 (2020) 178–194.
[46] H.N. Singh, G.N. Tiwari, Evaluation of cloudiness/haziness factor for composite climate, Energy, 30 (2005) 1589–1601.
[47] P.K. Nag, Basic and Applied Thermodynamics, Tata McGraw-Hill, New Delhi, 2004.
[48] G.N. Tiwari, Solar Energy, Fundamentals, Design, Modeling and Application, Narosa Publishing House, New Delhi, 2013.
[49] S. Kumar, G.N. Tiwari., Life cycle cost analysis of single slope hybrid (PV/T) active solar still, Appl. Energy, 86 (2009a) 1995–2004.
[50] B.K. Sovacool, Valuing the greenhouse gas emissions from nuclear power: a critical survey, Energy Policy, 36 (2008) 2940–2953.
[51] International Labor Office, 1979, Introduction to Work Study, International Labor Organization, Geneva, 1979.
[52] P.I. Cooper, Digital simulation of experimental solar still data, Sol. Energy, 14 (1973) 451–456.
[53] R.V. Dunkle, Solar Water Distillation, the Roof Type Solar Still and Multi Effect Diffusion Still, International Developments in Heat Transfer, ASME, Proceedings of International Heat transfer, Part V, University of Colorado, 1961, p. 895.


## Appendix A

$$U_{\text{tpa}} = \left[ \frac{R_{o2} \ln\left(\frac{R_{i2}}{R_{i1}}\right)}{K_g} + \frac{1}{C_{\text{ev}}} + \frac{R_{o2} \ln\left(\frac{R_{o2}}{R_{o1}}\right)}{K_g} + \frac{1}{h_o} \right]^{-1} \qquad h_{\text{pf}} = 100 \text{ Wm}^{-2}\text{K}^{-1} \qquad h_o = 5.7 + 3.8\,V$$

$$\text{PF}_1 = \frac{F' h_{\text{pf}}}{F' h_{\text{pf}} + U_{\text{tpa}}} \qquad (\alpha\tau)_{\text{eff}} = \rho\alpha\tau^2 \left(\frac{A_a}{A_r}\right) \qquad (A_r F_r) = \frac{\dot{m}_f C_f}{U_L}\left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right)\right]$$

$$K_K = 1 - \frac{A_r F_r U_L}{\dot{m}_f C_f} \qquad h_{\text{bw}} = 100 \text{ Wm}^{-2}\text{K}^{-1} \qquad U_{\text{cE}} = \frac{\frac{K_g}{L_g} h_{1\text{gE}}}{\frac{K_g}{L_g} + h_{1\text{gE}}} \qquad U_{\text{cW}} = \frac{\frac{K_g}{L_g} h_{1\text{gE}}}{\frac{K_g}{L_g} + h_{1\text{gE}}}$$

$$U_2 = h_{1\text{wW}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gW}} + U_{\text{cW}}A_{\text{gW}} \qquad R_1 = \alpha'_g I_{\text{SE}} + U_{\text{cE}}T_a \qquad R_2 = \alpha'_g I_{\text{SW}} + U_{\text{cW}}T_a$$

$$A_1 = R_1U_2A_{\text{gE}} + R_2h_{\text{EW}}A_{\text{gW}} \qquad A_2 = h_{1\text{WE}}\frac{A_b}{2} + \frac{h_{\text{Ew}}}{U_2}h_{1\text{wW}}\frac{A_b}{2}$$

$$U_1 = h_{1\text{wE}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gE}} + U_{\text{cE}}A_{\text{gE}} \qquad P = U_2U_1 - \frac{h_{\text{EW}}^2A_{\text{gW}}}{A_{\text{gE}}} \qquad B_1 = \frac{\left(R_2P + h_{\text{EW}}A_1\right)A_{\text{gW}}}{U_2A_{\text{gE}}}$$

$$B_2 = \frac{\text{Ph}_{1\text{wW}}\frac{A_b}{2} + h_{\text{EW}}A_{\text{gW}}A_2}{U_2A_{\text{gE}}} \qquad h_1 = \frac{h_{\text{bw}}}{2\left(h_{\text{bw}} + h_{\text{ba}}\right)} \qquad U_b = \frac{h_{\text{ba}}h_{\text{bw}}}{h_{\text{ba}} + h_{\text{bw}}}$$

$$a = \frac{1}{M_wC_w}\left[\left(A_rF_r\right)U_L\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)} + U_bA_b + \left(h_{1\text{wE}} + h_{1\text{wE}}\right)\frac{A_b}{2} - \left(\frac{h_{1\text{wE}}A_2}{P}\right)\frac{A_b}{2} - \left(\frac{h_{1\text{wW}}B_2}{P}\right)\frac{A_b}{2}\right]$$

$$f(t) = \frac{1}{M_wC_w}\left[\left(\frac{\alpha'_w}{2} + h_1\alpha'_b\right)A_b\left(I_{\text{SE}}(t) + I_{\text{SW}}(t)\right) + U_bA_bT_b + \frac{\left(h_{1\text{wE}}A_1 + h_{1\text{wW}}B_1\right)}{P}\frac{A_b}{2} + \left(\text{PF}_1\right)\left(\alpha\tau\right)_{\text{eff}}\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}I_b + \left(A_rF_r\right)U_L\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)}T_a\right]$$

$$h_{\text{ewE}} = 16.273\times10^{-3}h_{\text{cwE}}\left[\frac{P_w - P_{\text{giE}}}{T_w - T_{\text{giE}}}\right]\left(\text{Cooper}[52]\right)$$

$$h_{\text{ewW}} = 16.273\times10^{-3}h_{\text{cwW}}\left[\frac{P_w - P_{\text{giW}}}{T_w - T_{\text{giW}}}\right]\left(\text{Cooper}[52]\right)$$

$$h_{\text{ewE}} = 0.884\left[\left(T_w - T_{\text{giE}}\right) + \frac{\left(P_w - P_{\text{giE}}\right)\left(T_w + 273\right)}{268.9\times10^3 - P_w}\right]^{\frac{1}{3}}\left(\text{Dunkle}[53]\right)$$

$$h_{\text{ewW}} = 0.884\left[\left(T_w - T_{\text{giW}}\right) + \frac{\left(P_w - P_{\text{giW}}\right)\left(T_w + 273\right)}{268.9\times10^3 - P_w}\right]^{\frac{1}{3}}\left(\text{Dunkle}[53]\right)$$

$$P_w = \exp\left[25.317 - \frac{5144}{T_w + 273}\right] \qquad p_{\text{giE}} = \exp\left[25.317 - \frac{5144}{T_{\text{giE}} + 273}\right] \qquad P_{\text{giW}} = \exp\left[25.317 - \frac{5144}{T_{\text{giW}} + 273}\right]$$