RESEARCH ARTICLE

Exergo-enviro-economic and yearly productivity analyses of conical passive solar still for sustainable solar distillation

Gajendra Singh[1] · Pawan Kumar Singh[1] · Abhishek Saxena[2] · Ritvik Dobriyal[3] · Navneet Kumar[4] ·
Desh Bandhu Singh[3]

Abstract

This paper focuses on exergo-enviro-economic and yearly productivity analyses for conical passive solar still having the potential to fulfil the sustainable development goal of the United Nations. A new approach for thermal modelling of conical passive solar still has been carried out with experimental validation in the present work, wherein different weather conditions have been considered for the analysis of the proposed system. The carried out work has been done for each month of the year. In further methodology, the computational code in MATLAB has been used for the computation of hourly freshwater production, exergy, and energy followed by the estimation of their annual values. Thereafter, exergo-enviro-economic parameters, yearly productivity, payback period, and freshwater cost have been estimated, and the obtained results have been compared with the earlier published research. Concludingly, the exergo-economic parameter, enviro-economic parameter, and yearly productivity for the proposed system have been found higher by 44.25%, 25.68%, and 44.07%, respectively, than the conventional solar still. The comparative freshwater cost is 13.56% less than the conventional solar still for 0.025 m water depth. Additionally, the payback period for the proposed system will remain at 2.75 years, which is 13.82% less in comparison to the conventional solar still considering a 2% interest rate.

Keywords Exergo-enviro-economic parameters · Productivity · Cost of freshwater · Conical solar still · Payback period

Introduction

The design and analysis of solar still are the demand of time as there is scarcity of freshwater worldwide particularly in underdeveloped and developing nations. The conical passive solar still (CPSS) is self-subsistent which makes it installable even in inaccessible locations where sunlight is present in abundance. It has good potential to mitigate the contemporary issue of water shortage worldwide which will ultimately help in the realisation of the sustainable development goal of the United Nations. Due to industrial growth and poor waste management of the waste from different sources, the water is getting polluted at a very fast rate. Also, the RO system available for purifying water requires electrical power for its functioning, and a large population is not able to access the electrical power due to poor electrification speed. So, solar

✉ Desh Bandhu Singh
deshbandhusingh.me@geu.ac.in

Gajendra Singh
gajendra.18dp000382@mech.iitism.ac.in

Pawan Kumar Singh
pawan@iitism.ac.in

Abhishek Saxena
abhishek_me@dbuu.ac.in; culturebeat94@yahoo.com

Ritvik Dobriyal
ritvikdobriyal@geu.ac.in

Navneet Kumar
navneet.kumar@galgotiacollege.edu;
navneet_mech48@yahoo.com

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

[2] Department of Mechanical Engineering, School of Engineering, Dev Bhoomi Uttarakhand University, Dehradun, India

[3] Department of Mechanical Engineering, Graphic Era Deemed to Be University, Bell Road, Clement Town, Dehradun, Uttarakhand 248002, India

[4] Galgotias College of Engineering and Technology, Greater Noida, UP, India

still will prove itself a boon for such type of population. Solar still uses simple technology, it is environment friendly as it does not emit any pollutants, an unskilled person can easily maintain it, and most importantly, it can be fabricated using locally available materials. The solar still is a box-type structure that solely works on solar energy and produces distilled water which can be consumed either as it is or after adding some minerals to overcome the deficiencies of water-based minerals. Solar still makes use of the principle of the greenhouse effect for the freshwater production.

Exergy signifies the quality of energy, and it can be fully utilised because of being high-grade energy. For example, electrical energy can be fully converted into heat. Exergy is the maximum amount of work that can be attained while carrying the system at a particular temperature to a state that is in equilibrium with the surrounding. Exergy can be estimated using either Carnot's efficiency or the entropy concept (Pathak et al. 2023). The objective of exergy analysis is to locate exergy loss in different elements of the system and focus on the element with the highest exergy loss so that exergy loss can be minimised resulting in the improvement in the output of the system. When economic analysis is combined with exergy analysis, exergo-economic analysis comes into the picture. The exergo-economic analysis aims to estimate the exergo-economic parameter which can be defined as the ratio of either exergy loss or exergy gain to uniform end-of-year annual cost (UEC). In the case of exergy loss, the objective is of minimisation type and vice versa. For comparative analysis of solar systems, one can consider exergo-economic parameter as the ratio of exergy output to UEC (Singh and Tiwari 2017) and the objective function will be maximisation type.

In the contemporary situation, enviro-economic analysis is relevant because people are trying to minimise pollution worldwide. In this context, green technology can play a major role as the conventional system which uses conventional sources of energy can be replaced by a system that uses renewable energy. Solar energy–based systems can be made competitive by creating cheaper technology by focusing on research in the area of solar energy. Due to the limited resource of conventional sources of energy, people are trying to develop efficient solar energy systems worldwide so that the future can be made better by fulfilling the energy demand from renewable sources. Recently, Indian Oil Corporation Limited has developed a solar cooker that can be kept in the kitchen for use which will prove a boon for the hilly area where electricity and cooking gas are scarce (Kumar et al. 2023).

