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Gaurav Kumar Sharma

IITISM: Indian Institute of Technology

Ashis Mallick

IITISM: Indian Institute of Technology

Ram Kumar Sharma

UPES: University of Petroleum and Energy Studies

Ritvik Dobriyal

Graphic Era Deemed to be University

Navneet Kumar

Galgotias College of Engineering and Technology

Desh Bandhu Singh (✉ dbsiit76@gmail.com)

GEU: Graphic Era Deemed to be University <https://orcid.org/0000-0002-6092-5465>

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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

Gaurav Kumar Sharma¹, Ashis Mallick¹, Ram Kumar Sharma², Ritvik Dobriyal³, Navneet Kumar⁴, Desh Bandhu Singh^{3,*}

¹Department of Mechanical Engineering, Indian Institute of Technology (ISM), Dhanbad, Jharkhand, India

²University of Petroleum and Energy Studies (UPES), Bidholi, Premnagar, Dehradun - 248007, Uttarakhand, India

³Department of Mechanical Engineering, Graphic Era Deemed to be University, Bell Road, Clement Town, Dehradun - 248002, Uttarakhand, India

⁴Galgotias College of Engineering and Technology, Plot No. 1, Knowledge Park II, Greater Noida - 201306, G.B. Nagar, UP, India

*Corresponding author email id: deshbandhusingh.me@geu.ac.in/dbsiit76@gmail.com

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 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 exegoeconomic 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.

Key words: Exergo-enviro-economic parameters, Overall yearly energy and exergy, mass flow rate, N , solar still of single slope type

1. 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 with the contemporary issue of fresh water 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 complete utilization is possible; whereas, heat is considered 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, solar thermal etc. 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 green house 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 kg to 3 kg for unit basin area in most cases. 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 fresh water 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. (2015) 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 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 et al. (2017) reported the use of nanofluid in DS type solar still in active mode for enhancing the fresh water 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 PVT-FPCs 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 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. Kouadri 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 potable 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. 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 ($\dot{m}_f$) and number of collectors (N) at 0.14 m water depth due to better distribution of solar energy in the case of DS type.

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 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 fresh water 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. (2021) 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.

From the extant research, it is seen that the effect of $\dot{m}_f$ and N on exergo-enviro-economic parameters for NPVTFPC-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 NPVTFPC-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 NPVTFPC-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.

2 System metaphors

The specification of NPVTFPC-SS has been revealed as Table 1. Fig. 1 represents NPVTFPC-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 fresh water 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 has been covered with insulator to prevent heat loss.

Fig. 1: Schematic diagram of solar still of single slope type integrated with N similar partially covered PVTFPCs having series connection

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 the bottom. Due to the absorption of solar flux, basin liner gets heated and transfer 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 and 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.

Table 1: Specifications of solar still of single slope type integrated with N similar partially covered PVTFPCs having series connection

Solar still of single slope type			
Component	Specification	Component	Specification
Length	2m	Orientation	South
Width	1m	Thickness of glass cover	0.004 m
Inclination of glass cover	15°	K_g	0.816 W/m-K
Height of smaller side	0.2m	Thickness of insulation	0.1 m
Material of body	GRP	Thermal conductivity of insulation	0.166 W/m-K
Material of stand	GI	Cover material	Glass
PVT-FPC collector			
Component	Specification	Component	Specification
Type and no of collectors	Tube in plate type ,N	Aperture area	2 m ²
Receiver Area of solar water collector	1.0 m×1.0 m	Area of module	0.25 m ×1.0 m
Collector plate thickness	0.002	Area of collector	0.75 m ×1.0 m
Thickness of Copper Tubes	0.00056 m	F'	0.968
Length of each Copper Tubes	1.0 m	ρ	0.84
$K_i (Wm^{-1}K^{-1})$	0.166	τ_g	0.95
FF	0.8	α_c	0.9
Thickness of insulation	0.1 m	β_c	0.89
Angle of CPC with Horizontal	30°	α_p	0.8
Thickness of toughen glass on FPC	0.004 m	Pipe diameter	0.0125 m
Effective area of collector under glass	0.75 m ²	DC motor rating	12 V, 24W

3. Mathematical modeling based on energy balance equations

Mathematical modeling of N similar partially covered 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:

