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Sensitivity investigation for solar still of double slope type included with N similar CPC integrated ETC by incorporating yield and efficiency

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ABSTRACT

This work investigates solar still of double slope type included with N similar CPC integrated ETC having a series connection for sensitivity analysis using one at a time method by incorporating yield and efficiency. The energy-based analysis has been done by feeding all expressions of different parameters to computer code written in MATLAB-2015a for May month of New Delhi climatic situation. Fresh water yielding and energy efficiency values have been estimated for dissimilarities of mass flow rate maintaining all other parameters at the input of system constant and this procedure has been repeated till estimation is completed for all parameters at the input of system. All results so obtained have been 2D plotted. The fresh water yielding and energy efficiency for the considered system has been estimated to be most sensitive with respect to concentration ratio having mean sensitivity figure values as 0.91 and 0.78 in that order. Sensible conclusions have been presented based on the current analysis.

Keywords: Sensitivity analysis; CPCETC; Double slope solar still; Potable water yielding; Efficiency

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1. Introduction

The analysis of solar still of double slope type included with N similar solar collectors commonly known as a solar still of double slope type in active mode is the need of time as the conventional source of energy is very limited and the active type solar still which solely works on solar energy has the potential to mitigate the issue of fresh water scarcity prevailing throughout the globe. The working of this type of solar still is based on the greenhouse effect and it does not emit any pollutants to the surrounding. Hence, it is environment friendly. Also, the technology is very simple and the repair people can be made locally available after imparting short training to laymen. The application of solar energy technology for purification of dirty water assists in the growth of eco-friendly ambiance in broad spatial coverage of the earth. It is the suitable application for remote locations on the earth. The study tells that 2/3rd

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population of the world is going to face the scarcity of fresh water by 2025 because of the unavailability of various natural resources as only less than 1% of the available water is accessible and this small percentage of water is also getting polluted because of an assortment of anthropogenic activities. The sustainable defense of fresh water for drinking and other uses is the main challenge in the contemporary situation. Also, the issue of drought and flood are challenging, and it occurs throughout the globe. In the near future, the fresh water quality is expected to be poor and not fit for drinking as per UN report.

The active type of solar energy-based water purifier (SEBWP) came into existence in 1983 [1] and from that time, many new designs have been reported by various researchers around the globe. Rai and Tiwari [1] reported the enhancement in yield of active type SEBWP by incorporating one conventional flat plate collector (FPC) over passive type SEBWP of the same basin area due to the addition of heat to the basin in the active mode of operation. This water purifier was not self-sustainable as the pump needed some electric power for working which was supplied through the grid. The active type SEBWP in the forced mode of operation can be made self-sustainable by incorporating solar panels. Kumar and Tiwari [2] proposed the integration of PVT with FPC for supplying heat to the basin of passive type SEBWP taking inspiration from the work of Kern and Russell [3]. It was reported by Kern and Russell that the electrical efficiency of solar panel increased upon integration of solar panel with solar collector due to 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 SEBWP 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. [4] for double slope (DS) type SEBWP in active mode. Further, Singh et al. [5] and Tiwari et al. [6] reported the experimental investigation of SEBWP 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 [2]. The heat gain was less because more area of FPCs was covered by PVT. Further, active type SEBWP was studied under optimized situation [7–11]. It was reported that DS type SEBWP under optimized condition by incorporating N alike PVT-FPCs had 74.66% higher energy payback time (ENPBT) over passive type DS-SEBWP. The value of exergoeconomic parameter for single slope type SEBWP was found to be 47.37% higher than the passive type single slope SEBWP of same basin area. Sahota et al. [12] reported the use of nanofluid in DS type SEBWP in active mode for enhancing the fresh water output. Carranza et al. [13] have experimentally investigated the performance of DS type SEBWP 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 the base fluid. Kouadri et al. [14] have investigated solar still by incorporating zinc and copper oxides for the location of Algeria and compared the yield with conventional SEBWP and concluded that the water yield was improved by 79.39% due to having the better thermophysical characteristic of nanofluid.

The output of SEBWP 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. [15] proposed PVT integrated compound parabolic concentrator collector (CPC) and reported its thermal model which was further extended by Tripathi et al. [16] for N collectors connected in series and loop was opened. Singh and Tiwari [17–19], Gupta et al. [20,21], Singh et al. [22,23], and Sharma et al. [24] investigated SEBWP of basin type by incorporating characteristic equations development and concluded that SEBWP of double slope type performs better than SEBWP of single slope type under optimized conditions of mass flow rate and number of collectors at 0.14 m water depth due to better distribution of solar energy in the case of double slope type. Prasad et al. [25], Bharti et al. [26], and Singh [27] investigated SEBWP of double slope type from sensitivity viewpoint and concluded that the sensitivity analysis helps designer and installer of solar systems as which parameter should be focused more for a particular application.

The heat gain by solar collector can be enhanced by providing evacuated tubes because convection loss does not take place through vacuum. Sampathkumar et al. [28] investigated SEBWP by incorporating evacuated tubular collector and reported an increase of 129% over the SEBWP of the same basin area due to the addition of heat to the basin by collectors. An investigation of SEBWP in natural mode of operation by incorporating evacuated tubes was done by Singh et al. [29] and reported exergy efficiency lying in the range of 0.15%–8%. Further, an investigation of SEBWP incorporated with evacuated tubes was done in the 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 [30]. Mishra et al. [31] reported characteristic equation development for N alike series-connected ETC. The work reported by Mishra et al. [31] was further extended by Singh et al. [32–34]. The thermal modeling of basin type SEBWP by incorporating N alike ETCs was reported by them, and comparison was also made between single slope active water purifier and DS type SEBWP in active mode taking energy, exergy, energy metrics, exergoeconomic, and enviroeconomic parameters as basis. Issa and Chang [35] further extended the work of Singh et al. by connecting ETCs in mixed mode of operation experimentally and reported enhanced output as compared to similar set up in passive mode due to heat addition by collectors in active mode. Moreover, Singh and Al-Helal [36], Singh [37], and Sharma et al. [38, 39] reported development of characteristic equations and the observations based on the energy metrics for SEBWP by incorporating evacuated tubular collector as well as compound parabolic concentrator integrated evacuated tubular collector.

Patel et al. [40–42] have reviewed SEBWP recently by incorporating different types of collectors. Further, Singh et al. [43] reviewed SEBWP by incorporating different types of collectors and loaded with nanofluid with an aim to find the effect of nanofluid on the performance of active SEBWP. Nanofuid is obtained by mixing a small amount of nanoparticles to water. The effect of adding nanoparticles to water in SEBWP is to increase the output (potable water and exergy) of SEBWP. The better performance of nanofluid loaded SEBWP than loaded with water is due to the possession of better thermo-physical characteristics of nanofluid as compared to water. Bansal et al. [44] have reported the mini-review of changing the material of absorber on the performance of solar still. Shankar et al. [45] have studied ETC integrated SEBWP in natural as well-forced mode and concluded that forced mode is better for the environment as higher carbon credit was observed in forced mode due to more addition of heat to the basin in the case of forced mode. Abdallah et al. [46] have investigated spherical and pyramid basin SEBWP and concluded that the spherical basin SEBWP gave 57.1% higher water yield due to better utilization of solar radiation in the case of the spherical basin.