The study of PSSs from exergo-enviro-economic viewpoint is very limited. Most of the work on PSSs revolves around the analysis considering an energy viewpoint. The contribution made by researchers for PSSs from an energy analysis viewpoint is (a) the effect of inclination on the performance (Aderibigbe 1985), (b) the effect of dye on yield (Rajvanshi and

Hsieh 1979), (c) the effect of charcoal on yield (Akinsete and Duru 1979), (d) the effect of air blow (El-Sebaii 2004), (e) the effect of water mass in basin (Cooper 1969; El-Sebaii 2004), (f) the effect of solar flux (Tiwari and Tiwari 2007), (g) the effect of surrounding temperature (Cooper 1969; Morse and Read 1968), (h) the effect of insulation at the bottom (Nayak et al. 1980), (i) the effect of reflecting surface (Tamini 1987), (j) the effect of regeneration in back wall (Wibulswas and Tadtium 1984), and (k) the effect of use of internal condenser (Ahmed 1988). Furthermore, Singh and Tiwari (1991) studied the effect of flowing water on the transparent condensing cover surface for PSS, and they concluded that the efficiency of PSS having the arrangement of flowing water over the transparent condensing surface was higher in comparison to conventional PSS due to enhancement in temperature difference between water surface and transparent condensing cover surface. Fath and Elsherbiny (1993) made an experimental study on the effect of incorporating condenser with PSS, and they reported that the efficacy of the system was increased by 50% over the conventional solar still due to the increase in evaporation rate. El-Sebaii (2004) investigated the effect of blowing air on the performance of PSS and reported that there was a freshwater production increase as wind blow increased if the water mass was higher than the critical mass in the basin. An experimental study on conical PSS was done by Gad et al. (2015), and they reported an improvement in the freshwater yield by 42.90% over conventional solar still due to a reduction in shading. Moreover, some significant contributions have also been made by different researchers worldwide in PSS considering the viewpoint of the 2nd law of thermodynamics which has been summarised in the next paragraph.

Dincer (2002) stated about the relation that exists between energy and exergy. Hepbalsi (2007) made use of exergetic analysis comprehensively for designing, simulating, and forecasting of performance of energy systems. Torchia-Núñez et al. (2008) executed an analytical analysis on exergy of PSS, and it was concluded that the irreversibility produced was highest during the interaction between the sun and the receiver surface. Furthermore, Vaithilingam and Esakkimuthu (2015) carried out the energy and exergy analyses of PSS and verified the previous outcomes of Torchia-Núñez et al. (2008). Dwivedi (2009) investigated PSS from energy and exergy viewpoints and reported better performance of double slope passive solar still (DPS) than single slope passive solar still (SPS) based on thermal efficiency when the area of DPS and SPS was considered 2 m^2 and 1 m^2, respectively. Singh et al. (2011) analysed different PSSs from an exergy viewpoint and reported that the SPS registered better performance than DPS. Zeroual et al. (2011) and Rajamanickam and Ragupathy (2012) studied DPS having condenser and stated an enhancement in freshwater yielding as 11.82%. Muftah et al. (2014) reported a comprehensive review of solar still till 2012, and they reported that the freshwater yielding was affected by climatic, operational,

and design parameters. Atheaya and Atheaya (2017) reviewed the solar energy systems from environmental sustainability point of view and reported that the use of solar energy for thermal and electrical energies applications would lead to the protection of the environment and ultimately support the sustainable development goals. Mohsenzadeh et al. (2021) and Chaurasiya et al. (2022) reviewed PSSs comprehensively and reported the effect of different designs of components on the performance and focused on various techniques for improving the performance of PSS. Sharma et al. (2022) experimented with a hybrid solar drying system, wherein the exergy efficacy for tomato drying was 46%. In conclusion, they reported that the drying system would provide a competitive option to users for drying food in less time.

Gupta et al. (2019) experimented a solar desalting unit by incorporating cleaning mechanism of photovoltaic and concluded that the efficiency of photovoltaic was improved by 1.34% when cleaning was done. Parsa et al. (2021) studied the effect of height on the performance of solar still and concluded that the solar still performed better at a higher height due to low pressure. Essa et al. (2021) did a parametric study of PSS composed of the evacuated tubular collector with the validation of a thermal model having a maximum error of 8.6%, and it was concluded that condensate enhanced with the enhancement in ambient temperature as well as solar intensity probably due to increase in water temperature. Ho et al. (2022) studied PSS with a Fresnel lens by incorporating phase change material and concluded that the efficiency was improved by 60% over the conventional solar still due to the concentration of solar energy. Abimbola et al. (2022) studied multi-mode PSS and reported a maximum daily yield of 5.78 kg/m^2.

Rashidi et al. (2020) presented a review of the various solar thermal systems including solar still from the entropy generation viewpoint, and it was concluded that the entropy generation minimisation concept is a very efficient tool for the optimisation of the solar energy systems. El-Sebaii and Khallaf (2020) reported the thermal modelling of pyramid solar still with the experimental validation, and they reported that the daily freshwater output of solar still varied between 4.22 and 4.43 kg/m^2. Balachandran et al. (2020) investigated the improvement in freshwater production in SPS by allowing water film cooling, and they reported an improvement of 31% in freshwater over conventional solar still due to increased temperature difference between condensing cover and water temperatures. Suraparaju et al. (2021) studied SPS by incorporating pond fibres and concluded that the improvement in freshwater production was 29.67% over conventional SPS due to the increase in evaporation area. A detailed review of passive tubular solar still was reported by Akkala and Kaviti (2022), and they concluded that the polythene film is an excellent cover material for tubular PSS.

