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

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Abstract
This paper investigates analytically the effect of dissimilarity of mass flow rate ($\dot{m}_f$) and number of collectors ($N$) on exergo-enviro-economic parameters for solar still of single slope type integrated with $N$ similar photovoltaic thermal flat plate collectors having series connection (NPVTFPC-SS) keeping water depth as 0.14 m. All four kinds of weather conditions for New Delhi have been taken for the computation of different parameters. All relevant equations obtained using energy balance equations for all components of the system have been fed to a computer code inscribed in MATLAB-2015a for computing different parameters. The computation of different relevant parameters has been performed for various values of $\dot{m}_f$ and $N$ while keeping water depth as constant to know the effect of variation of $\dot{m}_f$ and $N$ on exergo-enviro-economic parameters for NPVTFPC-SS. It has been concluded that the value of carbon credit earned, enviroeconomic and exergoeconomic parameters, and productivity diminishes with the enhancement in $\dot{m}_f$ at given $N$. The optimum value of $N$ for given value of $\dot{m}_f$ has been found to be 10 from exergoeconomic parameter viewpoint and 6 from productivity viewpoint.

Keywords Exergo-enviro-economic parameters · Overall yearly energy and exergy · Mass flow rate · $N$ · Solar still of single slope type

Introduction
The exergo-enviro-economic analysis of solar still of single slope type integrated with $N$ similar PVT flat plate collectors (NPVTFPC-SS) having series connection is the need of time as the globe is facing the contemporary issue of freshwater scarcity. Exergy of solar energy-based water purifier commonly known as solar still can be calculated using first and second laws of thermodynamics. Exergy can be written as the maximum work output taken from the system in carrying out the system from current state to equilibrium state with the surrounding. If the given system is at temperature $T$ and surrounding temperature is $T_a$, the maximum work that can be obtained in carrying the system from temperature $T$ to temperature $T_a$ is exergy. Exergy is high grade energy because its complete utilization is possible, whereas heat is considered as low-grade energy because heat can never be completely used. Some portion of the heat is bound to loss. Electrical energy which can be also generated using green technology, namely, PV module and solar thermal without disturbing the environment from pollution viewpoint, is high-grade energy because it can be utilized fully. One of the examples of complete utilization is conversion of electrical energy into heat in heat application processes. The economic analysis can be carried out using present value method.
The working principle of solar still is based on greenhouse effect and it has the potential to meet the scarcity of fresh water partly/fully. The solar still is self-sustainable due to which it can be installed in remote location for producing fresh water from impure water. Moreover, solar still takes solar energy as input which is freely available and will continue to survive till the survival of life on the planet earth. It does not emit pollutants and hence environment friendly. The solar still is broadly divided into passive and active solar stills. The output of passive solar still ranges from 1 to 3 kg for unit basin area in most cases (Tiwari and Mishra, 2012). This issue of passive type solar still having low output can be taken care by adding some kind of arrangement that can supply heat to basin of solar still and the resulting system is commonly known as active solar still. The rise in temperature of water kept in basin gets improved due to the addition of heat which compels water in basin to evaporate faster and improved freshwater yielding is obtained. The active type of solar still was first of all introduced by Rai and Tiwari in 1983, and a lot of improvements in that system have been addressed by researchers around the globe. Their findings have been summarized in paragraphs that follow.

Rai and Tiwari (1983) reported the enhancement in fresh water yielding of solar still of single slope type in active mode by incorporating one conventional flat plate collector (FPC) over passive type solar still of the identical basin area due to the addition of heat to the basin in active mode of operation. This water purifier was not self-sustainable as the pump needed some electric power for working which was supplied through grid. The active type solar still in the forced mode of operation can be made self-sustainable by incorporating solar panel to the system. Kumar and Tiwari (2008) proposed the integration of PVT with FPC for supplying heat to basin of passive type solar still taking inspiration from the work of Kern and Russell (1958). It was reported by Kern and Russell that the electrical efficiency of solar panel got increased upon integration of solar panel with solar collector due the removal of heat by fluid passing below the panel. Kumar and Tiwari reported the improvement in output by 3.5 times over the similar passive type solar still due to the addition of heat by two collectors in which only one of them was integrated with PVT for making the system self-sustainable. The work of Kumar and Tiwari was extended by Singh et al. (2011) for double slope (DS) type solar still in active mode. Further, Tiwari et al. (2013) and Singh et al. (2016) reported the experimental investigation of solar still by incorporating two FPCs in which both FPCs were partially integrated with PVT. They reported an enhancement in direct current (DC) electrical output; however, the yield of fresh water was less as compared to the system reported by Kumar and Tiwari (2008). The heat gain was less because more area of FPCs was covered by PVT. Sahota and Tiwari (2017) reported the use of nanofluid in DS type solar still in active mode for enhancing the freshwater output. Further, active type solar still was studied under optimized situation by Singh (2018). It was reported that the DS type solar still under optimized condition by incorporating N alike PVTFPCs had 74.66% higher energy payback time (ENPBT) over passive type DS solar still. The value of exergoeconomic parameter for single slope type solar still was found to be 47.37% higher than the passive type of single slope solar still of same basin area. Carranza et al. (2021) have experimentally investigated the performance of DS type solar still loaded with nanofluid by incorporating preheating of saline water and concluded that water yield increases due to better thermophysical properties of nanofluid as compared to base fluid. Koubaji et al. (2021) have investigated solar still by incorporating zinc and copper oxides for the location of Algeria and compared the yield with conventional solar still and they revealed that the potential water yielding was improved by 79.39% due to having better thermophysical characteristic of nanofluid.

The output of solar still could further be enhanced by changing the design of solar collector which could absorb higher amount of heat from the sun or by changing the design of solar still. PVT integrated FPC could gain higher heat if some concentrating part was integrated with FPC. With this concept in mind, Atheaya et al. (2015) proposed PVT integrated compound parabolic concentrator collector (CPC) and reported its thermal model which was further extended by Tripathi et al. (2016) for N collectors connected in series and loop was opened. Atheaya et al. (2016) verified PVTCPC experimentally and reported a fair agreement between theoretical and experimental values of outlet fluid temperature with coefficient of correlation as 0.99. Singh and Tiwari (2017) investigated solar still of basin type by incorporating characteristic equations development and they revealed that solar still of DS type performs better than solar still of single slope type under optimized conditions of mass flow rate \( (\dot{m}_h) \) and number of collectors \( (N) \) at 0.14 m water depth due to better distribution of solar energy in the case of DS type. Saurabh et al. (2020) reviewed PVT thermal collector system and concluded that PVT thermal collector system had a great potential for developing country like India.

The heat gain by solar collector can be enhanced by providing evacuated tubes as the loss of heat by convection does not occur when vacuum is present. Sampathkumar et al. (2013) studied solar still by incorporating evacuated tubular collector (ETC) and they revealed an increase of 129% over the conventional type solar still having same basin area because of the supply of heat to the basin by ETCs. An investigation of solar still in natural mode of operation by incorporating evacuated tubes (ETs) was done by Singh et al. (2013) and they revealed that the exergy efficiency ranges between 0.15 and 8%. Further, an investigation of solar still incorporated with ETs was done in forced mode of operation.
by inserting pump between collector and basin and reported enhanced freshwater output as compared to the similar system operated in natural mode due to better circulation of fluid in the forced mode of operation (Kumar et al., 2014). Further, Issa and Chang (2017) reported solar still of single slope type included with ETCs in mixed mode of operation experimentally and concluded that the output was enhanced as compared to similar set up in passive mode due to supply of heat by ETCs in active mode.