From the extant research, it is clear that the energy-based sensitivity investigation for solar still of double slope type included with N similar compound parabolic concentrators (CPC) integrated evacuated tubular collectors (ETCs) having a series connection (NCPCETCDS) have not been carried out by incorporating fresh water yielding and efficiency by any researcher throughout the globe. This type of analysis for NCPCETCDS will help the designer and installer in deciding the level of different input parameters. Hence, the proposed research deals with the sensitivity investigation of NCPCETCDS by incorporating fresh water yielding and efficiency. The prime objects of present research work are as under:

- To inspect the outcomes by varying mass flow rate to see its effect on fresh water yielding as well as thermal efficiency maintaining other parameters at the input of NCPCETCDS constant followed by 2D plotting and the estimation of sensitivity figures.
- To examine the outcomes by varying N value to see its effect on the fresh water yielding as well as thermal efficiency for the chosen value of mass flow rate, concentration ratio (CR), and water depth followed by 2D plotting and sensitivity figures estimation.
- To inspect the influence of variation in water depth on fresh water yielding as well as thermal efficiency for NCPCETCDS taking other parameters at the input as constant and estimation of corresponding sensitivity figures.
- To find the influence of changing CR on fresh water yielding as well as thermal efficiency for NCPCETCDS maintaining other parameters at the input of the system constant followed by estimation of sensitivity figures.
- To compare performance parameters on the basis of mean values of sensitivity figure.

2. System description

The detailed illustration of NCPCETCDS and sectional interpretation of 1st CPCETC collector have been revealed as Figs. 1 and 2 in that order. The solar still of double slope in active mode has been oriented east-west to get maximum annual energy for the New Delhi location. The used constraints and their corresponding values are tabulated in Table 1. The average wind velocity has been approximately taken as 4.02 m/s. During the study, for achieving higher water temperature at the exit side of Nth CPCETC; CPCETCs are joined in series to improve the gain of heat so that maximum heat can be transferred to water in the basin of NCPCETCDS. The distiller unit basin is covered

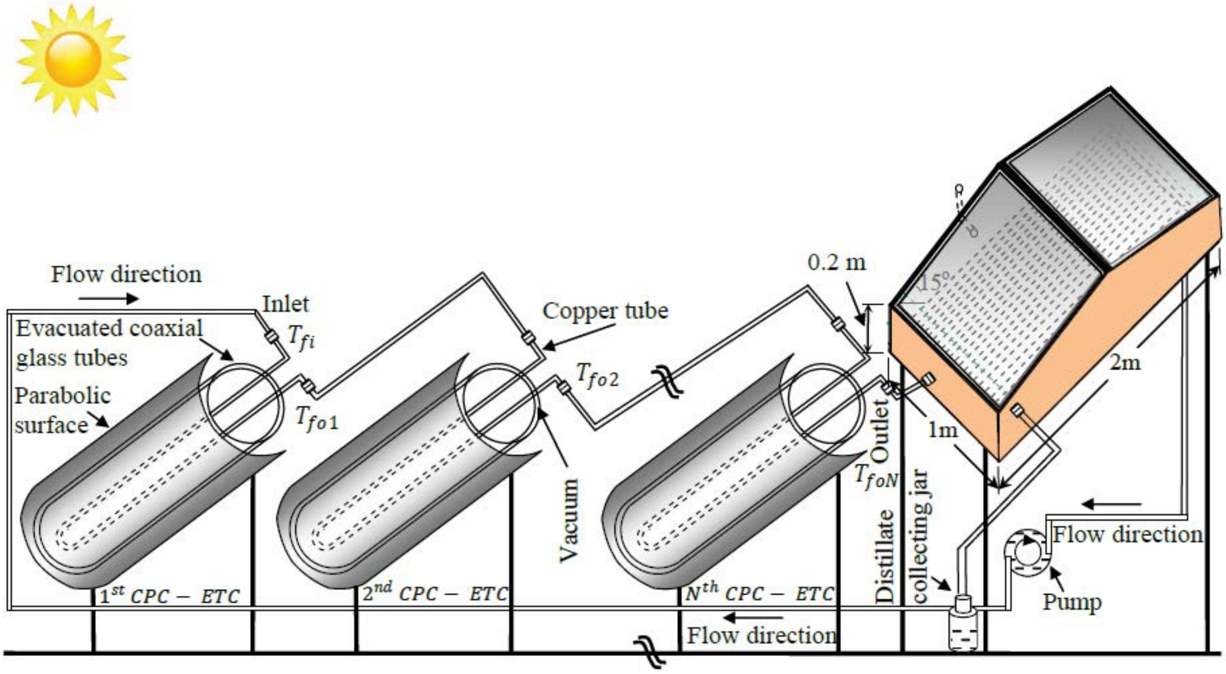


Fig. 1. N identical CPCETCs integrated double slope solar distiller unit (NCPCETCDS).

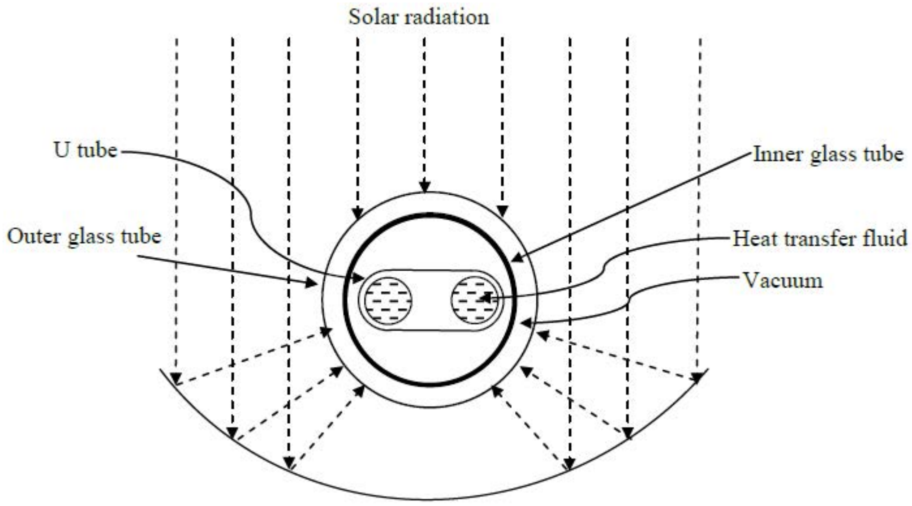


Fig. 2. Cross-section side view of the first CPCETC.

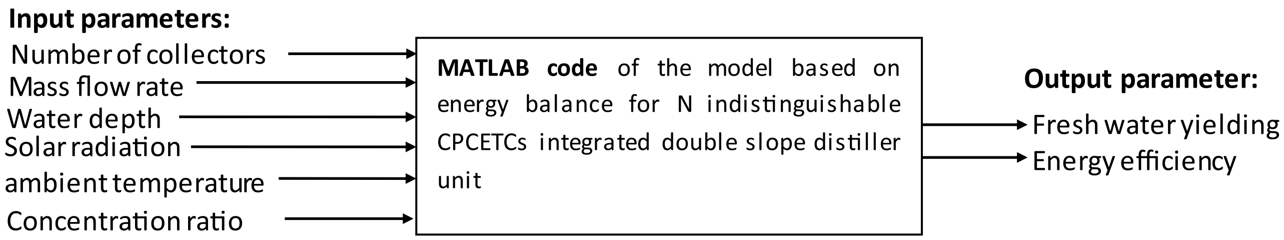


Fig. 3. Purification of saline/brackish water to potable water using CPCETCs integrated double slope solar desalination system.

with a transparent condensation cover through which, solar irradiance is transmitted to the basin after reflection and absorption. Further, the fraction of transmitted solar irradiance at water surface first reflected by the water surface, some is getting absorbed and remaining is being transferred to the basin liner. The basin liner is a blackened surface and absorbs almost the total solar irradiance transmitted through the water. Thereby the basin liner gets heated and transfers its heat to the available water depth in the basin. The basin water is also circulating through the coupled solar collectors; in this way, an additional indirect heat is also being added to the basin water. Hereafter, the temperature of basin water increases by the direct and indirect heating and evaporation of water started inside the basin. The evaporated water further gets condensed on the inner surface of condensation covered with essential phenomena of film condensation. Film condensation is required to maintain the transmittance of the transparent condensing cover for improving direct basin water heating. The condensed water trickles on the inner surface of condensing cover by the gravity effect as the condensing cover is inclined and collected through the channels provided at the corner. Finally, distilled water from the channels can be collected into the storage unit for further use.