Vigneswaran et al. (2023) experimented with a single slope passive solar desalting unit by incorporating a water jacket on side walls and concluded that the freshwater production improved by 30.15% as compared to the conventional solar desalting unit due to the increase in the condensing surface area in the case of the solar desalting unit with water jacket. Nicholas and Mabbett (2023) experimented with the single slope passive solar desalting unit for drying the dairy manure and used the distillate so obtained for irrigation. They concluded that the moisture content of dairy manure was reduced by 13% and the distillate obtained was fulfilling the guideline for irrigation. Patel et al. (2023) investigated a single slope solar desalting unit by incorporating a thermoelectric cooler and concluded that the maximum freshwater production was 23% more than the conventional solar desalting unit of the same geometrical details. Wang et al. (2023) developed a thermal model for a passive interfacial solar desalting unit and validated the developed thermal model with experimental data. They reported that there was a fair agreement between theoretical and experimental values with an average deviation of 7.84% and 12.40% for convective and diffusion mass transfers, respectively. Kabeel et al. (2023) experimented with hemispherical solar still by incorporating energy storage–corrugated absorbers for improving the production of freshwater and concluded that the freshwater production increased by 74% as compared to conventional hemispherical solar still. Hammoodi et al. (2023) experimented with pyramid solar still by incorporating wick materials for the climatic condition of Iraq and concluded that the freshwater production was increased by 136.6% as compared to conventional pyramid solar still. Atteya and Abbas (2023) experimented with stepped solar still by incorporating sand beds, cooling coils, and reflectors. They concluded that the freshwater production of stepped solar still with the black sand bed increased by 92% more than the conventional stepped solar still. Verma and Das (2023) optimised the thickness of water in the basin for a heat exchanger–assisted solar desalting unit and suggested the thickness of water mass in such a system to be designed at an optimum value for getting the best results.

Aboulfotoh et al. (2023) investigated the effect of salinity, water depth, and cover angle for the climatic condition of Iraq and concluded that freshwater production was improved with the decrease in salinity and water depth. Vellivel et al. (2023) experimented with the effect of water depth on energy, exergy, and efficiency of the solar desalting unit by incorporating black-painted wick material. They concluded that the exergy loss was minimal at a water depth of 2 cm. Hilarydoss (2023) studied inclined multi-effect vertical diffusion solar desalting unit by incorporating reflectors and concluded that the average freshwater production was 62% higher than the conventional solar desalting unit. Silva et al. (2023) experimented with double slope solar desalting unit and pyramid solar desalting unit for the climatic condition of Brazil and concluded that the freshwater production of the pyramid solar desalting unit was 7.13% higher than the double slope solar desalting unit of equal basin areas due to higher amount of solar energy in the case of pyramid-type set-up.

From the literature survey, it is clear that the development of a thermal model of CPSS followed by its exergo-enviro-economic analysis, annual productivity analysis, and payback period analysis has not been reported to date. Hence, this research work focuses on the development of a new approach for the thermal model of CPSS, wherein the conical condensing surface has been divided into four equal parts oriented towards four directions, viz. east, west, south, and north. The concept of thermodynamics has been used for writing equations based on making input energy equal to output energy for different components of the system followed by the simplification of equations so obtained to get the expression for different unknown parameters in terms of known parameters. An exhaustive study has been carried out considering all four types of climates of New Delhi for different months of the year. The work reported here is different from the work of Gad et al. (2015) in the sense that Gad et al. (2015) did an experimental study for a typical day for yield estimation, whereas this paper discusses the development of a new thermal model followed by exergo-enviro-economic analysis, annual productivity analysis, payback period estimation, and evaluation of production cost of freshwater. The analysis reported in this research work considers data for the entire year, whereas Gad et al. (2015) collected experimental data for daytime only for a typical day. Furthermore, the results of CPSS obtained in the current study have been compared with earlier research reported in the literature. The main objectives of the current research work can be stated as follows:

i. Development of a new thermal model for CPSS followed by the estimation of annual energy as well exergy for CPSS using computational code in MATLAB

ii. Evaluation of exergo-enviro-economic parameters, payback period, cost of freshwater, and annual productivity for CPSS

iii. Comparison of results of CPSS with earlier published results

The consequences of this research will be useful as distilled water produced by CPSS can be used for batteries, cosmetics, automobile coolants, pharma industry, and drinking (by adding required minerals). One can start a small business of distilled water with the help of such a system. CPSS can also be used for domestic purposes wherein it can be used to purify the harvested rainwater.

System description

The schematic diagram of CPSS (side view) has been shown in Fig. 1a, and its top view has been shown in Fig. 1b. The system specification has been provided in Table 1. Conical passive solar still is different from basin-type solar stills in the sense that the shading effect is less because of the presence of a transparent condensing surface towards all four sides. In the case of basin-type solar stills, the transparent condensing surface faces either one side as in SPS or two sides as in DPS. So, the shading effect is more in SPS and DPS as compared to CPSS. In the case of CPSS, a transparent condensing surface is present on all sides and hence the shading effect is minimised, and better performance is expected. When solar energy reaches to the condensing surface from all sides to the transparent condensing surface, the solar energy gets firstly reflected and secondly absorbed by the transparent condensing surface, and thirdly, the residual amount of solar energy is transmitted to the water surface. The same phenomenon takes place at the water's surface. All solar energy transmitted through water to the blackened surface at the bottom gets ideally absorbed wholly as the surface at the bottom is blackened.

The temperature of the blackened surface rises to a value higher than water temperature. So, the transfer of heat from the blackened surface at a higher temperature to water mass comparatively at a lower temperature occurs. In this way, water collects heat directly from sunlight and indirectly from the basin liner (blackened surface). Due to heat collection by water mass, water temperature upsurges resulting in the development of temperature difference between water mass and transparent condensing surface which compels the evaporation of water. Furthermore, the vapour gets converted into distilled water at the inner side of the transparent condensing surface through film-wise condensation, and the freshwater goes down along the inclined transparent condensing surface through gravity to the conduit fixed at the lower side from where freshwater is taken to the jar through the pipe.

Thermal modelling

Before writing energy balance equations, some assumptions are taken for making the analysis simple. The assumption (Singh et al. 2016a, 2016b) for writing energy balance equations are as follows:

i. The system is in quasi-steady sate condition.
ii. There is no leakage of vapour present in CPSS.
iii. The level of water in the basin has been assumed to be constant.
iv. Heat capacity of materials used in different components is neglected.
v. The condensation takes place as film-type.
vi. The temperature of the inner and outer condensing surfaces is the same.
vii. The interaction between two consecutive condensing surfaces is negligible.