3.1 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

$$\dot{Q}_{uN} = N(A_m + A_c)[(\alpha\tau)_{eff,N}I(t) - U_{L,N}(T_{fi} - T_a)] \quad (1)$$

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 NPVTFPC-SS. Water coming from the basin of the solar still of single slope type enters the first PVTFPC through the DC motor pump and the outlet from Nth PVTFPC discharges into the basin of NPVTFPC-SS. Therefore, T_{fi} turns out to be equal to T_w . The temperature of water coming out from Nth PVT-FPC (T_{foN}) is expressed as:

$$T_{foN} = \frac{(A F_R(\alpha\tau))_1 (1-K_k^N)}{\dot{m}_f C_f (1-K_k)} I(t) + \frac{(A F_R U_L)_1 (1-K_k^N)}{\dot{m}_f C_f (1-K_k)} T_a + K_k^N T_{fi} \quad (2)$$

where, $T_{fi} = T_w$. The water exiting the Nth PVTFPC enters the basin of NPVTFPC-SS at that temperature. Hence, $T_{wo} = T_{foN}$. The expression for the various terms occurring in equations (1) and (2) can be found in appendix - A.

The electrical efficiency of solar cells (η_{cN}) for a number (N) of PVTFPC as a function of temperature is given as [Schott (1985) and Evan (1981)]

$$\eta_{cN} = \eta_o[1 - \beta_o(\bar{T}_{cN} - T_o)] \quad (3)$$

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

3.2 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 equation (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 heat to output heat can be written as [Singh et al. (2016)]:

$$\frac{K_g}{L_g}(T_{gi} - T_{go})A_g = h_{1g}(T_{go} - T_a)A_g \quad (4)$$

Here, h_{1g} is total heat transfer coefficient (THTC) from exterior side of condensing cover to the surrounding. Fourier's law has been used for conductive heat transfer from inner surface to outer surface of condensing cover (expression on left side of equation (1)). 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 equation (4)). The expression for h_{1g} can be written as

$$h_{1g} = 5.7 + 3.8V \quad (5)$$

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:

$$\alpha'_g I(t) A_g + h_{1w} (T_w - T_{gi}) A_b = \frac{K_g}{L_g} (T_{gi} - T_{go}) A_g \quad (6)$$

Here, h_{1w} is THPTC (corresponding to convection, radiation and evaporation) from water surface to interior side of condensing cover. Hence, h_{1w} can be estimated as

$$h_{1w} = h_{cw} + h_{rw} + h_{ewg} \quad (7)$$

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

$$h_{cw} = 0.884 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{268.9 \times 10^3 - P_w} \right] \quad (8)$$

$$P_w = \exp \left[25.317 - \frac{5144}{T_w + 273} \right] \quad (9)$$

$$P_{gi} = \exp \left[25.317 - \frac{5144}{T_{gi} + 273} \right] \quad (10)$$

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

$$h_{rw} = (0.82 \times 5.67 \times 10^{-8}) [(T_w + 273)^2 + (T_{gi} + 273)^2] [T_w + T_{gi} + 546] \quad (11)$$

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

$$h_{ewg} = 16.273 \times 10^{-3} h_{cw} \left[\frac{P_w - P_{gi}}{T_w - T_{gi}} \right] \quad (12)$$

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

$$231 \quad \alpha'_b I(t) A_b = h_{bw}(T_b - T_w) A_b + h_{ba}(T_b - T_a) A_b \quad (13)$$

232 Here, h_{bw} is HTC from basin liner to water and h_{ba} is HTC from basin liner to the surrounding.
 233 The value of h_{bw} is taken as 100 W/m²-K.
 234

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

$$239 \quad (M_w C_w) \frac{dT_w}{dt} = \alpha'_w I(t) A_b + h_w(T_b - T_w) A_b + \dot{Q}_{u,N} - h_{1w}(T_w - T_{gi}) A_b \quad (14)$$

240 Solving equation (1) to (14) using simple mathematics, one can obtain expression for
 241 water temperature (T_w) as a function of time which can be written as

$$242 \quad T_w = \frac{\bar{f}_1(t)}{a_1} (1 - e^{-a_1 t}) + T_{w0} e^{-a_1 t} \quad (15)$$