3. Mathematical equations for NCPCETCDS

Mathematical modeling of NCPCETCDS means writing equations for all its components by equating input energy to output energy. Following assumptions presented in Gupta et al. [20], the mathematical modeling can be done as follows:

3.1. Heat gain for NCPCETCs

The useful heat gain from NETCs and temperature at the outlet of Nth ETC can be transcribed as [31,38,39]:

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

$$T_{\text{foN}} = \frac{\left(\text{PF}_1\right)\left(\alpha\tau\right)_{\text{eff}}\left(A_r F_r\right)}{\dot{m}_f C_f} \frac{\left(1-K_K^N\right)}{\left(1-K_K\right)} I_b\left(t\right) + \frac{\left(A_r F_r\right) U_L}{\dot{m}_f C_f} \frac{\left(1-K_K^N\right)}{\left(1-K_K\right)} T_a + K_K^N T_{\text{fi}} \tag{2}$$

where T_{foN} and T_{fi} are temperatures at the exit side of Nth CPCETC and at the inlet of 1st CPCETC in that order. Here, T_{fi} will be the same as T_w due to the fact that water from the basin of NCPCETCDS is allowed to enter 1st CPCETC through the passage using a pump resulting in the formation

Table 1
Specification of NCPCETCDS

Double slope active solar still	
Component	Specification
Length, m	2
Width, m	1
Inclination of glass cover, °	15
Height of smaller side, m	0.2
Material of body	GRP
Material of stand	GI
Cover material	Glass
Orientation	East–West
Thickness of glass cover, m	0.004
K_g, W/m-K	0.816
Thickness of insulation, m	0.1
K_i, W/m-K	0.166
CPCETC	
Component	Specification
Type and no. of collectors	ETC, N
DC motor rating	12 V, 24 W
Radius of inner copper tube, m	0.0125
Thickness of copper tube, m	0.0005
Outer radius of outer glass tube of evacuated coaxial glass tube, m	0.024
Inner radius of inner glass tube of evacuated coaxial glass tube, m	0.0165
α_p	0.8
F'	0.968
τ_g	0.95
K_g (W m^{-1} K^{-1})	1.09
Angle of ETC with horizontal	30°
Length of each copper tube, m	2.0
CR	2

of a closed-loop. Also, water having enhanced temperature at the exit side of Nth CPCETC is allowed to enter the basin of NCPCETCDS again, and hence, T_{wo} will be the same as T_{foN}. All unknown terms in Eqs. (1) and (2) have been given in the appendix of Sharma et al. [39].

3.2. EBEs for double slope solar still

Following Singh et al. [5], Tiwari et al. [6], and Sharma et al. [38,39], the fundamental EBEs for various components of DS can be written. Further, these equations can be solved using Eqs. (1) and (2) to get water temperature (T_w), east oriented glass cover temperature at its surface (T_{giE}, T_{goE}), and west oriented glass cover temperature at the inner surface of (T_{giW}, T_{goW}) as follows:

$$T_w = \frac{\overline{f}(t)}{a}\left(1 - e^{-at}\right) + T_{w0}e^{-at} \tag{3}$$

$$T_{giE} = \frac{A_1 + A_2 T_w}{P} \tag{4}$$

$$T_{giW} = \frac{B_1 + B_2 T_w}{P} \tag{5}$$

The various unknown terms are used in all the equations are given in the appendix of Singh and Tiwari [34]. After evaluating the values of T_w and T_{gi} from Eqs. (5) and (6), respectively, one can evaluate the value of hourly PW output as:

$$\dot{m}_{ew} = \frac{\left[h_{ewE}\left(T_w - T_{giE}\right) + h_{ewW}\left(T_w - T_{giW}\right)\right]\left(A_b / 2\right)}{L'} \times 3{,}600 \tag{6}$$

Evaporative heat transfer coefficient (h_{ewg}) from the outer surface of the water to the inner surface of glass cover can be computed as:

$$h_{ewgE} = 16.273 \times 10^{-3} h_{cwgE}\left[\frac{P_w - P_{giE}}{T_w - T_{giE}}\right] \tag{7}$$

$$h_{ewgW} = 16.273 \times 10^{-3} h_{cwgW}\left[\frac{P_w - P_{giW}}{T_w - T_{giW}}\right] \tag{7a}$$

$$\text{Here, } h_{cwgE} = 0.884\left[\left(T_w - T_{giE}\right) + \frac{\left(P_w - P_{giE}\right)\left(T_w + 273\right)}{\left(268.9 \times 10^3 - P_w\right)}\right] \tag{8}$$

$$h_{cwgW} = 0.884\left[\left(T_w - T_{giW}\right) + \frac{\left(P_w - P_{giW}\right)\left(T_w + 273\right)}{\left(268.9 \times 10^3 - P_w\right)}\right] \tag{8a}$$

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

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

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

Hourly energy efficiency for the solar distiller ($\eta_{NCPETCDS}$) can be computed as follows [17]:

$$\eta_{NCPCETCDS} = \frac{\dot{m}_{ew} \times L'}{\left[\dot{Q}_{uN} + \frac{A_b}{2}\left(I_{SE} + I_{SWE}\right) + \text{pumo work}\right] \times 3{,}600} \times 100 \tag{11}$$

The different terms used in Eqs. (1)–(11) have been presented in the appendix of Sharma et al. [38,39].

4. Sensitivity analysis for NCPCETCDS

In general, the sensitivity analysis measures the effect of some input variables on the output variables under some assumptions. The sensitivity analysis can understand the relationship between input and output parameters; it also provides a deep understanding of dependent and independent parameters, i.e., inputs and outputs variables. The sensitivity can be quantized by a sensitivity figure. Mathematically, the sensitivity figure can be expressed as follows:

$$\text{Sensitivity Figure} = \frac{\text{Percentage change in output paramater}}{\text{Percentage change in input paramater}} \tag{12}$$

The sensitivity analysis provides the information to the modeler that the system for which they want to design which parameters are critical ones followed by the other parameters [47,48]; this is the reason being involved with the sensitivity analysis, which provides it to the wide scope where the input and output variables involved. The sensitivity analysis results are very much appreciated; mathematically, it is defined as the ratio of change in output variables to change in input variables. Many sensitivity methods are available, and one of them is chosen for the present study because of its simplicity, most being used, and appreciable results. The selected sensitivity methods involve the effect on output parameters by changing the input variables/factors one at a time (OAT), while all the input variables are kept constant. This process of changing input variables is repeated while keeping other constants until all the input variables/factors are being completed. Fig. 3 shows the schematic representation of the sensitivity analysis for the present study, which includes the different input and output parameters. Many input variables are there out of which affect some input variables viz. wind velocity, ambient temperature, and solar flux intensity have not been considered in this sensitivity analysis because these are the variables that are highly dependent on the weather conditions. The effect of other input variables have been studied and being computed, and plot have been made for the corresponding input and output parameters.

5. Methodology

The sensitivity analysis has been done through a standard step-to-step methodology for the projected distillation system having N-identical evacuated collectors which are coupled in series and integrated with the single slope solar distillation unit.