The conical-shaped condensing surface has been divided into four parts facing the four directions, namely, east, west,

Fig. 1 a The schematic diagram of CPSS (side view). **b** Top view of CPSS

a

b
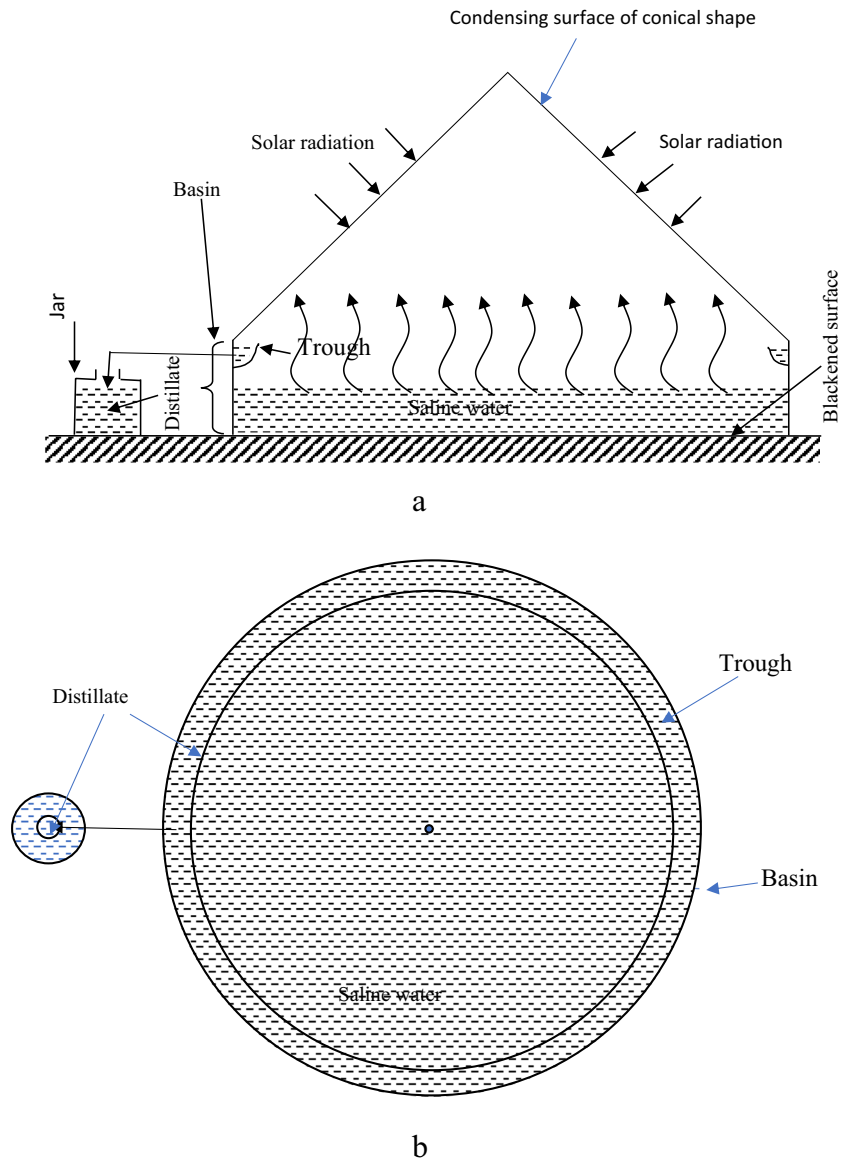
south, and north. So, energy balance equations have been written for all the components, namely, condensing surface (four in number), water mass, and basin liner.

Energy balance equation for east-facing condensing surface

$$\dot{\alpha}_g I_{SE}(t)\frac{A_g}{4} + h_{1wE}(T_w - T_{gE})\frac{A_b}{4} + h_{EW}(T_{gW} - T_{gE})\frac{A_g}{4} = h_{1gE}(T_{gE} - T_a)\frac{A_g}{4} \quad (1)$$

$[\text{Energy absorbed by condensing surface facing east in unit time}]$

$+ [\text{heat transferred from water surface to condensing cover facing east in unit time}]$

$+ [\text{heat interaction between east} - \text{facing and west} - \text{facing condensing surfaces in unit time}]$

$= [\text{heat loss from condensing surface facing east to the surrounding in unit time}]$

Here, h_{1wE} represents the equivalent heat transfer coefficient (EHTC) between water and east-facing glass surfaces, and it can be expressed as

$$h_{1wE} = h_{rwgE} + h_{cwgE} + h_{ewgE} \quad (2)$$

where h_{rwgE}, h_{cwgE}, and h_{ewgE} stand for radiative, convective, and evaporative heat transfer coefficients (HTCs), respectively, and h_{1gE} represents EHTC from east-facing condensing surface to the surrounding.

Table 1 Specifications and design parameters for CPSS (Gad et al. 2015) and mean air velocity

Component	Specification	Component	Specification
Basin area of conical passive solar still	1 m²	α_w	0.02
Shape of the basin	Circular	α_g	0.01
Material of condensing surface	Acrylic	α_b	0.82
Thickness of acrylic condensing surface	0.004 m	ε_w	0.96
Thickness of insulation	5 cm	ε_g	0.88
Material of insulation	Foam	σ	5.67×10^{-8} W/m²-K⁴
Condensing cover angle	30°	Reflectivity of acrylic	0.05
Basin material	Black-painted GI	Reflectivity of water	0.05
Thickness of insulation	0.1 m	Mass of water in the basin	25 kg
Thermal conductivity of insulation	0.166 W/m-K		

Mean air velocity for different months of the year

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Air velocity (m/s)	2.77	3.13	3.46	3.87	4.02	4.11	3.39	2.91	2.85	2.16	1.83	2.40