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

$$246 \quad T_{gi} = \frac{\alpha'_g I_s(t) A_g + h_{1w} T_w A_b + U_{c,ga} T_a A_g}{U_{c,ga} A_g + h_{1w} A_b} \quad (16)$$

$$247 \quad T_{go} = \frac{\frac{K_g}{L_g} T_{gi} + h_{1g} T_a}{\frac{K_g}{L_g} + h_{1g}} \quad (17)$$

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

$$249 \quad \dot{m}_{ew} = \frac{h_{ewg} A_b (T_w - T_{gi})}{L} \times 3600 \quad (18)$$

250 Here, L is latent heat which can be taken as 2400 kJ/kg-K.

251 3.3. Experimental Validation of NPVTFPC-SS

252 Singh et al. (2016) have validated NPVTFPC-SS for November 22, 2013 and February 18, 2014
 253 considering N=2. They revealed values of coefficients of variation for T_w , T_{gi} and potable water
 254 yielding as 0.979, 0.977 and 0.984 for November 22, 2013 respectively. Similarly, for February
 255 18, 2014, they revealed these values as 0.964, 0.98 and 0.988 respectively. They reported the
 256 system to be in fair agreement for theoretical and experimental values.

4. Analysis

For the analysis of the effect of dissimilarity of $\dot{m}_f$ and N on energy metrics based on energy as well exergy 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 (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 $7 \text{ h} \leq N' \leq 9 \text{ h}$
(c) Hazy and cloudy (partially)	$0.50 \leq r' \leq 0.75$ and $5 \text{ h} \leq N' \leq 7 \text{ h}$
(d) Cloudy day (fully)	$r' \geq 0.75$ and $N' \leq 5 \text{ h}$

4.1 Energy estimation

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

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

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 which is present in the denominator converts electrical energy into heat. This factor is basically efficacy of power output taken from conventional power plant [Huang (2001)].

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

$$\dot{E}x_e = A_m I_b(t) \sum_1^N (\alpha \tau_g \eta_{cN}) \quad (20)$$

The equation (9) can be used for evaluating daily electrical exergy of type (a) climatic situation by summing the hourly value 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 situation i.e. type (b) to type

(d). The value of net electrical energy on monthly basis has been worked out by summing electrical energies values for type (a) to type (d) climatic situations. The value of electrical energy (P_m) 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 fresh water yield (M_{ew}).

4.2 Exergy estimation

The estimation of exergy for NPVTFPC-SS has been carried out using 1st and 2nd laws of thermodynamics. The hourly output thermal exergy $\dot{E}x_{out}$ (W) for NPVTFPC-SS can be expressed as [Nag (2004)]

$$\dot{E}x_{out} = h_{ewg} \times \frac{A_b}{2} \times \left[(T_w - T_{gi}) - (T_a + 273) \times \ln \left\{ \frac{(T_w + 273)}{(T_{gi} + 273)} \right\} \right] \quad (21)$$

Where h_{ewg} can be estimated using equation (12). The equation (10) can be used for evaluating daily thermal exergy of type (a) climatic situation by summing the hourly value 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 situation 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 situation 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 NPVTFPC-SS has been expressed as follows:

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

4.3 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 view[point, the aim is to minimize the objective function. The value of exergoeconomic parameter (ξ) can be computed as:

$$\xi_{NPVTFPC-SS} = \frac{G_{ex,annual}}{UEOYAC} \quad (23)$$

Further, value of $G_{ex,annual}$ for NPVTFPC-SS can be estimated using equation (15). Following Tiwari (2012), value of UEOYAC for NPVTFPC-SS can be computed as:

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

Where PC, S_V , 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:

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

and S_{FF} can be written as

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

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

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

$$PC = PI + P_u + \frac{P_u}{(1+i)^{10}} + \frac{P_u}{(1+i)^{20}} \quad (27)$$

Where, PI = Cost of solar still + Cost of PVTFFPCs+ Fabrication cost (28)

334 The cost of fabrication includes piping and labor cost.

335 **4.4 Enviroeconomic analysis**

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

$$343 \text{ Energy based Carbon credited} = ((\text{Annual overall energy out}) \times n - \\ 344 \text{ Embodied energy}) * 0.002 \quad (29)$$

$$345 \text{ Energy based enviroeconomic parameter} = ((\text{Annual overall energy out}) \times n - \\ 346 \text{ Embodied energy})(0.002)(\text{CRP}) \quad (30)$$

$$347 \text{ Exergy based Carbon credited} = ((\text{Annual overall exergy out}) \times n - \\ 348 \text{ Embodied energy}) * 0.002 \quad (31)$$

$$349 \text{ Exergy based enviroeconomic parameter} = ((\text{Annual overall exergy out}) \times n - \\ 350 \text{ Embodied energy})(0.002)(\text{CRP}) \quad (32)$$