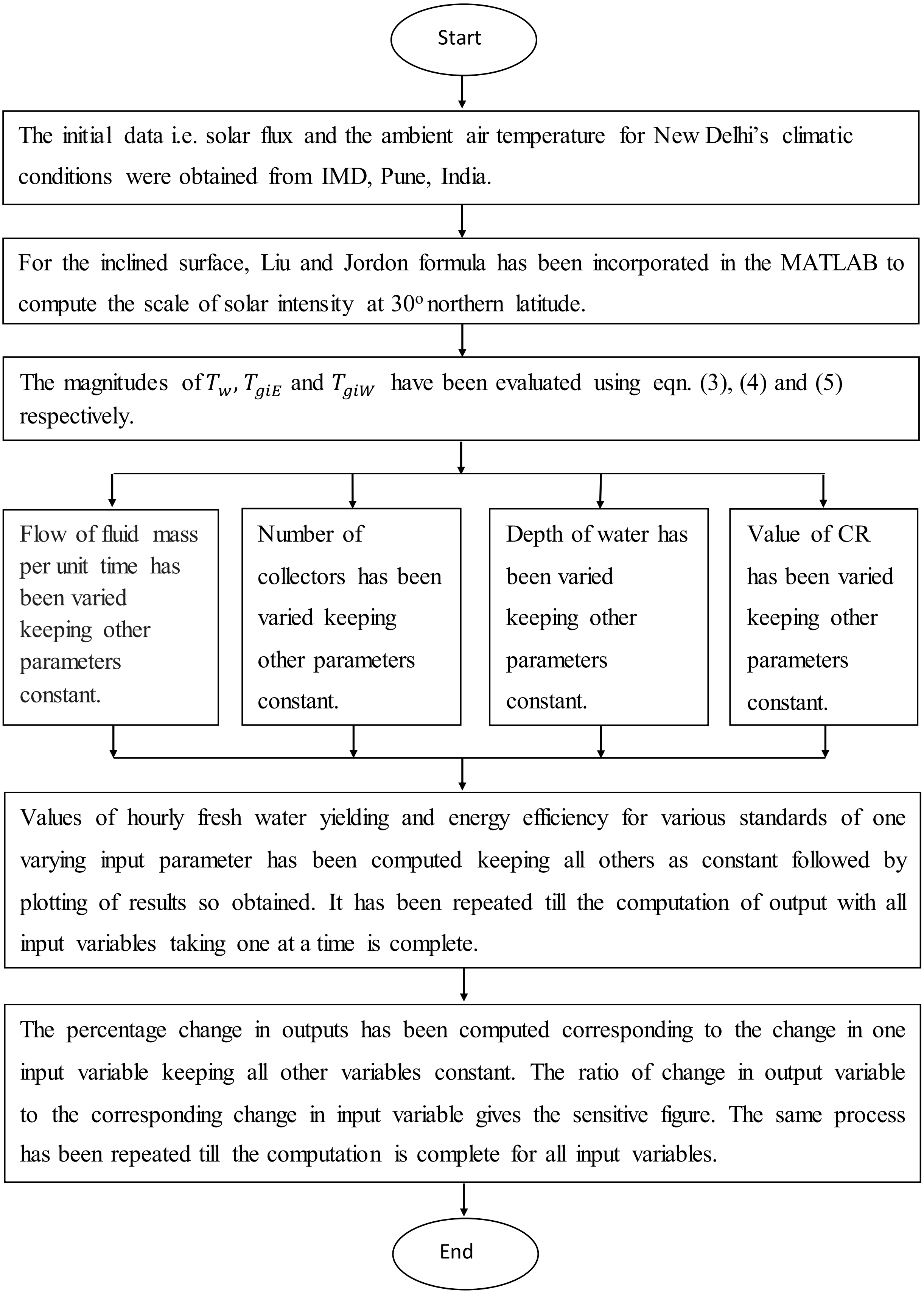
- *Step-I*: Data like ambient air temperature and available solar irradiance have been taken from the Indian Metrological Department, Pune, India for the ambient conditions of New Delhi. Also, Liu and Jordan relation has been used in the MATLAB-2015a to estimate solar intensity values at 30° northern latitudes for the inclined surface.
- *Step-II*: Primarily, values of T_w, T_{giE}, and T_{giW} have been estimated using Eqs. (3)–(5) in that order. Thereafter, the amount of hourly fresh water yielding has been estimated using Eq. (6) followed by the estimation of hourly exergy gain using Eq. (11). The summation of hourly values results in daily values of fresh water yielding.
- *Step-III*: Values of fresh water yielding as well as exergy gain has been estimated for the dissimilarity in one parameter at the input of the system while all other parameters at the input of the system are maintained constant.
- *Step-IV*: Then, repetition of Step-III has been done for all the considered input parameters. Each parameter has to be varied one at a time by keeping others constant excluding solar irradiance and ambient air temperature.
- *Step-V*: Then, the corresponding percentage change on output has to be computed for each input variable by keeping others constant. In this way, sensitivity figure for each variable can be obtained by the ratio of change in output to the corresponding change in the input variable.
- *Step-VI*: Step V has been reiterated until the computation is not over for all the input variables. Hereafter, the obtained results have been plotted on graphs.

The adopted methodology of sensitivity analysis can be better understood by the depicted flow chart in Fig. 4.

6. Results and discussion

All the relevant parameters at the input of active type solar still have been fed to the computer code written in MATLAB-2015a for performing sensitivity investigation of the system. Values of solar radiation and the surrounding temperature have been revealed as Fig. 5. They have been taken from IMD at Pune situated in India. The output received from the computer code has been revealed as Figs. 6–12. The sensitivity investigation in the present research work has been performed using OAT method of sensitivity analysis.

The dissimilarity in fresh water yielding as well as energy efficiency with mass flow rate for NCPCETCDS maintaining other input parameters as constant has been revealed as Fig. 6. It is observed from Fig. 6 that the value of daily fresh water yielding as well as energy efficiency diminishes with the rise in value of mass flow rate due to improved quantity of water per unit time flowing through tubes of collector and hence the diminished increase in temperature is observed at the outlet of Nth collector. It occurs because diminished energy absorption time is available for water flowing through tubes at increased mass flow rate. It is also observed from Fig. 6 that the value of fresh water yielding as well as energy efficiency becomes almost constant beyond a certain value of mass flow rate and steady-state is said to be achieved. At such state, heat absorption rate of water is approximately same as heat gained by the absorber plate. Here, one should note that increased value of mass flow rate adversely affects fresh water yielding and energy efficiency from the system.



The initial data i.e. solar flux and the ambient air temperature for New Delhi's climatic conditions were obtained from IMD, Pune, India.

For the inclined surface, Liu and Jordon formula has been incorporated in the MATLAB to compute the scale of solar intensity at 30° northern latitude.

The magnitudes of T_w, T_{giE} and T_{giW} have been evaluated using eqn. (3), (4) and (5) respectively.

Flow of fluid mass per unit time has been varied keeping other parameters constant.

Number of collectors has been varied keeping other parameters constant.

Depth of water has been varied keeping other parameters constant.

Value of CR has been varied keeping other parameters constant.

Values of hourly fresh water yielding and energy efficiency for various standards of one varying input parameter has been computed keeping all others as constant followed by plotting of results so obtained. It has been repeated till the computation of output with all input variables taking one at a time is complete.

The percentage change in outputs has been computed corresponding to the change in one input variable keeping all other variables constant. The ratio of change in output variable to the corresponding change in input variable gives the sensitive figure. The same process has been repeated till the computation is complete for all input variables.