Energy balance equation for west-facing condensing surface

$$\acute{\alpha}_g I_{SW}(t)\frac{A_g}{4} + h_{1wW}\left(T_w - T_{gW}\right)\frac{A_b}{4} - h_{EW}\left(T_{gW} - T_{gE}\right)\frac{A_g}{4} = h_{1gW}\left(T_{gW} - T_a\right)\frac{A_g}{4} \quad (3)$$

[Energy absorbed by condensing surface facing west in unit time]
+ [heat transferred from water surface to condensing cover facing west in unit time]
− [heat interaction between east − facing and west − facing condensing surfaces in unit time]
= [heat loss from condensing surface facing west to the surrounding in unit time]

Here, h_{1wW} represents the EHTC between water and west-facing glass surface, and it can be expressed as

$$h_{1wW} = h_{rwgW} + h_{cwgW} + h_{ewgW} \quad (4)$$

where h_{rwgW}, h_{cwgW}, and h_{ewgW} stand for radiative, convective, and evaporative HTCs, respectively, and h_{1gW} represents EHTC from west-facing condensing surface to the surrounding.

Energy balance equation for south-facing condensing surface

$$\acute{\alpha}_g I_{SS}(t)\frac{A_g}{4} + h_{1wS}\left(T_w - T_{gS}\right)\frac{A_b}{4} + h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1gS}\left(T_{gS} - T_a\right)\frac{A_g}{4} \quad (5)$$

[Energy absorbed by condensing surface facing south in unit time]
+ [heat transferred from water surface to condensing cover facing south in unit time]
+ [hHeat interaction between south − facing and north − facing condensing surfaces in unit time]
= [heat loss from condensing surface facing south to the surrounding in unit time]

Here, h_{1wS} represents EHTC between water and south-facing glass surface, and it can be expressed as

$$h_{1wS} = h_{rwgS} + h_{cwgS} + h_{ewgS} \quad (6)$$

where h_{rwgS}, h_{cwgS}, and h_{ewgS} stand for radiative, convective, and evaporative HTCs, respectively, and h_{1gS} represents the EHTC from south-facing condensing surface to the surrounding.

Energy balance equation for north-facing condensing surface

$$\acute{\alpha}_g I_{SN}(t)\frac{A_g}{4} + h_{1wN}\left(T_w - T_{gN}\right)\frac{A_b}{4} - h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1g}\left(T_{gN} - T_a\right)\frac{A_g}{4} \quad (7)$$

where $\acute{\alpha}_g = \left(1 - R_g\right)\alpha_g$ represents the fraction of solar flux absorbed by the glass cover.

[Energy absorbed by condensing surface facing north in unit time]

$+$ [heat transferred from water surface to condensing cover facing north in unit time]

$-$ [heat interaction between south $-$ facing and north $-$ facing condensing surfaces in unit time]

$=$ [heat loss from condensing surface facing north to the surrounding in unit time]

Here, h_{1wN} represents EHTC between water and north-facing glass surface, and it can be expressed as

$$h_{1wN} = h_{rwgN} + h_{cwgN} + h_{ewgN} \qquad (8)$$

where h_{rwgN}, h_{cwgN}, and h_{ewgN} stand for radiative, convective, and evaporative HTCs, respectively, and h_{1gN} represents the EHTC from north-facing condensing surface to the surrounding.

Energy balance equation for basin liner (blackened surface)

$$\left[\acute{\alpha}_b \left(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)\right) \frac{A_b}{4} \right] = h_{bw}\left(T_b - T_w\right)A_b + h_{ba}\left(T_b - T_a\right)A_b \qquad (9)$$

[Energy absorbed by basin liner or blackened surface at the bottom in unit time]

$=$ [heat transferred from basin liner to water mass in unit time]

$+$ [heat loss from basin liner to the surrounding in unit time]

where $\acute{\alpha}_b = \left(1-R_g\right)\left(1-\alpha_g\right)\left(1-R_w\right)\left(1-\alpha_w\right)\alpha_b$ which is the fraction of solar flux absorbed by basin liner.

Energy balance equation for water mass

$$[\acute{\alpha}_w \left(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)\right)\frac{A_b}{4}] + [h_{bw}\left(T_b - -T_w\right)A_b]$$
$$= h_{1wE}\left(T_w - -T_{gE}\right)\frac{A_b}{4} + h_{1wW}\left(T_w - -T_{gW}\right)\frac{A_b}{4}$$
$$+h_{1wS}\left(T_w - -T_{gS}\right)\frac{A_b}{4} + h_{1wN}\left(T_w - -T_{gN}\right)\frac{A_b}{4} + M_w C_w \frac{dT_w}{dt} \qquad (10)$$

[Energy absorbed by water mass directy from sunlight in unit time]

$+$ [heat transferred from basin liner to water mass in unit time]

$=$ [heat transferred from water surface to condensing cover facing east in unit time]

$+$ [heat transferred from water surface to condensing cover facing west in unit time]

$+$ [heat transferred from water surface to condensing cover facing south in unit time]

$+$ [heat transferred from water surface to condensing cover facing north in unit time]

$+$ [sensible heat gained by water mass in unit time]

where $\acute{\alpha}_w = \left(1-R_g\right)\left(1-\alpha_g\right)\left(1-R_w\right)\alpha_w$ which is the fraction of solar flux absorbed by water mass.