351 CRP stands for carbon dioxide reduction price which can be taken as \$14.5.

352 **4.5 Productivity analysis**

353 Productivity represents obtaining more and more with less and less resources in such a way that
354 the profit can be divided more equally among maximum number of people. It represents the
355 feasibility of the system. The system is said to be feasible if productivity is more than 100%. A
356 value of productivity lower than 100% indicates the system gives low energy as compared to
357 input energy. Productivity reveals association between input and output and it is defined as the
358 ration of output to input. However, it is different from efficiency in the sense that the
359 productivity is expected to be more than 100%; whereas, efficiency can never be more than
360 100% as per Carnot principle. A higher value of productivity is expected because higher
361 productivity means larger number of products are available for the consumer which ultimately
362 will reflect the living standard of people. It is also the function of effectiveness and efficiency.
363 Mathematically, the value of yearly productivity for NPVTFPC-SS can be estimated as:

$$\text{Yearly productivity} = \frac{\text{Output from NPVTFPC-SS}}{\text{Input provided to NPVTFP-SS}} \times 100 \quad (33)$$

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

$$\text{Output from NPVTFPC} - \text{SS} = [(\text{Annual yield}) \times (\text{Selling price of water})] + [(\text{Annual electric output}) \times (\text{Selling price of electricity})] \quad (34)$$

The input provided to NPVTFPC-SS will be UEOYAC and it can be estimated using equation (17). The productivity has been evaluated using equation (23).

5. 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 equation (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 equations (21) followed by the calculation for exergy on per year basis.

Step IV

390 The calculation for gross energy output values at various values of $\dot{m}_f$ for given N have been
 391 performed using equation (19) followed by calculation for gross energy output on per year basis.
 392 The calculation for gross exergy output values at various values of $\dot{m}_f$ for given N have been
 393 performed using equation (22) followed by calculation for gross exergy output on per year basis.

394 Step V

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

Table 2: Computation of yearly fresh water yield for solar still of single slope type integrated with N similar partially covered PVTFCs at $\dot{m}_f = 0.02 \text{ kg/s}$, N = 6 and water depth = 0.14 m

Month	Daily yield	No. of Days	Monthly yield	Daily yield	Days	Monthly yield	Daily yield	Days	Monthly yield	Daily yield	Days	Monthly yield	Monthly yield
	Kind a weather condition			Kind b weather condition			Kind c weather condition			Kind d weather condition			
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	99.88	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
April	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 fresh water yield (kg)													5622.21

400 6. Results and discussion

401 The required data and all relevant equations have been fed to computational program written in
 402 MATLAB-2015a. Data on the horizontal surface has been taken from IMD Pune India. Data on
 403 the inclined surface has been evaluated using Liu and Jordan formula with the help of
 404 MATLAB-2015a. The output of programme has been presented in Figs. 2-6 and Table 2 to Table
 405 4.

Fig. 2: Variation of yearly fresh water yield with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 3: Dissimilarity of yearly thermal exergy with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Table 2 represents the computation of yearly fresh water yielding for NPVTFPC-SS at $\dot{m}_f = 0.02 \text{ kg/s}$ 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. 2. It is clear from Fig. 2 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 has also been observed from fig. 3 that the value of fresh water yielding increases as the value of N is enhanced 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 evaporation rate and hence fresh water yielding gets enhanced with increase in N at given $\dot{m}_f$.