Fig. 4. Flow chart of the methodology for carrying out sensitivity analysis for ETCs integrated single slope solar desalination system.

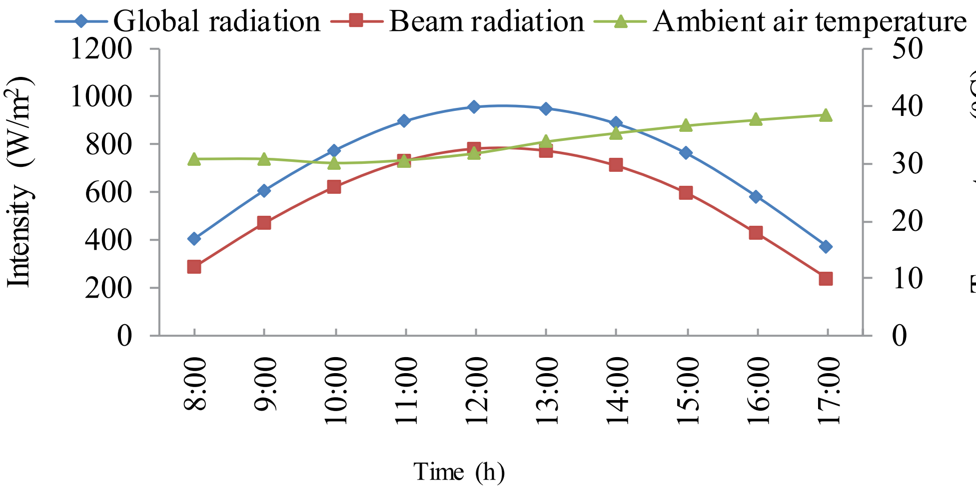


Fig. 5. Hourly variation of intensity and ambient air temperature for a typical day in the month of May.

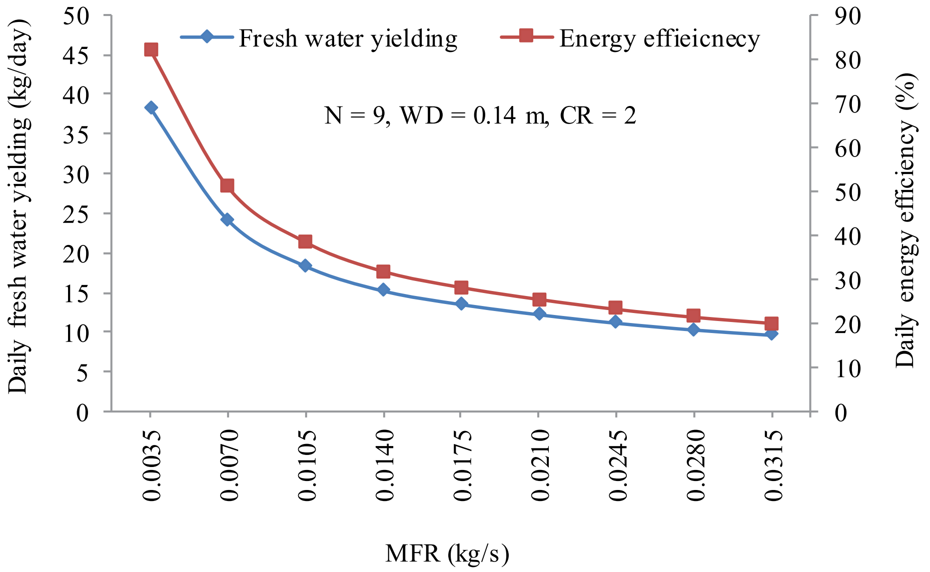


Fig. 6. Dissimilarity of daily fresh water yielding and daily energy efficiency with MFR at selected values of N, CR, and WD for NCPCETCDS.

The dissimilarity of percentage change in fresh water yielding as well as energy efficiency with the percentage change in mass flow rate maintaining other input parameters as constant for NCPCETCDS has been revealed as Fig. 7. The sensitivity figure of fresh water yielding and energy efficiency with regard to mass flow rate can be obtained as slope of the curves shown in Fig. 7. It is clear from Fig. 7 that the sensitivity in fresh water yielding and energy efficiency is higher at diminished values of mass flow rate and it tends to diminish at enhanced values of mass flow rate. It has been found to occur because of the fact that the percentage change in heat gain by N number of series-connected collectors corresponding to the percentage change in mass flow rate at its diminished values is higher which further happens due to higher change in temperature.

The dissimilarity in fresh water yielding as well as energy efficiency with N for NCPCETCDS maintaining other input parameters as constant has been revealed as Fig. 8. It is clear from Fig. 8, that the value of fresh water yielding as well as energy efficiency enhances with the enhanced value of N. It has been found to occur because of the fact that heat added to the water kept in basin also increases and with the increase in heat added to the water, the evaporation of water also increases, therefore with increase in the value of N, higher magnitudes of fresh water yielding is obtained. Due to the higher value of fresh water yielding, energy output is higher and hence energy efficiency is higher at the enhanced value of N.

The dissimilarity of percentage change in fresh water yielding as well as energy efficiency with the percentage change in N maintaining other input parameters as constant for NCPCETCDS has been revealed as Fig. 9. The sensitivity figure of fresh water yielding and energy efficiency with regard to N can be obtained as slope of the

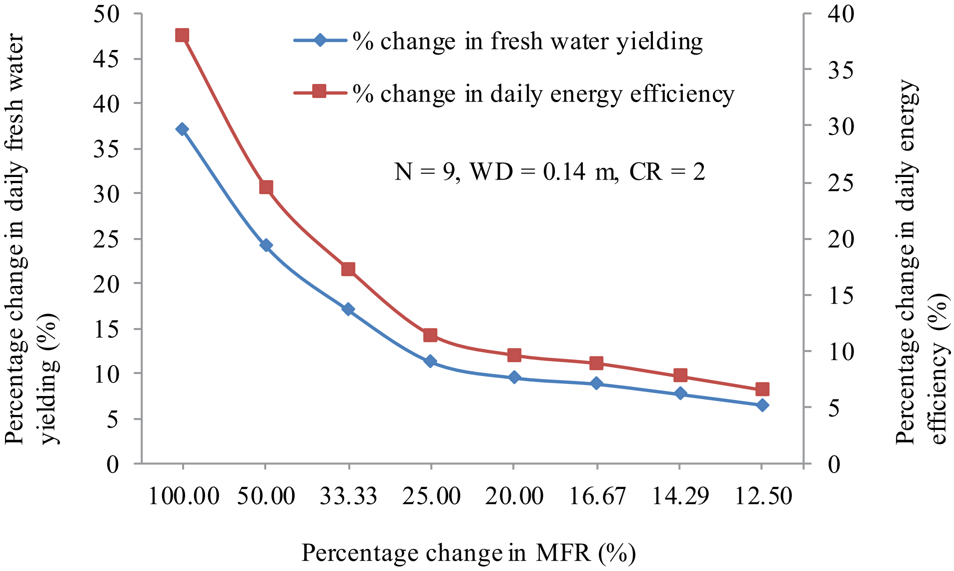


Fig. 7. Sensitivity of daily fresh water yielding and daily energy efficiency with regard to MFR at selected values of N, CR, and WD for NCPCETCDS.