Shankar et al. (2021) have studied ETC integrated solar distiller in natural and forced modes and concluded that forced mode is better for environment as higher carbon credit was observed in forced mode due to higher amount of heat supplied to basin in the case of forced mode. Abdallah et al. (2021) have investigated spherical and pyramid basin solar still and concluded that the spherical basin solar still gave 57.1% higher water yield due to more effective solar energy utilization in spherical basin type system. Sharma et al. (2022) have validated experimentally solar still of DS type by incorporating N identical ETCs and reported values of coefficient of correlation for glass and water temperatures and fresh water yielding as 0.9932, 0.9928 and 0.9951 in that order. Attia et al. (2021) studied experimentally solar stills of hemispherical type and single slope type and they revealed that the hemispherical solar still was more efficient than single slope solar still due to the better solar energy utilization by hemispherical type. Chandrika et al. (2021) studied conventional solar still by incorporating reflective surfaces and they revealed that the efficiency of considered solar still was 68.57% over conventional type solar still due to better utilization of solar flux in the solar still having reflecting surfaces. Recently, Purnachandrakumar et al. (2022) have reviewed on the application of computational fluid dynamics (CFD) concept to different solar stills and concluded that CFD is a cost-effective tool for the simulation of solar still.

From the extant research, it is seen that the effect of \( \dot{m}_f \) and \( N \) on exergo-enviro-economic parameters for NPVTFC-SS has not been reported by any researcher throughout the globe. All four kinds of weather situations have been considered while estimating values of energy, exergy, and exergo-enviro-economic parameters using computer code in MATLAB-2015a to know the dissimilarity in values of \( \dot{m}_f \) and \( N \) on exergo-enviro-economic parameters of NPVTFC-SS. The difference between the earlier reported work and the proposed work lies in the fact that effect of dissimilarities of \( \dot{m}_f \) and \( N \) on exergo-enviro-economic parameters has been estimated for NPVTFC-SS, whereas in the earlier reported works, exergo-enviro-economic parameters for the active system have been estimated at a particular selected values of \( \dot{m}_f \) and \( N \).

### System metaphors

The specification of NPVTFC-SS has been revealed as Table 1. Figure 1 represents NPVTFC-SS set up. It consists of series connected PVT flat plate collectors, pumping system, and solar still of single slope type. In the setup revealed as Fig. 1, series connected \( N \) number of PVTFPCs have been connected to solar still of SS type. A pump has been inserted between solar still and inlet of first PVTFPC for overcoming the head loss. Pump runs on the power generated by PVT. \( N \) similar PVTFPCs have been put in series connection due to the fact that the solar still needs fluid at higher temperature for higher freshwater production. The material for solar still is fiber reinforced plastic. The inner surface of solar still has been painted black for better absorption, and outside surfaces have been covered with insulator to prevent heat loss.

PVTFPC works on the principle of greenhouse effect. When sunlight falls on the surface of PVTFPC, some part of sunlight gets reflected, some part gets absorbed, and the remaining part is transmitted to PV. PV converts some parts of sunlight to electrical energy; some part is lost to the environment and remaining part of sunlight goes to absorber plate which further transmits heat to water flowing through tubes. Water flowing through tubes placed below PVT through absorber plate carries away heat from PV and improved efficiency of PVT is obtained. When sunlight falls on the part of collector where PV is not present, the sunlight gets first reflected, some part of sunlight is absorbed by glass and remaining part goes to the absorber plate which further transmits heat to water flowing through tubes. In this way, water is heated while flowing through collector tubes. As collectors are connected in series, water at the exit of last collector is having high temperature at low discharge. This heated water is further allowed to go to the basin and heat is added to waster kept in basin.

The condensing cover surface made of glass has been inclined by 15° with horizontal as most of the season in New Delhi is summer. When the short wavelength solar flux impinges on the surface of glass condensing cover surface, some part is reflected and absorbed by the glass and remaining part comes to the surface of water in basin. Water surface again reflects some part of received solar flux, some part is absorbed by water mass and the remaining is transmitted to basin liner kept at the bottom. Due to the absorption of solar flux, basin liner gets heated and transfers heat to water mass. Some part of energy from basin liner is lost to the environment. Water mass receives heat from \( N \) similar collectors, from sunlight directly and from basin liner indirectly. In this way, temperature of
Water gets enhanced, and evaporation occurs due to the temperature difference between water surface and glass condensing cover. The vapor further gets condensed on the inner surface of glass condensing cover surface and trickles down to the tray and then the distilled water is siphoned off to the beaker/jar.

Mathematical modeling based on energy balance equations

Mathematical modeling of NPVTFPC-SS means writing equations for all its components by equating input energy to output energy. Following assumptions presented in
Singh et al. [2015], the mathematical modeling can be done as follows:

**Useful energy gain for NPVTFPCs**

As per the study of Shyam et al. (2015), the rate at which useful thermal energy is gained from $N$ number of identical and partially covered PVTFPCs connected in series is given as

$$
Q_{wn} = N(A_m + A_c)[(\alpha t)_{eff,N}I(t) - U_{LN}(T_B - T_a)]
$$

(1)

In the set-up discussed in previous studies, a number ($N$) of PVT-FPC were connected in series in open loop configuration, while they have been connected with solar still of single slope type in closed loop in NPVTFC-SS. Water coming from the basin of the solar still of single slope type enters the first PVTFPC through DC motor pump and the outlet from Nth PVTFPC discharges into the basin of NPVTFC-SS. Therefore, $T_g$ turns out to be equal to $T_w$. The temperature of water coming out from Nth PVT-FPC ($T_{fon}$) is expressed as:

$$
T_{fon} = \frac{(AF_p \alpha t)_1 (1 - K_{cN})}{(1 - K_c) \beta w} I(t) + \frac{(AF_p U_L)_1 (1 - K_{cN})}{(1 - K_c) \beta w} T_a + K_{cN} T_f
$$

(2)

where $T_g = T_w$. The water exiting the Nth PVTFPC enters the basin of NPVTFC-SS at that temperature. Hence, $T_{wo} = T_{fon}$. The expression for the various terms occurring in Eqs. (1) and (2) can be found in the Appendix.

The electrical efficiency of solar cells ($\eta_{e,N}$) for a number ($N$) of PVTFPC as a function of temperature is given as

$$
\eta_{e,N} = \eta_0 \left[1 - \beta_w (T_c - T_{fo}) \right]
$$

(3)

Here, $\beta_w$ is the efficiency for a given standard test condition, while $T_c$ is mean temperature of the solar cell for the Nth PVTFPC. $T_{fo}$ is calculated using the results of Shyam et al. (2015) in which $T_g = T_w$ since a number ($N$) of series connected PVTFPCs are in a closed loop including the basin of NPVTFC-SS.

**For solar still of single slope type**

The equation based on equating input and output energies for various parts of solar still of single slope type can be written, and these equations can further be simplified by incorporating Eq. (1) following the principle of mathematics. Heat reaches to exterior side of condensing cover from the interior surface of condensing cover through conduction. The temperature of inner side of condensing cover is higher than the temperature of exterior side of condensing cover. Heat is lost by exterior side of condensing cover to the surrounding by heat mechanism named convection and radiation. Hence, the equation for exterior side of condensing cover based on balancing input to output heat can be written as Singh et al. (2016):

$$
\frac{K_g}{L_g} (T_{gi} - T_{go}) A_g = h_{1g} (T_{go} - T_{a}) A_g
$$

(4)

Here, $h_{1g}$ is total heat transfer coefficient (HTC) from exterior side of condensing cover to the surrounding. Fourier’s law has been used for conductive heat transfer from the basin of the solar still to the surrounding (expression on left side of Eq. (4)). Newton’s law of cooling has been used to write heat transfer from exterior side of condensing cover to the surrounding (expression on right side of Eq. (4)). The expression for $h_{1g}$ can be written as

$$
h_{1g} = 5.7 + 3.8V
$$

(5)

where $V$ is the velocity of blowing air.