Table 3: Computation of yearly thermal exergy for solar still of single slope type integrated with N similar partially covered PVTFCs at $\dot{m}_f = 0.02 \text{ kg/s}$, $N = 6$ and water depth = 0.14 m

Month	Daily exergy	No. of Days	Monthly exergy	Daily exergy	No. of Days	Monthly exergy	Daily exergy	No. of Days	Monthly exergy	Daily exergy	No. of Days	Monthly exergy	Monthly exergy
	Kind a weather condition			Kind b weather condition			Kind c weather condition			Kind d weather condition			
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

423

Table 3 represents the computation of yearly thermal exergy for NPVTFPC-SS at $\dot{m}_f = 0.02 \text{ kg/s}$ and $N = 6$. The water depth has been taken as 0.14 m. Similarly, thermal exergy at

other values of $\dot{m}_f$ has been evaluated and presented as Fig. 3. It is clear from Fig. 4 that the value of thermal exergy diminishes as the value of $\dot{m}_f$ is enhanced. It occurs due to the fact that water flowing through tubes of collector gets less time to absorb heat at higher value of $\dot{m}_f$ which result in less rise in temperature of water. The value of thermal exergy 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: Computation of yearly electrical exergy for solar still of single slope type integrated with N similar partially covered PVTFCs at $\dot{m}_f = 0.02 \text{ kg/s}$, $N = 6$ and water depth = 0.14 m

Daily exergy (kWh)	Days (Kind a) (kWh)	Monthly exergy (Kind a) (kWh)	Daily exergy (kWh)	Days (Kind b)	Monthly exergy (Kind b) (kWh)	Daily exergy (kWh)	Days (Kind c)	Monthly exergy (Kind c) (kWh)	Daily exergy (kWh)	Days (Kind d)	Monthly exergy (Kind d) (kWh)	Gross monthly exergy (kWh)
1.29	3	3.86	1.24	8	9.89	0.80	11	8.85	0.52	9	4.65	27.24
1.26	3	3.78	1.28	4	5.13	0.83	12	10.00	0.54	9	4.88	23.79
1.23	5	6.16	1.32	6	7.90	0.92	12	11.09	0.83	8	6.60	31.75
1.22	4	4.89	1.26	7	8.85	0.95	14	13.29	0.97	5	4.83	31.86
1.15	4	4.60	1.15	9	10.36	1.08	12	12.95	0.93	6	5.56	33.47
1.18	3	3.55	1.23	4	4.90	1.09	14	15.21	0.84	9	7.58	31.25
1.14	2	2.29	1.16	3	3.48	1.01	10	10.09	0.80	17	13.57	29.42
1.15	2	2.30	1.19	3	3.56	0.98	7	6.85	0.79	19	14.95	27.67
1.24	7	8.69	1.21	3	3.64	1.05	10	10.45	0.77	10	7.68	30.46
1.22	5	6.11	1.11	10	11.10	0.92	13	11.91	0.69	3	2.06	31.19
1.19	6	7.11	1.00	10	9.96	0.66	12	7.97	0.64	2	1.28	26.32
1.24	3	3.72	1.05	7	7.33	0.87	13	11.31	0.55	8	4.44	26.80
Yearly electrical exergy output (kWh)												351.20

Table 4 represents the computation of yearly electrical exergy for NPVTFPC-SS at $\dot{m}_f = 0.02 \text{ kg/s}$ 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. 4. It is clear from Fig. 4 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 water. 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 heat collection area as well PV area.

Fig. 4: Dissimilarity of yearly electrical exergy with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 5: Dissimilarity of yearly gross energy with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 5 and Fig. 6 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 fresh water 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. Table 5 reveals the estimation of embodied energy for NPVTFPC-SS and Table 6 reveals the estimation of solar energy falling on the surface of NPVTFPC-SS for its life span. The life span of NPVTFPC-SS has been considered as 30 years.

Fig. 6: Dissimilarity of yearly gross exergy with $\dot{m}_f$ at different values of N for NPVTFPC-SS

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 NPVTFPC-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. 7. It is clear from Fig. 7 that the value of exergoeconomic parameter first diminishes with the enhancement in the value of $\dot{m}_f$ and then it 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 if $\dot{m}_f$ 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

486 more as compared to the enhancement in the value of UEOYAC with the enhancement in the
487 value of N.