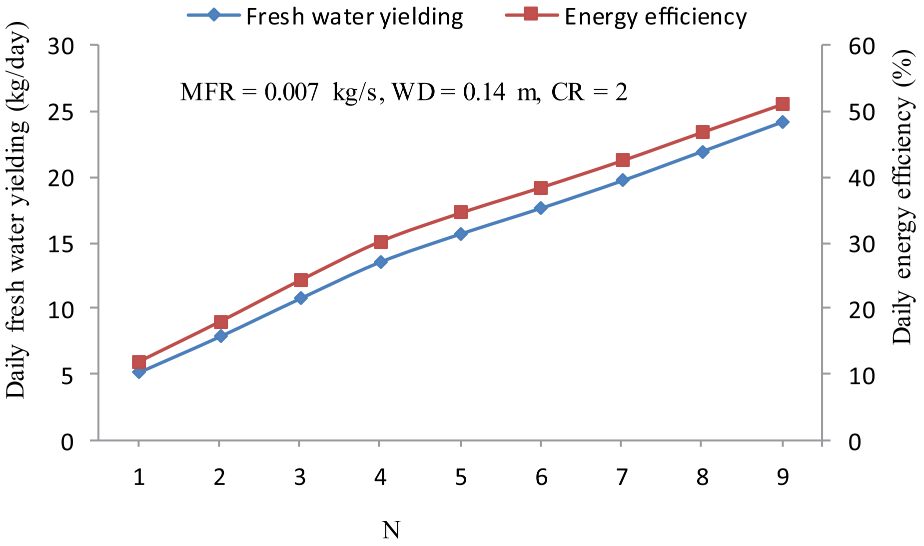


Fig. 8. Dissimilarity of daily fresh water yielding and daily energy efficiency with N at selected values of MFR, CR, and WD for NCPCETCDS.

curve shown in Fig. 9. It is clear from Fig. 9 that the sensitivity in fresh water yielding and energy efficiency is higher at diminished values of N and then the sensitivity tends to decrease at higher values of N. It has been found to happen due to the temperature difference between blackened surface of CPCETC and water flowing below the blackened surface is more at lower value of N and vice-versa. The area of each collector used for collecting heat is identical. It means the temperature of blackened surface of CPCETC is same for each CPCETC. However, the water/fluid coming from the basin and entering to inlet of collector will be having lower temperature at lower value of N. It results in the flowing of fluid at lower temperature below the blackened surface which further results in increased temperature difference between temperature of blackened surface and temperature of fluid which is responsible for increased heat transfer rate and ultimately amount of heat added is higher at lower values of N. Therefore, sensitivity in fresh water yielding comes out to be higher at diminished values of N.

The dissimilarity in fresh water yielding as well as energy efficiency with water depth for NCPCETCDS maintaining other input parameters as constant has been revealed as Fig. 10. It has been observed from Fig. 10 that daily fresh water yielding and energy efficiency increases as water depth enhances. It has been found to occur because higher sensible heat is stored by water at increased water depth during daytime as the amount of water is more at

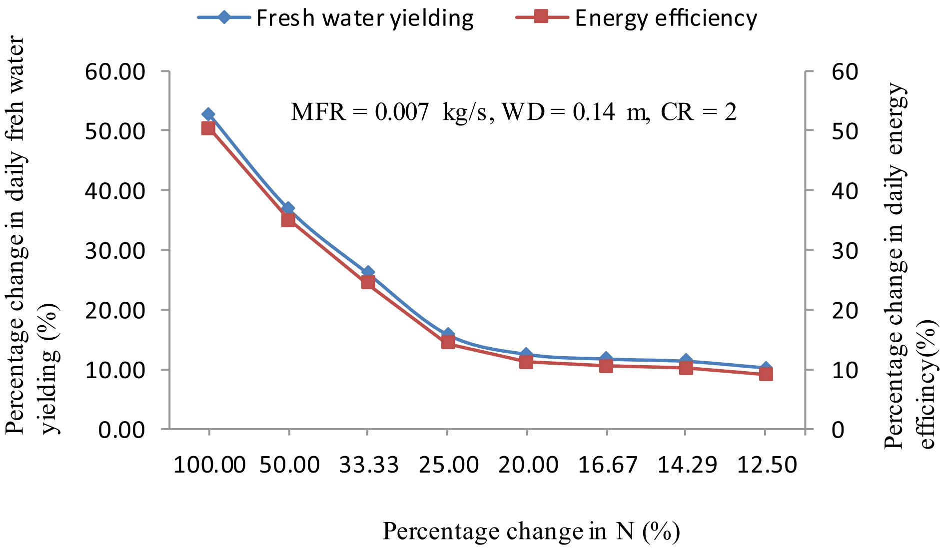


Fig. 9. Sensitivity of daily fresh water yielding and energy efficiency with regard to N at selected values of N, CR, and MFR for NCPCETCDS.

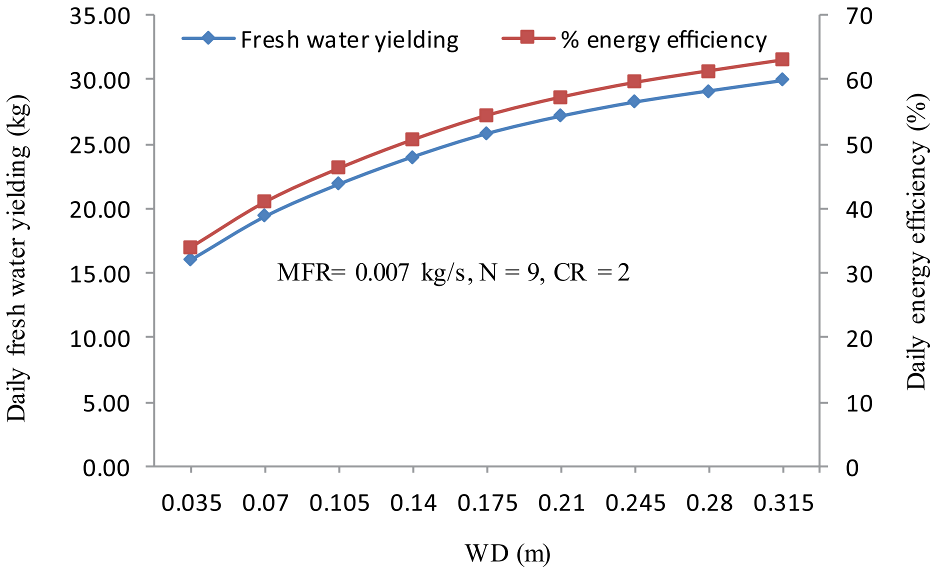


Fig. 10. Dissimilarity of daily fresh water yielding and daily energy efficiency with WD at selected values of N, CR, and MFR for NCPCETCDS.

enhanced water depth. This stored sensible heat is utilized during nighttime in the form of evaporation. With increased water depth, higher amount of sensible heat is stored during daytime and this higher amount of stored sensible heat is released during off sunshine hours for the same amount of heat added. Hence, daily fresh water yielding increases with the increase in the value of WD which further results in increased energy output and hence increased energy efficiency.

The dissimilarity of percentage change in fresh water yielding as well as energy efficiency with the percentage change in water depth maintaining other input parameters as constant for NCPCETCDS has been revealed as Fig. 11. The sensitivity figure of fresh water yielding and energy efficiency with respect to water depth can be obtained as the slope of the curves shown in Fig. 11. It is clear from Fig. 11 that the sensitivity in daily fresh water yielding and energy efficiency is higher at lower values of water depth and the sensitivity tends to decrease at higher values of water depth in basin. It has been found to occur due to higher rise in temperature of water in basin at lower water depth as water mass in the basin is lesser. Hence, a higher evaporation rate which results in a higher change in fresh water yielding as well as energy efficiency.