The inner condensing surface receives heat from water surface by heat mechanism named convection, radiation and evaporation. Further, heat is lost from inner surface to exterior side of condensing cover through conduction. Hence, the equation for interior side of condensing cover based on balancing input heat to output heat can be written as:

$$
a'_{g} I(t) A_g + h_{iw}(T_w - T_{gi}) A_g = \frac{K_g}{L_g} (T_{gi} - T_{go}) A_g
$$

(6)

Here, $h_{iw}$ is THTC (corresponding to convection, radiation and evaporation) from water surface to interior side of condensing cover. Hence, $h_{iw}$ can be estimated as

$$
h_{iw} = h_{cw} + h_{rw} + h_{ev}
$$

(7)

Here, $h_{cw}$ is known as the convective heat transfer coefficient and can be estimated as

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

(8)

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

(9)

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

(10)

$h_{rw}$ is known as the radiative heat transfer coefficient (HTC) and can be estimated as

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

(11)


\( h_{ewg} \) is known as evaporative HTC and can be estimated as

\[
h_{ewg} = 16.273 \times 10^{-3} h_{cw} \left\{ \frac{P_w - P_g}{T_w - T_g} \right\} \tag{12}
\]

The basin liner receives heat from the sun and heat is lost by basin liner to the surrounding as well as water mass. Hence, the equation for basin liner based on balancing input heat to output heat can be written as:

\[
a'_{gl} A_b = h_{bw}(T_b - T_w) A_b + h_{bw}(T_b - T_a) A_b \tag{13}
\]

Here, \( h_{bw} \) is HTC from basin liner to water and \( h_{tg} \) is HTC from basin liner to the surrounding. The value of \( h_{bw} \) is taken as 100 W/m² K.

Water mass receives heat from basin liner, collectors and sun. Heat is lost by water mass to interior side of condensing cover. The difference of heat received, and heat lost by water mass is contained by water and the temperature of water increases. Hence, the equation for water mass based on balancing input heat to output heat can be written as:

\[
(M_a C_w) \frac{dT_w}{dt} = a'_u I(t) A_b + h_u(T_b - T_w) A_b + Q_{a,N} - h_{lw}(T_w - T_g) A_b \tag{14}
\]

Solving Eqs. (1) to (14) using simple mathematics, one can obtain expression for water temperature \( (T_w) \) as a function of time which can be written as:

\[
T_w = \frac{\bar{f}_1(t)}{a_1} (1 - e^{-a_1 t}) + T_{w0} e^{-a_1 t} \tag{15}
\]

where \( T_{w0} \) is the temperature of water at the initial condition \((t = 0)\) and \( \bar{f}_1(t) \) is the average value of \( f_1(t) \) over the time interval from 0 to \( t \). Once \( T_{w0} \) is computed from Eq. (15), one can compute the temperature of inner and outer sides of glass cover \((T_{gi} \) and \( T_{go} \) as:

\[
T_{gi} = \frac{a'_{gl} I_s(t) A_g + h_{lw} T_w A_b + U_{c_go} T_a A_g}{U_{c_go} A_g + h_{lw} A_b} \tag{16}
\]

\[
T_{go} = \frac{K_s T_{gi} + h_{lg} T_a}{K_s L_s + h_{lg}} \tag{17}
\]

The value of potable water yielding can be computed after evaluating \( T_w \) and \( T_{gi} \) as follows:

\[
\dot{m}_{ew} = h_{ewg} A_b \left( \frac{T_w - T_{gi}}{L} \right) \times 3600 \tag{18}
\]

Here, \( L \) is latent heat which can be taken as 2400 kJ/kg K.

### Experimental Validation of NPVTFPC-SS

Singh et al. (2016) have validated NPVTFPC-SS for November 22, 2013 and February 18, 2014 considering \( N = 2 \). They revealed values of coefficients of variation for \( T_w, T_{gi} \), and potable water yielding as 0.979, 0.977, and 0.984 for November 22, 2013, respectively. Similarly, for February 18, 2014, they revealed these values as 0.964, 0.98, and 0.988 respectively. They reported the system to be in fair agreement for theoretical and experimental values.

### Analysis

For the analysis of the effect of dissimilarity of \( m_r \) and \( N \) on exergo-enviro-economic parameters for NPVTFPC-SS, 4 climatic situations for each month of year have been taken. These climatic situations can be defined by number of sunshine hours \((N')\) and daily diffuse to daily global irradiation ratio \((r')\) as follows (Singh and Tiwari 2005):

(a) Clear day (blue sky) \( r' \leq 0.25 \) and \( N' \geq 9 \) h
(b) Hazy day (fully) \( 0.25 \leq r' \leq 0.50 \) and \( 7 \leq N' \leq 9 \) h
(c) Hazy and cloudy (partially) \( 0.50 \leq r' \leq 0.75 \) and \( 5 \leq N' \leq 7 \) h
(d) Cloudy day (fully) \( r' \geq 0.75 \) and \( N' \leq 5 \) h

### Energy estimation

The expression of yearly overall energy \((E_{out})\) for NPVTFPC-SS considering 1st law of thermodynamics can be expressed as

\[
E_{out} = \frac{(M_{ew} \times L)}{3600} + \frac{(P_m - P_u)}{0.38} \tag{19}
\]

where \( M_{ew} \) is annual potable water output obtained from NPVTFPC-SS, \( P_m \) is yearly electrical power received from PVT, \( P_u \) is yearly electrical power utilized by pump, and \( L \) is latent heat. Here, factor 0.38 is present in the denominator converts electrical energy into heat. This factor is basically efficacy of power output taken from conventional power plant (Huang et al. 2001).

The amount of electrical energy \((\dot{E}_{ex})\) on per hour basis for the solar panel used in NPVTFPC-SS can be expressed as follows:

\[
\dot{E}_{ex} = A_m I(t) \sum_{i=1}^{N} (\alpha r_i \times h) \tag{20}
\]

Equation (20) can be used for evaluating daily electrical exergy of type (a) climatic situation by summing the hourly values of 10 h because the solar flux exists for 10 h only. The similar approach has been used to work out the daily
electrical energy for rest types of climatic situation, i.e., type (b) to type (d). The value of electrical energy on monthly basis for type (a) climatic situation has been evaluated as the multiplication of electrical energy on daily basis and the corresponding value of number of clear days ($n'$). The similar approach has been used to work out the electrical energy on monthly basis for rest types of climatic situations, i.e., type (b) to type (d). The value of net electrical energy on monthly basis has been worked out by summing electrical energy values for type (a) to type (d) climatic situations. The value of electrical energy ($P_n$) on annual basis has been worked out by the summing of electrical energy on monthly basis for 12 months. The similar approach has been followed for the estimation of annual freshwater yield ($M_{fu}$).