One can get the solution of Eqs. (1) to (8) using the computational tool as follows:

$$T_{gE} = -\frac{\begin{matrix} -A_g^2 h_{1g}^2 T_a - A_b A_g h_{1g} h_{1wW} T_a - 2A_g^2 h_{1g} h_{EW} T_a - A_b A_g h_{1wE} h_{1g} T_w - A_b^2 h_{1wE} h_{1wW} T_w \\ - A_b A_g h_{1wE} h_{EW} T_w - A_b A_g h_{1wW} h_{EW} T_w - A_g^2 h_{1g} I_{SE} \acute{\alpha}_g - A_b A_g h_{1wW} I_{SE} \acute{\alpha}_g - A_g^2 h_{EW} I_{SE} \acute{\alpha}_g \\ - A_g^2 h_{EW} I_{SW} \acute{\alpha}_g \end{matrix}}{A_b A_g h_{1wE} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wW} h_{1g} + A_b A_g h_{1wE} h_{EW} + 2A_g^2 h_{1g} h_{EW} + A_b A_g h_{1wW} h_{EW}} \qquad (11)$$

$$T_{gW} = -\frac{\begin{matrix} -A_g^2 h_{1g}^2 T_a - A_b A_g h_{1g} h_{1wE} T_a - 2A_g^2 h_{1g} h_{EW} T_a - A_b A_g h_{1wE} h_{1g} T_w - A_b^2 h_{1wE} h_{1wW} T_w \\ - A_b A_g h_{1wE} h_{EW} T_w - A_b A_g h_{1wW} h_{EW} T_w - A_g^2 h_{1g} I_{SE} \acute{\alpha}_g - A_b A_g h_{1wE} I_{SW} \acute{\alpha}_g - A_g^2 h_{EW} I_{SW} \acute{\alpha}_g \\ - A_g^2 h_{EW} I_{SW} \acute{\alpha}_g \end{matrix}}{A_b A_g h_{1wE} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wW} h_{1g} + A_b A_g h_{1wE} h_{EW} + 2A_g^2 h_{1g} h_{EW} + A_b A_g h_{1wW} h_{EW}} \qquad (12)$$

$$T_{gS} = -\frac{\begin{matrix} -A_g^2 h_{1g}^2 T_a - A_b A_g h_{1g} h_{1wN} T_a + 2A_g^2 h_{1g} h_{NS} T_a - A_b A_g h_{1wS} h_{1g} T_w - A_b^2 h_{1wN} h_{1wS} T_w \\ + A_b A_g h_{1wN} h_{NS} T_w + A_b A_g h_{1wS} h_{NS} T_w - A_g^2 h_{1g} I_{SS} \acute{\alpha}_g - A_b A_g h_{1wN} I_{SS} \acute{\alpha}_g + A_g^2 h_{NS} I_{SN} \acute{\alpha}_g \\ + A_g^2 h_{NS} I_{SS} \acute{\alpha}_g \end{matrix}}{A_b A_g h_{1wN} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wN} h_{1wS} + A_b A_g h_{1wS} h_{1g} - A_b A_g h_{1wS} h_{NS} - 2A_g^2 h_{1g} h_{NS} - A_b A_g h_{1wN} h_{NS}} \qquad (13)$$

$$T_{gN} = -\frac{\begin{matrix} A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wS} T_a - 2A_g^2 h_{1g} h_{NS} T_a + A_b A_g h_{1wN} h_{1g} T_w + A_b^2 h_{1wN} h_{1wS} T_w \\ - A_b A_g h_{1wN} h_{NS} T_w - A_b A_g h_{1wS} h_{NS} T_w + A_g^2 h_{1g} I_{SN} \acute{\alpha}_g + A_b A_g h_{1wS} I_{SN} \acute{\alpha}_g - A_g^2 h_{NS} I_{SN} \acute{\alpha}_g \\ - A_g^2 h_{NS} I_{SS} \acute{\alpha}_g \end{matrix}}{-A_b A_g h_{1wN} h_{1g} - A_g^2 h_{1g}^2 - A_b^2 h_{1wN} h_{1wS} - A_b A_g h_{1wS} h_{1g} + A_b A_g h_{1wS} h_{NS} + 2A_g^2 h_{1g} h_{NS} + A_b A_g h_{1wN} h_{NS}} \qquad (14)$$

Equations (11) to (14) can further be simplified and can be expressed as follows:

$$T_{gE} = \frac{A_1 + A_2 T_w}{P_1} \tag{15}$$

$$T_{gW} = \frac{B_1 + B_2 T_w}{P_1} \tag{16}$$

$$T_{gS} = \frac{C_1 + C_2 T_w}{P_2} \tag{17}$$

$$T_{gN} = \frac{D_1 + D_2 T_w}{P_2} \tag{18}$$

Equations (15) and (16) are similar in form to equations reported in Gupta et al. (2020) and Sharma et al. (2020). Expressions for all unknown parameters can be seen in Appendix 1. Furthermore, Eq. (9) can be rearranged as

$$h_{bw}(T_b - T_w)A_b = \dot{\alpha}_b h_1 (I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t))A_b - U_b A_b (T_w - T_a) \tag{19}$$

where

$$h_1 = \frac{h_{bw}}{4(h_{bw} + h_{ba})} \tag{20}$$

$$U_b = \frac{h_{ba}h_{bw}}{(h_{bw} + h_{ba})} \tag{21}$$

Now, putting values of T_{gE}, T_{gW}, T_{gS}, T_{gN}, and $h_{bw}(T_b - T_w)A_b$ in Eq. (10) and upon further simplification, one can get the first-order differential equation as

$$\frac{dT_w}{dt} + a_1 T_w = f(t) \tag{22}$$

where,

$$f(t) = \frac{1}{M_w C_w}\left[\left(\frac{\dot{\alpha}_w}{4} + \dot{\alpha}_b h_1\right)A_b\left(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)\right) - E_1 + \left(U_b A_b + F_1\right)T_a\right]$$

$$a_1 = \left(\frac{F_1 + U_b A_b}{M_w C_w}\right) \tag{24}$$

Table 2 Different types of climatic situations for each month of the year for New Delhi climate

Type of climatic situation	Description	Remarks
a	Clear day (blue sky)	$\gamma \leq 0.25$ and $S \geq 9$ h
b	Hazy day (fully)	$0.25 \leq \gamma \leq 0.50$ and 7 h $\leq S \leq 9$ h
c	Hazy and cloudy (partially)	$0.50 \leq \gamma \leq 0.75$ and 5 h $\leq S \leq 7$ h
d	Cloudy day (fully)	$\gamma \geq 0.75$ and $S \leq 5$ h