The dissimilarity in fresh water yielding as well as energy efficiency with concentration ratio (CR) for NCPCETCDS maintaining other input parameters as constant has been revealed as Fig. 12. It has been observed from Fig. 12 that

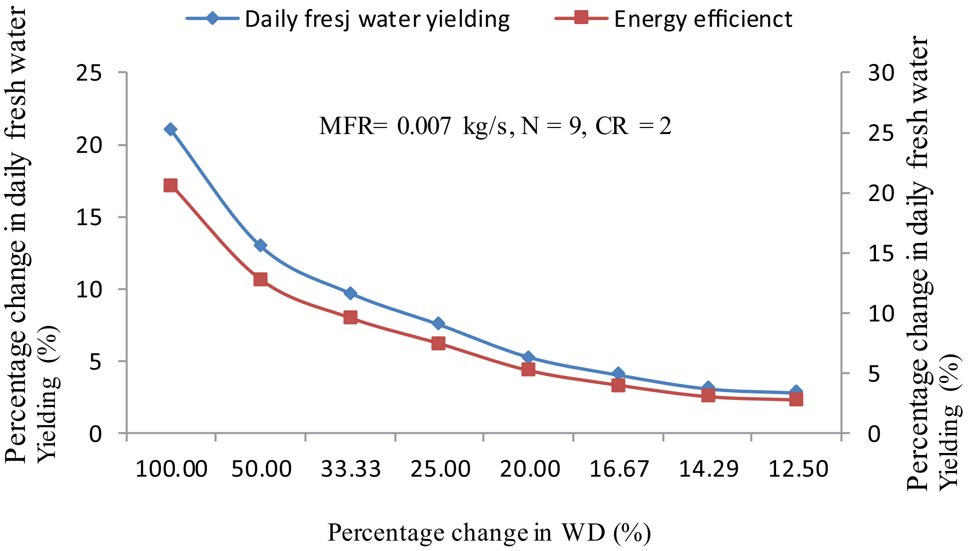


Fig. 11. Sensitivity of daily fresh water yielding and energy efficiency with regard to WD at selected values of N, CR, and MFR for NCPCETCDS.

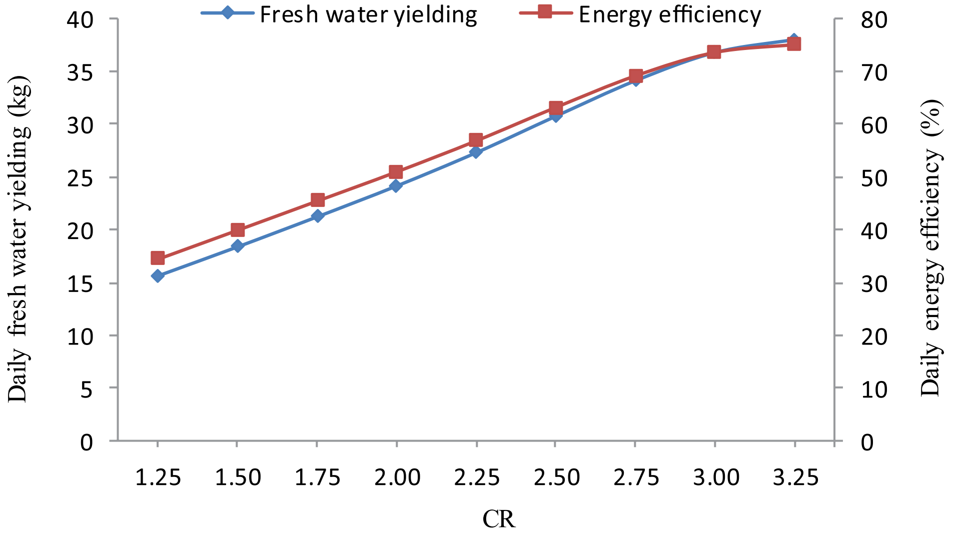


Fig. 12. Dissimilarity of daily fresh water yielding with CR at selected values of N, WD, and MFR for NCPCETCDS.

daily fresh water yielding as well as energy efficiency enhances as CR enhances. It has been found to occur because heat gain by collectors increases as the collection area of collector increases with the increase in the value of CR. The dissimilarity of percentage change in fresh water yielding as well as energy efficiency with the percentage change in CR maintaining other input parameters as constant for NCPCETCDS has been revealed as Fig. 13. It is clear from Fig. 13 that decrease in percentage change is higher for higher percentage change in CR at lower values of CR.

A comparison among mean values of sensitivity figures of daily fresh water yielding and energy efficiency with regard to parameters at the input of system for NCPCETCDS has been revealed as Fig. 14. It is clear from Fig. 14 that the mean sensitivity figure of fresh water yielding for NCPCETCDS has been found to be highest with regards to CR with mean sensitivity figure as 0.91 followed by N, MFRm, and WD with mean sensitivity figures values as 0.70, 0.48, and 0.24, respectively. Further, mean sensitivity figure of energy efficiency for NCPCETCDS has been found to be highest with regards to CR with a mean sensitivity figure as 0.79 followed by N, MFR, and WD with mean sensitivity figures values as 0.73, 0.50, and 0.25, respectively. It means that the designer has to give priority to CR while designing and installing such systems followed by N, MFR, and WD. Limits of input parameters that affect the output of NCPCETCDS have been revealed as Table 2. As per the discussion, the recommended values of MFR and WD are, respectively, 0.007 kg/s and 9 as the temperature of water becomes higher than 100°C if value of N is higher than 9 at 0.007 kg/s MFR and vice versa. Higher values of water depth as well as CR are recommended. However, one should

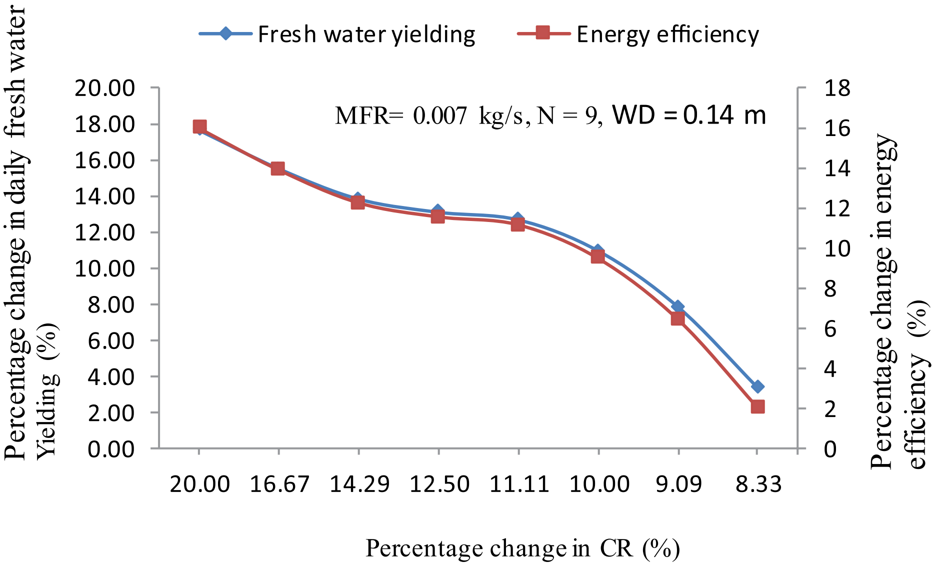


Fig. 13. Sensitivity of daily fresh water yielding and energy efficiency with regard to CR at selected values of N, WD, and MFR for NCPCETCDS.