**Exergy estimation**

The estimation of exergy for NPVTFC-SS has been carried out using 1st and 2nd laws of thermodynamics. The hourly output thermal exergy $Ex_{out} (\text{W})$ for NPVTFC-SS can be expressed as (Nag 2004):

$$Ex_{out} = h_{evg} \times \frac{A_b}{2} \times \left[ (T_a - T_g) - (T_a + 273) \times \ln \left( \frac{(T_a + 273)}{(T_g + 273)} \right) \right]$$  \hfill (21)

where $h_{evg}$ can be estimated using Eq. (12). Equation (21) can be used for evaluating daily thermal exergy of type (a) climatic situation by summing the hourly values of 10 h because the solar flux exists for 10 h only. The similar approach has been used to work out the value of thermal exergy on per day basis for rest types of climatic situations, i.e., type (b) to type (d). The value of thermal exergy on monthly basis for type (a) climatic situation has been evaluated as the multiplication of thermal exergy on daily basis and the corresponding value of number of clear days ($n'$). The similar approach has been used to work out the thermal exergy on monthly basis for rest types of climatic situations i.e., type (b) to type (d). The value of net thermal exergy on monthly basis has been worked out by summing thermal exergy values for type (a) to type (d) climatic situations. The value of thermal exergy on yearly basis has been worked out by the summing of thermal exergy on monthly basis for 12 months.

The value of yearly overall annual exergy gain ($G_{ex,annual}$) for NPVTFC-SS has been expressed as follows:

$$G_{ex,annual} = Ex_{out} + (P_m - P_u)$$  \hfill (22)

**Exergoeconomic analysis**

This parameter correlates exergy with uniform end-of-year annual cost (UEOYAC). The value of exergy gain from the system which represents the quality of energy can be estimated using 1st and 2nd laws of thermodynamics. The exergoeconomic parameter reveals the fact that the considered system is designed and installed in such a fashion that an overall optimum design is achieved by effectively harmonizing exergy and economic parameters. The exergoeconomic parameter considers either exergy loss or exergy gain in combination with UEOYAC. For exergy gain viewpoint, the main aim is to maximize the objective function, whereas, for exergy loss viewpoint, the aim is to minimize the objective function. The value of exergoeconomic parameter ($\xi_{NPVTFC−SS}$) can be computed as:

$$\xi_{NPVTFC−SS} = \frac{G_{ex,annual}}{UEOYAC}$$  \hfill (23)

Further, value of $G_{ex,annual}$ for NPVTFC-SS can be estimated using Eq. (22). Following Tiwari (2012), value of UEOYAC for NPVTFC-SS can be computed as:

$$UEOYAC = PC \times C_{RF} + MC \times C_{RF} - S_Y \times S_{FF}$$  \hfill (24)

where PC, $S_Y$, $C_{RF}$, $S_{FF}$, and MC stand for present cost, salvage value, capital recovery factor, sinking fund factor, and maintenance cost in that order. The value of MC may be estimated as the multiplication of PC with maintenance cost factor that is normally considered as 0.1. The value of $C_{RF}$ which is used to convert PC into UEOYAC and can be expressed as:

$$C_{RF} = \frac{i \times (1 + i)^n}{(1 + i)^n - 1}$$  \hfill (25)

and $S_{FF}$ can be written as

$$S_{FF} = \frac{i}{(1 + i)^n - 1}$$  \hfill (26)

$S_{FF}$ is used to convert $S_Y$ into UEOYAC. In this case, $i$ and $n$ stand for the rate of interest and system life, respectively.

The value of PC for a NPVTFC-SS with a 30-year life span can be calculated as

$$PC = PI + P_u + \frac{P_u}{(1 + i)^0} + \frac{P_u}{(1 + i)^20}$$  \hfill (27)

where

$$PI = (\text{Cost of solar still}) + (\text{Cost of PVTFPCs}) + (\text{Fabrication cost})$$  \hfill (28)

The cost of fabrication includes piping and labor cost.

**Enviroeconomic analysis**

The analysis of system from enviroeconomic viewpoint is important because world is facing with the issue of
environmental pollution. The pollution level can be lowered by replacing the conventional system with a system using greenhouse effect and based on green technology. The enviroeconomic analysis promotes the use of green technology by providing incentive for controlling environmental pollution which acts as motivation for the use of green technology-based system and helps in reduction of pollution. The carbon credit and hence enviroeconomic parameter can be computed as:

\[
\text{Energy based Carbon credited } = \frac{(\text{Annual overall energy out}) \times n - (\text{Embodied energy})}{0.002}
\]

(29)

\[
\text{Energy based enviroeconomic parameter } = \frac{(\text{Annual overall energy out}) \times n - (\text{Embodied energy})}{(0.002) \times (\text{CRP})}
\]

(30)

\[
\text{Exergy based Carbon credited } = \frac{(\text{Annual overall exergy out}) \times n - (\text{Embodied energy})}{(0.002) \times (\text{CRP})}
\]

(31)

\[
\text{Exergy based enviroeconomic parameter } = \frac{(\text{Annual overall exergy out}) \times n - (\text{Embodied energy})}{(0.002) \times (\text{CRP})}
\]

(32)

CRP stands for carbon dioxide reduction price which can be taken as $14.5/tCO_2$.

**Productivity analysis**

Productivity represents obtaining more and more with less and less input of resources in such a way that the profit can be divided more equally among maximum number of people. It represents the feasibility of the system. The system is said to be feasible if productivity is more than 100%. A value of productivity lower than 100% indicates the system gives low energy as compared to input energy. Productivity reveals association between input and output and it is defined as the ratio of output to input. However, it is different from efficiency in the sense that the productivity is expected to be more than 100%, whereas, efficiency can never be more than 100% as per Carnot principle. A higher value of productivity is expected because higher productivity means larger number of products are available for the consumer which will ultimately reflect the living standard of people. It is also the function of effectiveness and efficiency. Mathematically, the value of yearly productivity for NPVTFPC-SS can be estimated as:

\[
\text{Yearly productivity } = \frac{(\text{Output from NPVTFPC} - \text{SS})}{(\text{Input provided to NPVTFPC} - \text{SS})} \times 100
\]

(33)

Here, output from the system means the yearly potable water yielding from the system. This yearly potable water yield can be converted to monetary value by multiplying the amount of yearly potable water yielding in kg with its unit cost (Rs./kg) in the market. Hence, output from NPVTFPC-SS in terms of Rs. can be written as

\[
\text{Output from NPVTFPC} - \text{SS} = [(\text{Annual yield}) \times (\text{Selling price of water})]
\]

\[
+ [(\text{Annual electric output}) \times (\text{Selling price of electricity})]
\]

(34)

The input provided to NPVTFPC-SS will be UEOYAC and it can be estimated using Eq. (24). The productivity has been evaluated using Eq. (33).

**Methodology**

The methodology to investigate the effect of \( \dot{m}_f \) and \( N \) on exergo-enviro-economic parameters for NPVTFPC-SS are as follows:

**Step I**

Taking the value of solar flux on the horizontal plane from IMD located at Pune in India, the value of solar flux on inclined plane has been evaluated using Liu and Jordan formula by computational program in MATLAB. The data for surrounding temperature has been accessed from IMD situated at Pune in India.

**Step II**

The computation for potable water yielding per hour basis for different values of \( \dot{m}_f \) and \( N \) has been carried out with the help of Eq. (18) followed by the computation of potable water yielding on per year basis.

**Step III**

The computation for exergy on the basis of per hour for different values of \( \dot{m}_f \) and \( N \) has been carried out with the help of Eq. (21) followed by the calculation for exergy on per year basis.

**Step IV**

The calculation for gross energy output values at various values of \( \dot{m}_f \) and \( N \) has been performed using Eq. (19) followed by calculation for gross energy output on per year basis. The calculation for gross exergy output values at various values of \( \dot{m}_f \) and \( N \) have been performed using Eq. (22) followed by calculation for gross exergy output on per year basis.
Step V

Exergoeconomic parameter for different values of \( \dot{m}_f \) and \( N \) has been estimated using Eq. (23). Energy based carbon credit and enviroeconomic parameter have been estimated using Eqs. (29) and (30) in that order. Exergy based carbon credit and enviroeconomic parameter have been estimated using Eqs. (31) and (32) in that order. Further, yearly productivity has been estimated with the help of Eq. (33).