S signifies sunshine hours and γ signifies ratio of daily diffuse to daily global irradiation

Equation (22) can be solved using mathematical concepts under the assumption that (a) the time interval is small $(0 < t < \Delta t)$ and (b) solar intensity and surrounding temperature are having their average values so that $f(t)$ is constant and the mean value of $f(t)$ is $\overline{f}(t)$. Also, a_1 remains the same for the interval Δt. The solution of the differential equation (22) can be written as

$$T_w = \frac{\overline{f}(t)}{a_1}\left(1 - e^{-a_1 t}\right) + T_{wo}e^{-a_1 t} \tag{25}$$

where,

$$\overline{f}(t) = \frac{1}{M_w C_w}\left[\left(\frac{\dot{\alpha}_w}{4} + \dot{\alpha}_b h_1\right)A_b\left(\overline{I}_{SE}(t) + \overline{I}_{SW}(t) + \overline{I}_{SN}(t) + \overline{I}_{SS}(t)\right) - E_1 + \left(U_b A_b + F_1\right)\overline{T}_a\right]$$

Expressions for all unknown parameters are given in Appendix 1.

The rate of evaporative heat transfer can be written as

$$\dot{q}_{ew} = \left[h_{ewgE}(T_w - T_{gE}) + h_{ewgW}(T_w - T_{gW}) + h_{ewgS}(T_w - T_{gS}) + h_{ewgN}(T_w - T_{gN})\right]\left(\frac{A_b}{4}\right) \tag{26}$$

The production of freshwater from CPSS on per hour basis can be written as

$$\text{Hourly freshwater production} = \frac{\dot{q}_{ew} \times 3600}{(\text{Latent heat})} \tag{27}$$

The developed thermal model for CPSS has been vali-

$$\tag{23}$$

dated by experimental data available in Gad et al. (2015) with a fair agreement between theoretical and experimental values of water temperature, condensing surface temperature and freshwater production. The coefficient of correlation

for water temperature, condensing surface temperature, and freshwater yield has been obtained as 0.96, 0.99, and 0.99, respectively.

Analysis

For the analysis of CPSS, four climatic situations for each month of the year have been considered, and they are presented in Table 2 (Singh and Tiwari 2004).

Exergy analysis

The analysis of CPSS from an exergy viewpoint can be carried out using the second law of thermodynamics. The main objective of carrying out exergy analysis for CPSS is to locate thermodynamic inefficiencies followed by the determination of the magnitude and reason for the same. The traditional way of carrying out the exergy analysis pinpoints components and processes having a high level of irreversibility (Petrakopoulou et al. 2012). However, some limitations exist in such analysis which can be overcome by advanced ways of carrying out exergy analysis. The advanced exergy analysis provides engineers with better information associated with energy system improvement potential. The advanced way of carrying out the analysis from an exergy viewpoint divides the destruction of exergy into two parts, namely, avoidable and unavoidable (Tsatsaronis and Park 2002).

Exergy destruction may also be categorised as endogenous and exogenous exergy destructions. Jafarkazemi and Ahmadifard (2012) have utilised the concept of entropy for exergetic estimation of flat plate collector. The value of exergy output $\left(\dot{\mathrm{Ex}}_{\mathrm{hourly}} \right)$ from CPSS on per hour basis can be estimated as (Nag 2004)

types of weather situations, viz. type 'b', type 'c', and type 'd', can be estimated. The value of total monthly exergy for a particular month can be evaluated by adding monthly exergies for type 'a', type 'b', type 'c', and type 'd' weather situations. The net annual exergy for CPSS can then be estimated by adding monthly exergies for 12 months in a year.

Annual freshwater production and energy analysis

The value of annual freshwater production can be computed using Eq. (27). Firstly, one can estimate the value of daily freshwater output for type 'a' weather situation by summing values of hourly freshwater for 24-h time. Likewise, daily freshwater output for the other three types of weather situations, viz. type 'b', type 'c', and type 'd', can be computed. The value of monthly freshwater output for type 'a' weather situation can be obtained by multiplying daily freshwater output with the number of days for type 'a' weather condition. Similarly, monthly freshwater output for the other three types of weather situations, viz. type 'b', type 'c', and type 'd', can be estimated. The value of monthly freshwater output for a particular month can be evaluated by adding monthly freshwater outputs for type 'a', type 'b', type 'c', and type 'd' weather situations. The net annual freshwater output for CPSS can then be estimated by adding monthly freshwater outputs for 12 months in a year.

The analysis of CPSS from an energy viewpoint can be carried out using the first law of thermodynamics. The hourly energy can be estimated as

$$\text{Hourly energy} = \frac{(\text{Hourly freshwater production}) \times (\text{Latent heat})}{3600} \qquad (29)$$

One can estimate the value of daily energy output for type 'a' weather situation by summing values of hourly energy for 24-h time. Likewise, daily energy for the other three types of weather situations, viz. type 'b', type 'c', and type