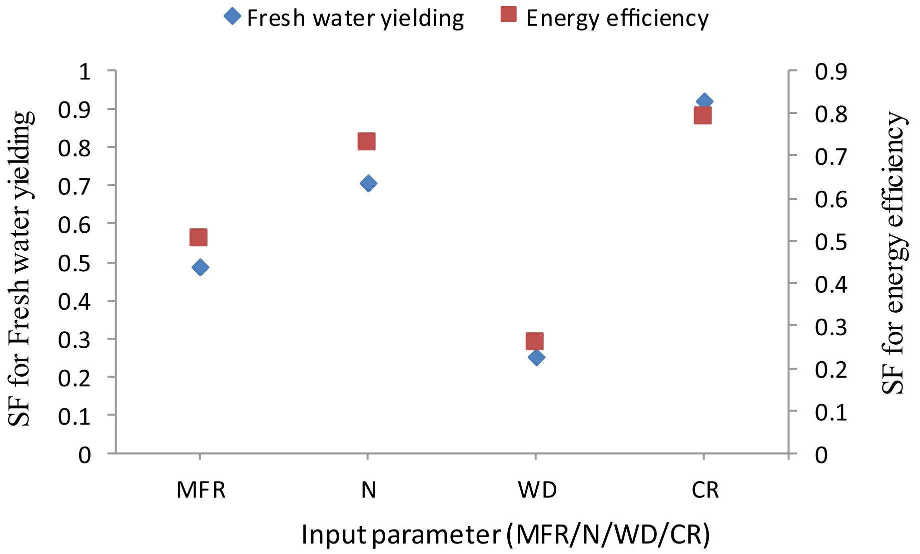


Fig. 14. Comparative sensitivity figure (SF) of fresh water yielding as well as energy efficiency with respect to input parameter (MFR/N/WD/CR) for NCPCETCDS.

keep in mind that higher values of CR will need a tracking system for better available solar energy utilization.

7. Conclusions

The sensitivity investigation of solar still of double slope type included with N similar compound parabolic concentrators integrated ETCs having series connection has been studied by incorporating fresh water yielding as well as energy efficiency. Based on research outcomes, the subsequent conclusions have been transcribed as:

- Values of fresh water yielding and energy efficiency from the system have been found to diminish by increasing mass flow rate for a constant water depth, CR, and N. However, the increase in the number of N leads to raising the values of fresh water yielding as well as energy efficiency maintaining other parameters at input of the system as constant. However, the temperature of fluid/water should be less than its boiling point while deciding the value of N during design and installation phases.
- The fresh water yielding on an hourly basis and daily energy efficiency have been found to increase with the rise in water depth maintaining all other parameters at the input of system constant. Hence, a higher value of water depth should be adopted.
- The fresh water yielding on an hourly basis and daily exergy gain have been found to enhance with rise in

Table 2
Limits of input parameters that affect the output of double slope solar still included with N identical compound parabolic concentrators integrated evacuated tubular collectors (NCPCETCDS)

Variable	Range	Remarks
Number of collectors (N)	1–9	Value of fresh water yielding has been found increasing as the value of N is enhanced. However, increase in N results in the enhancements of both initial investments as well as water temperature. Hence, it is recommended to keep in mind the boiling point of water and initial investment while deciding the value of N. Temperature of water should be less than its boiling point. Also, the revenue obtained by selling fresh water yielding should justify the initial investment.
Mass flow rate (MFR)	0.007–0.008 kg/s	The value of fresh water yielding as well as exergy has been found to diminish with the enhancement in the value of MFR. Also, one need to keep in mind that water temperature in the basin should not go beyond its boiling point. The recommended value of MFR is 0.007 kg/s.
Depth of water in the basin (WD)	0.035–0.315 m	Value fresh water yielding gets enhanced with the enhancement in the value of water depth. Value of fresh water yielding increases due to the utilization of sensible heat at night which is collected during the sunshine hours. Hence, higher values of depth of water are recommended.
Concentration ratio (CR)	1.25–3	The value of fresh water yielding increases as the value of CR increases due to higher gain of collector at enhanced values of CR because of higher solar energy concentration to receiving surface of the collector. So, a higher value of CR is recommended for the summer season. However, tracking will be required for getting full utilization of available solar energy if higher values of CR are selected.

CR value keeping all other parameters at the input of the system constant. Hence, higher values of collector inclination should be preferred. However, one should keep in mind that higher values of CR require a tracking mechanism for better utilization of available solar energy.

- The sensitivity investigation of NCPCETCDS indicates that the fresh water yielding as well as energy efficiency is most sensitive with regard to CR followed by N, mass flow rate, and water depth.
- The mean sensitivity figure values of fresh water yielding and energy efficiency for NCPCETCDS come out to be 0.91 and 0.79 with regard to CR; 0.70 and 0.72 with regard to N; 0.48 and 0.50 with regard to MFR; 0.24 and 0.25 with regard to WD, respectively.

8. Recommendations

The results of this sensitivity analysis can be used by designers of solar still of double slope type included with N similar CPC integrated ETC for selecting the input parameters as per the need of customer while installing the system for applications like distillation. After selecting input parameters based on the importance of each parameter, one can proceed for the value of that parameter as per the need. The analysis has been done for the location of New Delhi, a similar analysis can be performed for different locations and weather conditions. The authors plan to extend this research to include geographic and weather variations in future research.

Symbols

A_b — Area of basin, m^2
A_g — Area of glass cover, m^2
C — Specific heat capacity, J/kg-K
CPC — Compound parabolic concentrator
CR — Concentration ratio
DS — Double slope solar still
F' — Collector efficiency factor, dimensionless
ETC — Evacuated tubular collector
HTC — Heat transfer coefficient
h_{cwg} — Convective HTC from water to the inner surface of the glass cover, W/m^2-K
h_{ewg} — Evaporative HTC from water surface to the inner surface of the glass cover, W/m^2-K
h_{ba} — HTC from blackened surface to water mass, W/m^2-K
h_{bw} — HTC from blackened surface to water mass, W/m^2-K
h_{rwg} — Radiative HTC from water surface to the inner surface of the glass cover, W/m^2-K
h_r — Radiative HTC, W/m^2-K
h_{1w} — Total HTC from water surface to inner surface of glass cover, W/m^2-K
h_{1g} — Total HTC from outer surface of glass cover facing to ambient, W/m^2-K
$I(t)$ — Solar intensity on collector, W/m^2
$I_S(t)$ — Solar intensity on glass cover of solar still, W/m^2
K — Thermal conductivity, W/m-K
L_g — Thickness of glass, m
L — Latent heat, J/kg
L' — Length, m
MFR/$\dot{m}_f$ — Mass flow rate of fuid/water, kg/s
$\dot{m}_{ew}$ — Mass of distillate per hour from NCPCETCDS, kg

N — Number of collectors
NCPCETCDS — Solar still of DS type included with N similar CPCETCs having series connection
PF_c — Penalty factor due to the glass covers for the glazed portion
PF_1 — Penalty factor first, dimensionless
PF_2 — Penalty factor second, dimensionless
PW — Potable water
SA — Sensitivity analysis
SF — Sensitivity figure
SEBWP — Solar energy based water purifier
T_{foN} — Outlet water temperature at the end of Nth water collector, °C
T_a — Ambient air temperature, °C
T_{gi} — Glass temperature at inner surface of glass cover, °C
t — Time, h
T_{wo} — Water temperature at $t = 0$, °C
T_w — Water temperature, °C
U_L — Overall heat transfer coefficient, $\text{W/m}^2\text{-K}$
V — Velocity of air, m/s
WD — Water depth

Subscript

eff — Effective
ex — Exergy
f — Fluid
g — Glass
in — Incoming
out — Outgoing
w — Water

Greek letters

α — Absorptivity (fraction)
η — Efficiency, %
$(\alpha\tau)_{\text{eff}}$ — Product of effective absorptivity and transmittivity
σ — Stefan–Boltzmann constant, $\text{W/m}^2\text{-K}^4$
τ — Transmittivity

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