For better understanding of methodology, the flow chart has been presented as Fig. 2.

Results and discussion

The required data and all relevant equations have been fed to computational program written in MATLAB-2015a. Data on the horizontal surface has been taken from IMD Pune India. Data on the inclined surface has been evaluated using Liu and Jordan formula with the help of MATLAB-2015a. The output of program has been presented in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13 and Tables 2, 3, and 4.

Table 2 represents the computation of yearly fresh water yielding for NPVTFPC-SS at \( \dot{m}_f = 0.02 \) kg/s and \( N=6 \). The water depth has been considered as 0.14 m. Similarly, fresh water yielding at other values of \( \dot{m}_f \) and \( N \) has been evaluated and presented as Fig. 3. It is clear from Fig. 3 that values of fresh water yielding diminish as the value of \( \dot{m}_f \) increases at given \( N \). It happens because water flowing through tubes of collector gets less time to absorb heat at higher value of \( \dot{m}_f \). The value of fresh water yielding based on year decreases as the value of \( \dot{m}_f \) increases and then it becomes almost constant because after certain value of \( \dot{m}_f \), heat absorbed by water is very small as water flowing through tubes does not get time due to increased speed and the system behaves as working in passive mode. It is also clear from Fig. 4 that the value of yearly thermal exergy increases with the enhancement in value of \( N \) at given value of \( \dot{m}_f \), because increase in \( N \) results in the addition of more heat at enhanced value of \( N \) which further enhances the temperature of water and hence yearly thermal exergy gets enhanced with increase in \( N \) at given \( \dot{m}_f \).

Table 4 represents the computation of yearly electrical exergy for NPVTFPC-SS at \( \dot{m}_f = 0.02 \) kg/s and \( N=6 \). The water depth has been taken as 0.14 m. Similarly, electrical exergy at other values of \( \dot{m}_f \) has been evaluated and presented as Fig. 5. It is clear from Fig. 5 that the value of electrical exergy increases as the value of \( \dot{m}_f \) increases. It has been found to happen due to the fact that water flowing through tubes of collector takes away higher amount of heat from PVT at higher value of \( \dot{m}_f \) which results in decrease in temperature of solar cell. Due to decreased temperature rise of solar cell, better efficiency is obtained and hence higher electrical energy output. It is also seen that the value of electrical exergy output becomes almost constant after certain value of \( \dot{m}_f \) and then it becomes almost constant. It has been found to occur because water is not able to take away heat from PVT at very high velocity of water because water does not have time to consume heat. It is also clear from Fig. 5 that the value of electrical exergy increases as the value of \( N \) is enhanced at given value of \( \dot{m}_f \) because increase in \( N \) results in the addition of heat collection area as well as PV area.

Figures 6 and 7 represent the variation of yearly overall energy and yearly overall exergy respectively with different values of \( \dot{m}_f \) and \( N \). It is clear from Fig. 6 that the yearly gross energy decreases as the value of \( \dot{m}_f \) increases due to similar variation in yearly fresh water yielding. The variation in yearly yield and yearly electrical exergy is opposite; however, the decrease in yearly freshwater yield overcome the increases in electrical energy with the enhancement in value of \( \dot{m}_f \). Similar variation is seen in yearly overall thermal exergy.

The capital investment for different components of NPVTFPC-SS has been revealed as Table 5. The cost of items has been taken based on the price of these items in the local market. The life of the system is 30 years, whereas life of the pump is 10 years only. So, three pumps are required for the entire life span of NPVTBPV-SS. The inflation rate has been considered as 4% for the estimation of salvage value. The estimation of UEOYAC has been revealed as Table 6. The rate of interest has been considered as 5%. It is clear from Table 6 that the value of UEOYAC increases as the value of \( N \) is enhanced because of the increase in the amount of investment with the enhancement in the value of \( N \). The dissimilarity of exergoeconomic parameter with \( \dot{m}_f \)
at different values of \( N \) for NPVTFPC-SS has been revealed as Fig. 8. It is clear from Fig. 8 that the value of exergoeconomic parameter first diminishes with the enhancement in the value of \( \dot{m}_f \) and then becomes almost constant beyond \( \dot{m}_f = 0.10 \) kg/s for all value of \( N \). It happens due to the similar variation in the value of exergy as the value of \( \dot{m}_f \) is increased. It is further seen that the value of exergoeconomic parameter increases with the enhancement in the value of \( N \) at given \( \dot{m}_f \). It is also observed that the value of exergoeconomic parameter beyond \( N = 10 \) is very small and it can be considered as almost constant. So, the optimal value of \( N \) is registered as 10. It has been found to occur because increase in \( N \) results in the enhancement in value of both exergy and UEOYAC; however, increment in exergy with the enhancement in \( N \) a given \( \dot{m}_f \) is more as compared to the enhancement in the value of UEOYAC with the enhancement in the value of \( N \).

The estimation of embodied energy for different values of \( N \) for NPVTFPC-SS has been revealed as Table 7. The value of embodied energy increases with the enhancement
in the value of $N$ due to the requirement of more energy as the value of $N$ is increased. The dissimilarity of energy-based carbon credit earned with $\dot{m}_f$ at different values of $N$ for NPVTFPC-SS has been revealed as Fig. 9. It is clear from Fig. 9 that value of carbon credit earned at given $N$ first diminishes with the enhancement in $\dot{m}_f$ value and then becomes almost constant beyond $\dot{m}_f = 0.10$ kg/s due to the similar variation in the value of overall energy output from NPVTFPC-SS. It is further seen that the value of energy-based carbon credit earned at given $\dot{m}_f$ increases with the
enhancement in the value of $N$ due to similar variation in overall energy output. The dissimilarity of exergy-based carbon credit earned with $\dot{m}_f$ at different values of $N$ for NPVTFPC-SS has been revealed as Fig. 10. It is clear from Fig. 10 that value of exergy-based carbon credit earned at given $N$ first diminishes with the enhancement in $\dot{m}_f$ value and then becomes almost constant beyond $\dot{m}_f = 0.10$ kg/s due to the similar variation in the value of overall exergy output from NPVTFPC-SS. It is further seen that the value of exergy-based carbon credit earned at given $\dot{m}_f$ increases with the enhancement in the value of $N$ due to similar variation in overall exergy output. The value of exergy-based carbon credit earned comes out to be negative for $N = 2$ and $\dot{m}_f \geq 0.04$ kg/s. The negative value represents that there is no carbon credit earned and the system is not feasible for $N \leq 2$ and $\dot{m}_f \geq 0.04$ kg/s from exergy viewpoint because embodied energy is not recovered from overall exergy output obtained for $N \leq 2$ and $\dot{m}_f \geq 0.04$ kg/s.