488 Table 5: Capital investment for NPVTFPC-SS

S.N.	Parameter	Cost (₹)
1	Cost of solar still	23143.00
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 @ 4% in India, [using present value of scrap material sold in Indian market] for N = 2	14311.36

489

490 Table 6: Estimation of UEOYAC for NPVTCPC-SS

n Year	N	i %	PC Rs.	MC Rs.	SV Rs.	CRF Fraction	SFF Fraction	UEOYAC Rs.
30	2	5	50124.00	5012.40	14311.36	0.0651	0.0151	3371.30
30	4	5	67124.61	6712.46	19825.14	0.0651	0.0151	4504.81
30	6	5	84124.61	8412.46	25338.91	0.0651	0.0151	5638.28
30	8	5	101124.61	10112.46	30852.69	0.0651	0.0151	6771.75
30	10	5	118124.61	11812.46	36366.47	0.0651	0.0151	7905.23
30	10	5	135124.60	13512.46	41880.24	0.0651	0.0151	9038.70

491

492 Table 7: Embodied energy computation for NPVTFPC-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	11327.55

493

Fig. 7: Dissimilarity of exergoeconomic parameter with $\dot{m}_f$ at different values of N for NPVTFPC-SS

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. 8. It is clear from Fig. 8 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. 9. It is clear from Fig. 9 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.

Fig. 8: Dissimilarity of energy based carbon credit earned with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 9: Dissimilarity of exergy based carbon credit earned with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 10: Dissimilarity of energy based enviroeconomic parameter with $\dot{m}_f$ at different values of N for NPVTFPC-SS

Fig. 11: Dissimilarity of exergy based enviroeconomic parameter with $\dot{m}_f$ at different values of N for NPVTFPC-SS

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. 10 and 11 respectively. It is clear from Figs. 10 and 11 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 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 $\dot{m}_f$ 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. 11 that the value of exergy based enviroeconomic parameter comes out to be negative for $N=2$ and $\dot{m}_f \geq 0.04$ kg/s. The negative value represents that 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.

Fig. 12: Dissimilarity of yearly productivity with $\dot{m}_f$ at different values of N for NPVTFPC-SS

The dissimilarity of yearly productivity with $\dot{m}_f$ at different values of N for NPVTFPC-SS has been revealed as Fig. 12. It is clear from Fig. 12 that the value of yearly productivity first diminishes with the enhancement in $\dot{m}_f$ value and then becomes almost constant at given N. It has been found to occur because yearly productivity depends on fresh water yielding and electrical energy output and both fresh water yielding and electrical energy output first diminish with the enhancement in $\dot{m}_f$ value and then become almost constant as revealed in Figs. 2 and 4 respectively. It is further seen that the value of yearly productivity first increases with the enhancement in value of N at given $\dot{m}_f$ and it becomes either constant or diminishes beyond $N=6$ at given $\dot{m}_f$. It means that the optimum value of N is 6 for productivity viewpoint.

7. Conclusions

An investigation on dissimilarity of $\dot{m}_f$ and N on exergo-enviro-economic parameters for NPVTFFPC-SS has been done considering all four kinds of atmospheric situations to know the effect of dissimilarities of $\dot{m}_f$ 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 $\dot{m}_f$ and it becomes almost constant beyond $\dot{m}_f = 0.10$ 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 $\dot{m}_f$ and it becomes almost constant beyond $\dot{m}_f = 0.10$ kg/s; however, values of energy and exergy based carbon credits earned increases with the enhancement in the value of N at given $\dot{m}_f$.
- iii. The value of energy as well as exergy based enviroeconomic parameters with the enhancement in $\dot{m}_f$ and it becomes almost constant beyond $\dot{m}_f = 0.10$ kg/s; however, values of energy and exergy based enviroeconomic 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-A

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

$$U_{tca} = \left[\frac{1}{h_o} + \frac{L_g}{K_g} \right]^{-1} ; \quad U_{tcp} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1} ;$$

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

$$U_{tpa} = \left[\frac{1}{U_{tca}} + \frac{1}{U_{tcp}} \right]^{-1} + \left[\frac{1}{h_i} + \frac{1}{h_{pf}} + \frac{L_i}{K_i} \right]^{-1} ;$$