The dissimilarity of energy and exergy based enviroeconomic parameters with $\dot{m}_f$ at different values of $N$ for NPVTFPC-SS has been revealed as Figs. 11 and 12, respectively. It is clear from Figs. 11 and 12 that values of both energy and exergy based enviroeconomic parameters first diminish with the enhancement in the $\dot{m}_f$ value and then become almost constant beyond $\dot{m}_f = 0.01$ kg/s due to the
Table 2 Computation of yearly freshwater yield for NPVTFFC-SS at $\dot{m}_f = 0.02\text{kg/s}$, $N=6$, and water depth=0.14 m

| Month | Daily yield (kg) | No. of days | Monthly yield (kg) | Daily yield (kg) | No. of Days | Monthly yield (kg) | Daily yield (kg) | No. of Days | Monthly yield (kg) | Daily yield (kg) | No. of Days | Monthly yield (kg) | Daily yield (kg) | No. of Days | Monthly yield (kg) |
|-------|-----------------|-------------|-------------------|-----------------|-------------|-------------------|-----------------|-------------|-------------------|-----------------|-------------|-------------------|-----------------|-------------|-------------------|
| Jan   | 17.85           | 3           | 53.54             | 16.74           | 8           | 133.95            | 7.33            | 11           | 80.67             | 3.22            | 9           | 28.95             | 297.12          |
| Feb   | 18.36           | 3           | 55.07             | 18.96           | 4           | 75.83             | 8.32            | 12           | 98.88             | 3.79            | 9           | 34.13             | 264.91          |
| Mar   | 21.02           | 5           | 105.08            | 23.19           | 6           | 139.13            | 13.02           | 12           | 156.28            | 10.81           | 8           | 86.44             | 486.93          |
| Apr   | 23.90           | 4           | 95.61             | 24.84           | 7           | 173.89            | 16.29           | 14           | 228.08            | 16.67           | 5           | 83.34             | 580.93          |
| May   | 24.27           | 4           | 97.07             | 24.08           | 9           | 216.74            | 22.07           | 12           | 264.88            | 17.70           | 6           | 106.20            | 684.89          |
| June  | 23.52           | 3           | 70.55             | 24.71           | 4           | 98.84             | 20.76           | 14           | 290.61            | 14.16           | 9           | 127.44            | 587.44          |
| July  | 21.88           | 2           | 43.75             | 21.86           | 3           | 65.58             | 17.75           | 10           | 177.45            | 12.15           | 17          | 206.48            | 493.26          |
| Aug   | 20.54           | 2           | 41.08             | 21.58           | 3           | 64.73             | 15.98           | 7            | 111.84            | 11.46           | 19          | 217.70            | 435.34          |
| Sept  | 24.81           | 7           | 173.70            | 24.21           | 3           | 72.63             | 19.92           | 10           | 199.23            | 12.91           | 10          | 129.10            | 574.66          |
| Oct   | 22.11           | 5           | 110.55            | 18.81           | 10          | 188.08            | 14.02           | 13           | 182.21            | 8.98            | 3           | 26.94             | 507.78          |
| Nov   | 19.74           | 6           | 118.41            | 15.45           | 10          | 154.51            | 7.79            | 12           | 93.51             | 7.43            | 2           | 14.86             | 381.30          |
| Dec   | 20.46           | 3           | 61.39             | 15.50           | 7           | 108.52            | 9.64            | 13           | 125.34            | 4.05            | 8           | 32.39             | 327.64          |

Yearly freshwater yield (kg) 5622.21

Table 3 Computation of yearly thermal exergy for NPVTFFC-SS at $\dot{m}_f = 0.02\text{kg/s}$, $N=6$ and water depth=0.14 m

| Month | Daily exergy (kWh) | No. of days | Monthly exergy (kWh) | Daily exergy (kWh) | No. of Days | Monthly exergy (kWh) | Daily exergy (kWh) | No. of Days | Monthly exergy (kWh) | Daily exergy (kWh) | No. of Days | Monthly exergy (kWh) | Daily exergy (kWh) | No. of Days | Monthly exergy (kWh) |
|-------|-------------------|-------------|---------------------|-------------------|-------------|---------------------|-------------------|-------------|---------------------|-------------------|-------------|---------------------|-------------------|-------------|---------------------|
| Jan   | 1.53              | 3           | 4.59                | 1.38              | 8           | 11.05               | 0.38              | 11           | 4.18                | 0.11              | 9           | 0.95                | 20.78             |
| Feb   | 1.46              | 3           | 4.39                | 1.54              | 4           | 6.18                | 0.41              | 12           | 4.98                | 0.12              | 9           | 1.09                | 16.64             |
| Mar   | 1.64              | 5           | 8.18                | 1.94              | 6           | 11.62               | 0.74              | 12           | 8.85                | 0.54              | 8           | 4.36                | 33.01             |
| April | 1.78              | 4           | 7.13                | 1.92              | 7           | 13.46               | 0.91              | 14           | 12.68               | 0.95              | 5           | 4.75                | 38.02             |
| May   | 1.69              | 4           | 6.75                | 1.66              | 9           | 14.94               | 1.42              | 12           | 16.99               | 0.95              | 6           | 5.71                | 44.38             |
| June  | 1.65              | 3           | 4.96                | 1.81              | 4           | 7.22                | 1.32              | 14           | 18.45               | 0.68              | 9           | 6.16                | 36.79             |
| July  | 1.59              | 2           | 3.18                | 1.60              | 3           | 4.80                | 1.11              | 10           | 11.08               | 0.58              | 17          | 9.81                | 28.87             |
| Aug   | 1.58              | 2           | 3.16                | 1.72              | 3           | 5.15                | 1.02              | 7            | 7.11                | 0.59              | 19          | 11.12               | 26.54             |
| Sept  | 2.09              | 7           | 14.65               | 1.99              | 3           | 5.98                | 1.39              | 10           | 13.91               | 0.66              | 10          | 6.58                | 41.12             |
| Oct   | 1.78              | 5           | 8.88                | 1.35              | 10          | 13.51               | 0.82              | 13           | 10.64               | 0.38              | 3           | 1.15                | 34.19             |
| Nov   | 1.71              | 6           | 10.24               | 1.11              | 10          | 11.08               | 0.37              | 12           | 4.46                | 0.35              | 2           | 0.69                | 26.47             |
| Dec   | 1.78              | 3           | 5.34                | 1.19              | 7           | 8.32                | 0.56              | 13           | 7.30                | 0.14              | 8           | 1.15                | 22.11             |

Yearly exergy gain (kWh) 368.91
similar variations in values of energy and exergy-based carbon credits earned. It is further seen that the value of energy and exergy based enviroeconomic parameters at given \( m_f \) increase with the enhancement in the value of \( N \) due to similar variation in energy and exergy-based carbon credits earned. It is also clear from Fig. 12 that the value of exergy based enviroeconomic parameter comes out to be negative for \( N \leq 2 \) and \( m_f \geq 0.04 \text{ kg/s} \). The negative value represents that the system is not feasible for \( N \leq 2 \) and \( m_f \geq 0.04 \text{ kg/s} \) from exergy viewpoint because embodied energy is not recovered from overall exergy output obtained for \( N \leq 2 \) and \( m_f \geq 0.04 \text{ kg/s} \).

The dissimilarity of yearly productivity with \( m_f \) at different values of \( N \) for NPVTFPFPC-SS has been revealed as Fig. 13. It is clear from Fig. 13 that the value of yearly productivity first diminishes with the enhancement in \( m_f \) value and then becomes almost constant as revealed in Figs. 3 and 5 respectively. It is further seen that the value of yearly productivity first increases with the enhancement in the value of \( N \) at given \( m_f \) and it becomes either constant or diminishes beyond \( N=6 \) at given \( m_f \). It means that the optimum value of \( N \) is 6 for productivity viewpoint.