$$\begin{aligned}
586 \quad h'_i &= 2.8 + 3V, \quad Wm^{-2}K^{-1} ; \\
587 \quad U_{L1} &= \frac{U_{tcp}U_{tca}}{U_{tcp}+U_{tca}} ; & U_{L2} &= U_{L1} + U_{tpa} ; \\
588 \quad U_{Lm} &= \frac{h_{pf}U_{L2}}{F'h_{pf}+U_{L2}} ; & U_{Lc} &= \frac{h_{pf}U_{tpa}}{F'h_{pf}+U_{tpa}} ; \\
589 \quad PF_1 &= \frac{U_{tcp}}{U_{tcp}+U_{tca}} ; & PF_2 &= \frac{h_{pf}}{F'h_{pf}+U_{L2}} ; \\
590 \quad PF_c &= \frac{h_{pf}}{F'h_{pf}+U_{tpa}} ; & (\alpha\tau)_{1eff} &= (\alpha_c - \eta_c)\tau_g\beta_c ; \\
591 \quad (\alpha\tau)_{2eff} &= \alpha_p\tau_g^2(1 - \beta_c) ; & (\alpha\tau)_{meff} &= [(\alpha\tau)_{2eff} + PF_1(\alpha\tau)_{1eff}] ; \\
592 \quad (\alpha\tau)_{ceff} &= PF_c \cdot \alpha_p\tau_g ; & A_m &= WL_m ; & A_c &= WL_c ; \\
593 \quad A_cF_{Rc} &= \frac{\dot{m}_f c_f}{U_{Lc}} \left[1 - \exp\left(\frac{-F'U_{Lc}A_c}{\dot{m}_f c_f}\right) \right] ; \\
594 \quad A_mF_{Rm} &= \frac{\dot{m}_f c_f}{U_{Lm}} \left[1 - \exp\left(\frac{-F'U_{Lm}A_m}{\dot{m}_f c_f}\right) \right] ; \\
595 \quad (AF_R(\alpha\tau))_1 &= \left[A_cF_{Rc}(\alpha\tau)_{ceff} + PF_2(\alpha\tau)_{meff}A_mF_{Rm}\left(1 - \frac{A_cF_{Rc}U_{Lc}}{\dot{m}_f c_f}\right) \right] ; \\
596 \quad (AF_RU_L)_1 &= \left[A_cF_{Rc}U_{Lc} + A_mF_{Rm}U_{Lm}\left(1 - \frac{A_cF_{Rc}U_{Lc}}{\dot{m}_f c_f}\right) \right] ; \\
597 \quad K_K &= \left(1 - \frac{(AF_RU_L)_1}{\dot{m}_f c_f} \right) ; & (AF_R(\alpha\tau))_{m1} &= PF_2(\alpha\tau)_{meff}A_mF_{Rm} ; \\
598 \quad (AF_RU_L)_{m1} &= A_mF_{Rm}U_{Lm} ; & K_m &= \left(1 - \frac{A_mF_{Rm}U_{Lm}}{\dot{m}_f c_f} \right) ; \\
599 \quad (\alpha\tau)_{eff,N} &= \frac{(AF_R(\alpha\tau))_1}{(A_c+A_m)} \left[\frac{1-(K_K)^N}{N(1-K_K)} \right] ; \\
600 \quad U_{L,N} &= \frac{(AF_RU_L)_1}{(A_c+A_m)} \left[\frac{1-(K_K)^N}{N(1-K_K)} \right] \\
601 \quad a_1 &= \frac{1}{M_w C_w} [\dot{m}_f C_f (1 - K_K^N) + U_s A_b] ; \\
602 \quad \bar{f}_1(t) &= \frac{1}{M_w C_w} \left[\alpha'_{eff} A_b \bar{I}_s(t) + \frac{(1-K_K^N)}{(1-K_K)} (A F_R(\alpha\tau))_1 \bar{I}_c(t) + \left(\frac{(1-K_K^N)}{(1-K_K)} (A F_R U_L)_1 + U_s A_b \right) \bar{T}_a \right] ; \\
603 \quad \alpha'_{eff} &= \alpha'_w + h_1 \alpha'_b + h'_1 \alpha'_g ; \quad h_1 = \frac{h_{bw}}{h_{bw}+h_{ba}} ;
\end{aligned}$$

$$h'_1 = \frac{h_{1w}A_g}{U_{c,ga}A_g + h_{1w}A_b} ; \quad h_{1w} = h_{r wg} + h_{c wg} + h_{e wg} ;$$

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

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

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

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

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

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

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

612

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686

Nomenclature

A_m	area covered by PV module (m^2)
A_c	area covered by glass (m^2)
A_g	area of glass cover (m^2)
A_b	area of basin (m^2)