### Conclusions

An investigation on dissimilarity of \( m_f \) and \( N \) on exergoeconomic parameters for NPVTFPFPC-SS has been done considering all four kinds of atmospheric situations to know the effect of dissimilarities of \( m_f \) and \( N \) on exergoeconomic and enviroeconomic parameters and productivity. Based on the current research study, the following conclusions have been drawn:

i. The value of exergoeconomic parameter increases with the enhancement in \( m_f \), and it becomes almost constant beyond \( m_f = 0.10 \text{ kg/s} \). The optimum value of \( N \) has been found as 10 from exergoeconomic parameter estimation viewpoint.

ii. The value of energy as well as exergy-based carbon credits earned diminish with the enhancement in \( m_f \), and it becomes almost constant beyond \( m_f = 0.10 \text{ kg/s} \); however, values of energy and exergy-based carbon credits earned increases with the enhancement in the value of \( N \) at given \( m_f \).

iii. The value of energy as well as exergy based enviroeconomic parameters with the enhancement in \( m_f \) and it becomes almost constant beyond \( m_f = 0.10 \text{ kg/s} \);
however, values of energy and exergy based enviro-economic parameters has been found to increase with the enhancement in the value of $N$ at given $\dot{m}_f$.

iv. The system is not feasible for $N \leq 2$ and $\dot{m}_f \geq 0.04$ kg/s from exergy-based carbon credit and enviroeconomic parameter viewpoints.

v. The value of yearly productivity increases with the enhancement in $\dot{m}_f$, and it becomes almost constant beyond $\dot{m}_f = 0.10$ kg/s; however, values of yearly productivity has been found to increase with the enhancement in the value of $N$ at given $\dot{m}_f$ till $N = 6$. Beyond $N = 6$, the value yearly productivity remains either constant or diminishes. So, the optimum value of $N$ at given $\dot{m}_f$ is 6 from yearly productivity viewpoint.

### Appendix

Expressions for various terms used in Eqs. (1) to (9) are as follows.

$$U_{H_{\text{EC}}} = \left[ \frac{1}{h_i} + \frac{L_i}{K_i} \right]^{-1} ; \quad U_{H_{\text{EP}}} = \left[ \frac{1}{h_f} + \frac{L_f}{K_f} \right]^{-1} ;$$

$$h_i = 5.7 + 3.8 V, Wm^{-2}K^{-1} ; \quad h_f = 5.7, Wm^{-2}K^{-1} ;$$

$$U_{\text{PC}} = \left[ \frac{1}{U_{\text{EC}}} + \frac{1}{U_{\text{EP}}} \right]^{-1} + \left[ \frac{1}{h_i} + \frac{1}{h_f} + \frac{L_i}{K_i} \right]^{-1} ;$$

$$h_i' = 2.8 + 3V, Wm^{-2}K^{-1} ;$$

$$U_{L1} = \frac{U_{\text{EP}}U_{\text{PC}}}{U_{\text{EP}}+U_{\text{PC}}} ; \quad U_{L2} = U_{L1} + U_{\text{PC}} ;$$

$$U_{Lm} = \frac{h_p U_{\text{PC}}}{F' h_p + U_{\text{PC}}} ; \quad U_{Le} = \frac{h_p U_{\text{PC}}}{F' h_p + U_{\text{PC}}} ;$$

$$PF_1 = \frac{U_{\text{EP}}}{U_{\text{EP}}+U_{\text{PC}}} ; \quad PF_2 = \frac{h_p}{F' h_p + U_{\text{PC}}} ;$$

### Table 5 Capital investment for NPVTFTP-SS

| S.N | Parameter                                      | Cost (₹)  |
|-----|-----------------------------------------------|-----------|
| 1   | Cost of solar still                           | 23,143.00 |
| 2   | Cost of each PVT collectors                   | 8500.00   |
| 3   | Cost of motor and pump                        | 2000.00   |
| 4   | Fabrication cost                              | 6000.00   |
| 5   | Salvage value of the system after 30 years, if inflation remains at 4% in India, (using present value of scrap material sold in Indian market) for $N = 2$ | 14,311.36 |

### Table 6 Estimation of UEOYAC for NPVTCP-SS

| Year | $N$ | $i$ | PC | MC | SV | CRF | SFF | UEOYAC |
|------|-----|-----|----|----|----|-----|-----|--------|
| 30   | 2   | 5   | 50,124.00 | 5012.40 | 14,311.36 | 0.0651 | 0.0151 | 3371.30 |
| 30   | 4   | 5   | 67,124.61 | 6712.46 | 19,825.14 | 0.0651 | 0.0151 | 4504.81 |
| 30   | 6   | 5   | 84,124.61 | 8412.46 | 25,338.91 | 0.0651 | 0.0151 | 5638.28 |
| 30   | 8   | 5   | 101,124.61 | 10,112.46 | 30,852.69 | 0.0651 | 0.0151 | 6771.75 |
| 30   | 10  | 5   | 118,124.61 | 11,812.46 | 36,366.47 | 0.0651 | 0.0151 | 7905.23 |
| 30   | 10  | 5   | 135,124.60 | 13,512.46 | 41,880.24 | 0.0651 | 0.0151 | 9038.70 |

### Table 7 Embodied energy computation for NPVTFTP-SS

| Component                           | Embodied energy |
|-------------------------------------|-----------------|
|                                    | $N = 2$ | $N = 4$ | $N = 6$ | $N = 8$ | $N = 10$ | $N = 12$ |
| Solar still of single slope type    | 1737.79       | 1737.79       | 1737.79       | 1737.79       | 1737.79       | 1737.79       |
| Flat plate collector               | 1104.96       | 2209.92       | 3314.88       | 4419.84       | 5524.8        | 6629.76       |
| PVT                                 | 490            | 980            | 1470           | 1960           | 2450           | 2940           |
| Others                              | 20             | 20             | 20             | 20             | 20             | 20             |
| Total (kWh)                         | 3352.75        | 4947.71        | 6542.67        | 8137.63        | 9732.59        | 11,327.55      |
\[ PF_c = \frac{h_{\text{eff}}}{h_{\text{eff}} + U_{\text{kw}}} \cdot (\alpha_c \tau_c)_{\text{eff}} = (\alpha_c - \eta_c) \tau_c \beta_c; \]

\[(\alpha_c \tau_c)_{\text{eff}} = a_c \rho_c^2 (1 - \beta_c); (\alpha_c \tau_c)_{\text{med}} = [(\alpha_c \tau_c)_{\text{eff}} + PF_c (\alpha_c \tau_c)_{\text{eff}}]; \]

\[(\alpha_c \tau_c)_{\text{eff}} = PF_c \cdot \rho_c \cdot \tau_c; A_m = W L_m; A_c = W L_c; \]

\[ A_c F_{Rc} = \frac{m_f \rho_f}{U_{Lc}} \left[ 1 - \exp \left( \frac{-F' U_{Lc} A_c}{m_f \rho_f} \right) \right]; \]

\[ A_m F_{Rm} = \frac{m_f \rho_f}{U_{Lm}} \left[ 1 - \exp \left( \frac{-F' U_{Lm} A_m}{m_f \rho_f} \right) \right]; \]

\[ (AF_R(\alpha_r))_1 = \left[ A_c F_{Rc}(\alpha_c \tau_c)_{\text{eff}} + PF_2(\alpha_c \tau_c)_{\text{med}} A_m F_{Rm}(1 - \frac{A_c F_{Rc} U_{Lc}}{m_f \rho_f}) \right]; \]

\[ (AF_R(\alpha_r)U_l)_1 = \left[ A_c F_{Rc} U_{Lc} + A_m F_{Rm} U_{Lm}(1 - \frac{A_c F_{Rc} U_{Lc}}{m_f \rho_f}) \right]; \]

\[ K_K = \left( 1 - \frac{(AF_R(\alpha_r)_1)}{m_f \rho_f} \right); (AF_R(\alpha_r))_m = PF_2(\alpha_c \tau_c)_{\text{med}} A_m F_{Rm}; \]

\[ (AF_R(\alpha_r)U_l)_m = A_m F_{Rm} U_{Lm}; K_m = \left( 1 - \frac{A_m F_{Rm} U_{Lm}}{m_f \rho_f} \right); \]

\[ (\alpha_c \tau_c)_{\text{eff},N} = \frac{(AF_R(\alpha_r))_1}{(A_c + A_m)} \left[ 1 - \frac{(K_K)^N}{N(1 - K_K)} \right]; \]

\[ U_{LN} = \frac{(AF_R(\alpha_r)U_l)_1}{(A_c + A_m)} \left[ 1 - \frac{(K_K)^N}{N(1 - K_K)} \right]; \]

\[ a_1 = \frac{1}{M_w C_w} \left[ m_f C_f (1 - K_N^N) + U_A B \right]; \]

\[ b(t) = \frac{1}{M_w C_w} \left[ \alpha_{\text{eff}} A_b T_b(t) + \left( 1 - K_N^N \right) (AF_R(\alpha_r))_1 T_a(t) \right]; \]

\[ + \left( 1 - K_N^N \right) (AF_R(\alpha_r)U_L)_1 + U_s A_b \left[ T_a(t) \right]; \]

\[ \alpha_{\text{eff}} = \alpha_w + h_1 \alpha_b + h_1^* \alpha_g + h_1 = \frac{h_{\text{bw}}}{h_{\text{bw}} + h_{\text{wb}}}; \]

\[ h_{\text{bw}} = 16.273 \times 10^{-3} h_{\text{bw}} \left[ \frac{P_w - P_{gl}}{T_w - T_{gl}} \right]; \]

\[ h_{\text{bw}} = 0.884 \left[ \frac{(T_w - T_{gl}) + (P_w - P_{gl})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]; \]

\[ P_w = \exp \left[ 25.317 - \frac{5444}{T_w + 273} \right]; P_{gi} = \exp \left[ 25.317 - \frac{5444}{T_{gi} + 273} \right]; \]

\[ h_{\text{bw}} = (0.82 \times 10^{-5}) (T_w + 273)^2 + (T_{gi} + 273)^2 \frac{1}{T_w + T_{gi} + 546}; \]

\[ U_s = U_t + U_b; \]

\[ U_t = \frac{h_{\text{bw}} h_{\text{wb}}}{h_{\text{bw}} + h_{\text{wb}}}; \]

\[ U_{c,gl} = \frac{h_{\text{bw}}}{h_{\text{bw}} + h_{\text{wb}}}; \]

\[ h_{\text{bw}} = \frac{L}{K} \left( 1 - \frac{1}{h_{\text{bw}} + h_{\text{wb}}} \right) \]

\[ h_{\text{bw}} = h_{\text{bw}} + h_{\text{wb}} = 5.7 Wm^{-2}K^{-1}, h_{\text{bw}} = 250 Wm^{-2}K^{-1}; \]

**Nomenclature**

- \( A_m \): area covered by PV module (m²);
- \( A_c \): area covered by glass (m²);
- \( A_g \): area of glass cover (m²);
- \( A_r \): area of basin (m²);
- \( L \): latent heat (J/Kg);
- \( D \): double slope solar still;
- \( L_g \): thickness of glass cover (m);
- \( K_r \): thermal conductivity of glass (W/m K);
- \( T_l \): global radiation falling on collector (W/m²);
- \( T_a \): ambient temperature (°C);
- \( L_i \): thickness of insulation (m);
- \( K_i \): thermal conductivity of insulation (W/m–K);
- \( \alpha_1 \): absorptivity of the solar cell;
- \( m_f \): mass flow rate of water (kg/s);
- \( \varepsilon_g \): transmissivity of the glass (fraction);
- \( C_i / C_w \): specific heat of water (J/kg K);
- \( \beta \): temperature coefficient of efficiency (K⁻¹);
- \( L_m \): length of collector covered by glass;
- \( L_{cm} \): length of collector covered by PV module;
- \( \eta_c \): solar cell efficiency;
- \( \eta_m \): PV module efficiency;
- \( \eta_{N1} \): temperature dependent electrical efficiency of solar cells of a NPVTPC;
- \( b \): breath of collector (m);
- \( (\alpha_1 \text{eff}) \): product of effective absorptivity and transmittivity;
- \( F \): collector efficiency factor;
- \( T_s \): solar cell temperature (°C);
- \( T_{gl} \): absorber plate temperature (°C);
- \( L_a \): thickness of absorber plate (m);
- \( K_a \): thermal conductivity of absorber plate (W/m–K);
- \( T_c \): fluid temperature at collector inlet (°C);
- \( T_f \): fluid temperature of fluid in collector (°C);
- \( P_{gi} \): penalty factor due to the glass covers of module;
- \( P_{gi} \): penalty factor due to plate below the module;
- \( P_{gi} \): penalty factor due to the absorption plate for the glazed portion;
- \( P_{gi} \): penalty factor due to the glass covers for the glazed portion;
- \( \beta \): packing factor of the module;
- \( \eta_{lo} \): efficiency at standard test condition;
- \( T_{in} \): outlet water temperature at the end of Nth PVTPC water collector.
(°C); $h_i$: heat transfer coefficient for space between the glazing and absorption plate (W/m² K); $h'_i$: heat transfer coefficient from bottom of PVT to ambient (W/m² K); $h_o$: heat transfer coefficient from top of PVT to ambient (W/m² K); $U_{ent}$: overall heat transfer coefficient from cell to ambient (W/m² K); $U_{cp}$: overall heat transfer coefficient from cell to plate (W/m² K); $h_{p}$: heat transfer coefficient from blackened plate to fluid (W/m² K); $U_{pc}$: overall heat transfer coefficient from plate to ambient (W/m² K); $U_{lm}$: overall heat transfer coefficient from module to ambient (W/m² K); $U_{Lc}$: overall heat transfer coefficient from glazing to ambient (W/m² K); $P_{m}$: annual power generated from photovoltaic module (kWh); $P'_n$: annual power utilized by pump (kWh); $\varepsilon$: emissivity; $\alpha$: absorptivity; $E_i$: hourly exergy (W); $I_2(t)$: solar intensity on glass cover of solar still of single slope type (W/m²); $T_{gi}$: glass temperature at inner surface of glass cover (°C); $h_{wgg}$: radiative heat transfer coefficient from water to inner surface of glass cover (W/m² K); $h_{ewg}$: convective heat transfer coefficient from water to inner surface of glass cover (W/m² K); $h_{ewg}'$: evaporative heat transfer coefficient (W/m² K); $m_i$: mass of water in basin (kg); $m_{ds}$: mass of distillate from of double slope solar still (kg); $a$: clear days (blue sky); $b$: hazy days (fully); $c$: hazy and cloudy days (partially); $d$: cloudy days (fully); $Q_{in}$: the rate of useful thermal output from $N$ identical partially (25%) covered PVTFPC water collectors connected in series (kWh); $G_{ex,annual}$: annual exergy gain (kWh); $L$: natural logarithm; $SS$: single slope; $t$: time, h; $RSEBWP$: Reflectivity of solar energy based water purifier; $T_w$: temperature of water in basin, °C; $T_o$: ambient temperature, °C; $T_{bo}$: water temperature at $t=0$, °C; $E_{out}$: overall annual energy available from PVT-CPC solar distillation system (kWh); $N$: number of PVTFPC water collector; ET: evacuated tube; $E_{emb}$: embodied energy (kWh); ETC: evacuated tubular collector; FPC: flat plate collector; CPC: compound parabolic concentrator collector; PVT: photovoltaic thermal; CFD: computational fluid dynamics; $N'$: number of sunshine hours; $r'$: daily diffuse to daily global irradiation ratio

Subscript

$g$: glass; $w$: water; $in$: incoming; $out$: outgoing; $eff$: effective

Declarations

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