L	Latent heat(J/kg)
L_g	thickness of glass cover (m)
K_g	thermal conductivity of glass (W/m-K)
$I(t)$	global radiation falling on collector (W/m ²)
T_a	ambient temperature (°C)
L_i	thickness of insulation (m)
K_i	thermal conductivity of insulation (W/m-K)
α_c	absorptivity of the solar cell
$\dot{m}_f$	mass flow rate of water (kg/s)
τ_g	transmissivity of the glass (fraction)
C_f/C_w	specific heat of water (J/kg-K)
β_o	temperature coefficient of efficiency (K ⁻¹)
L_c	length of collector covered by glass
L_m	length of collector covered by PV module
η_c	solar cell efficiency
η_m	PV module efficiency
η_{cN}	temperature dependent electrical efficiency of solar cells of a NPVTFPCs
b	breath of collector (m)
$(\alpha\tau)_{eff}$	product of effective absorptivity and transmittivity
F'	collector efficiency factor
T_c	solar cell temperature (°C)
T_p	absorber plate temperature (°C)
L_p	thickness of absorber plate (m)
K_p	thermal conductivity of absorber plate(W/m-K)
T_{fi}	fluid temperature at collector inlet (°C)
T_f	temperature of fluid in collector (°C)
PF_1	penalty factor due to the glass covers of module
PF_2	penalty factor due to plate below the module
PF_3	penalty factor due to the absorption plate for the glazed portion
PF_c	penalty factor due to the glass covers for the glazed portion
β	packing factor of the module
η_o	efficiency at standard test condition
T_{foN}	outlet water temperature at the end of Nth PVTfPC water collector (°C)
h_i	heat transfer coefficient for space between theglazing and absorption plate (W/m ² -K)
h'_i	heat transfer coefficient from bottom of PVT to ambient (W/m ² -K)
h_o	heat transfer coefficient from top of PVT to ambient (W/m ² -K)
U_{tca}	overall heat transfer coefficient from cell toambient (W/m ² -K)
U_{tcp}	overall heat transfer coefficient from cell to plate(W/m ² -K)
h_{pf}	heat transfer coefficient from blackened plate to fluid (W/m ² -K)
U_{tpa}	overall heat transfer coefficient from plate to ambient (W/m ² -K)
U_{Lm}	overall heat transfer coefficient from module to ambient (W/m ² -K)
U_{Lc}	overall heat transfer coefficient from glazing to ambient (W/m ² -K)
P_m	annual power generated from photovoltaic module (kWh)

P_u	annual power utilized by pump (kWh)
ϵ	emissivity
α'	absorptivity
$\dot{E}x$	hourly exergy(W)
$I_S(t)$	solar intensity on glass cover of solar still of single slope type (W/m ²)
T_{gi}	glass temperature at inner surface of glass cover (°C)
h_{rwg}	radiative heat transfer coefficient from water to inner surface of glass cover (W/m ² -K)
h_{cwg}	convective heat transfer coefficient from water to inner surface of glass cover (W/m ² -K)
h_{ewg}	evaporative heat transfer coefficient (W/m ² -K)
M_w	mass of water in basin (kg)
$\dot{m}_{ew}$	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)
$\dot{Q}_{uN}$	the rate of useful thermal output from N identical partially (25%) covered PVT/FPC water collectors connected in series (kWh)
$G_{ex,annual}$	annual exergy gain (kWh)
$\ln$	natural logarithm
SS	single slope
t	time, h
R	Reflectivity
SEBWP	solar energy based water purifier
T_w	temperature of water in basin, °C
T_a	ambient temperature, °C
T_{wo}	water temperature at t=0, °C
E_{out}	overall annual energy available from PVT-CPC solar distillation system (kWh)
N	number of PVT/FPC water collector
E_{in}	embodied energy (kWh)
FPC	Flat plate collector
PVT	photovoltaic thermal
N'	number of sunshine hours
r'	daily diffuse to daily global irradiation ratio
Subscript	
g	glass
w	water
in	incoming
out	outgoing
eff	effective

688 **Declaration of competing Interest**

689 The authors declare that there is no competing interest

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691 All data are given in the manuscript

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699 Gaurav Kumar Sharma - Writing-review & editing

700 Ashis Mallick - Writing, Formal analysis

701 Ram K Sharma - Review & editing

702 Ritvik Dobrioyal- Review & editing

703 Navneet Kumar - Review & editing

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