$$
\begin{aligned}
\dot{\mathrm{Ex}}_{\mathrm{hourly}} &= h_{\mathrm{ewgE}} \times \frac{\mathrm{A_b}}{4} \times \left[\left(T_{\mathrm{w}} - T_{\mathrm{gE}} \right) - \left(T_{\mathrm{a}} + 273 \right) \times \ln \frac{\left(T_{\mathrm{w}} + 273 \right)}{\left(T_{\mathrm{gE}} + 273 \right)} \right] + h_{\mathrm{ewgW}} \times \frac{\mathrm{A_b}}{4} \times \left[\left(T_{\mathrm{w}} - T_{\mathrm{gW}} \right) - \left(T_{\mathrm{a}} + 273 \right) \times \ln \frac{\left(T_{\mathrm{w}} + 273 \right)}{\left(T_{\mathrm{gW}} + 273 \right)} \right] \\
&+ h_{\mathrm{ewgS}} \times \frac{\mathrm{A_b}}{4} \times \left[\left(T_{\mathrm{w}} - T_{\mathrm{gS}} \right) - \left(T_{\mathrm{a}} + 273 \right) \times \ln \frac{\left(T_{\mathrm{w}} + 273 \right)}{\left(T_{\mathrm{gS}} + 273 \right)} \right] + h_{\mathrm{ewgN}} \times \frac{\mathrm{A_b}}{4} \times \left[\left(T_{\mathrm{w}} - T_{\mathrm{gN}} \right) - \left(T_{\mathrm{a}} + 273 \right) \times \ln \frac{\left(T_{\mathrm{w}} + 273 \right)}{\left(T_{\mathrm{gN}} + 273 \right)} \right]
\end{aligned}
\qquad (28)
$$

One can estimate the value of daily exergy gain for type 'a' weather situation by summing values of hourly exergy for 24-h time. Likewise, daily exergy for all the other weather situations, viz. type 'b', type 'c', and type 'd', can be computed. The value of monthly exergy for type 'a' weather situation can be obtained by multiplying daily exergy with the number of days for type 'a' weather condition. Similarly, monthly exergy for all the other three

'd', can be computed. The value of monthly energy for type 'a' weather situation can be obtained by multiplying daily energy with the number of days for type 'a' weather condition. Similarly, monthly energy for the other three types of weather situations, viz. type 'b', type 'c', and type 'd' can be estimated. The value of monthly energy for a particular month can be evaluated by adding monthly energies for type 'a', type 'b', type 'c', and type 'd' weather situations. The

net annual energy for CPSS can then be estimated by adding monthly energies for 12 months in a year.

Exergo-economic analysis for CPSS

This analysis focuses on estimating cost optimal structure and facilitates the designer in finding ways of improving the performance of the system in a cost-effective manner. The exergo-economic parameter can be estimated as the ratio of annual exergy gain to UEC or the ratio of annual exergy loss to UEC. In the case of exergy loss, the objective function is of minimisation type, whereas the objective is of maximisation type if exergy gain is considered. The exergo-economic parameter can be estimated as (Singh and Tiwari 2017)

$$(\text{Exergo} - \text{economic parameter})_{\text{energy}} = \frac{\text{Annual energy output}}{\text{UEC}} \quad (30)$$

$$(\text{Exergo} - \text{economic parameter})_{\text{exergy}} = \frac{\text{Annual exergy gain}}{\text{UEC}} \quad (31)$$

In the case of solar energy system, exergy gain can be considered because one does not need to pay for solar energy. As solar energy is freely available, our prime objective should be to maximise exergy gain instead of locating the element in the system responsible for exergy loss and then try to minimise the loss.

The estimation of the term UEC can be done by using the concept of the present value method. After knowing the present cost, salvage value, and maintenance cost for CPSS, one can estimate UEC for CPSS as (Tiwari 2013)

$$\text{UEC} = (\text{Present value} + \text{Maintenance cost})$$
$$\times F_{\text{CR,i,n}} - (\text{Salvage value}) \times F_{\text{SR,i,n}} \quad (32)$$

Generally, maintenance cost is estimated as the product of the present value and 0.1, i.e. 10% of present value. $F_{\text{CR,i,n}}$ and $F_{\text{SR,i,n}}$ represent the capital recovery factor and sinking fund factor, respectively, and can be estimated as

$$F_{\text{CR,i,n}} = \frac{r \times (1 + r)^l}{(1 + r)^l - 1} \quad (33)$$

$$F_{\text{SR,i,n}} = \frac{r}{(1 + r)^l - 1} \quad (34)$$

where r is the interest rate and l is the proposed system's life span.

Payback period

The payback period in the economic analysis represents the time needed to retrieve the funds invested or to attain the break-even point. The payback period should be as low as possible. The lower the value of the payback period for the system, the better the system. However, the drawback with a payback period in economic analysis is that the time value of money is disregarded. The payback period can be mathematically expressed as (Kumar and Tiwari 2009)

$$\text{Payback period} = \frac{\ln\left[\frac{(\text{Annual cash flow})}{(\text{Annual cash flow}) - (\text{Net present cost} \times r)}\right]}{\ln(1 + r)} \quad (35)$$

The value of annual cash flow can be estimated as follows:

Annual cash flow = UEA, if the selling price of freshwater produced is equal to the production cost of freshwater.

Annual cash flow = (annual freshwater production) × (selling price), if the selling price of freshwater produced is more than the production cost of freshwater.

Enviro-economic analysis for CPSS

The production of freshwater from conventional methods using an RO system requires electrical energy for its operation. The electrical energy production process emits pollutants which is harmful to the environment. So, freshwater production using solar energy can be used for mitigating the contemporary need for freshwater, and it does not emit any pollutants during its operation. The enviro-economic analysis is a way to reduce pollution by providing incentives to diminish the release of polluting elements and motivate to use solar energy technology as solar energy technology does not emit polluting elements. The concept of enviro-economic analysis is based on the price of carbon dioxide emission reduction and diminish in carbon dioxide emission for the entire life of the system under consideration. Following Caliskan et al. (2012), the enviro-economic parameter for CPSS can be estimated as

$$\text{Enviro} - \text{economic parameter} = (\text{Carbon dioxide emission reduction price}) \times (\xi_{\text{carbon dioxide}}) \quad (36)$$

where $\xi_{\text{carbon dioxide}}$ is the reduction in the emission of carbon dioxide for the entire life of CPSS.

If a consumer makes use of unit electrical power, loss during distribution and transmission amounts to 40% and the domestic appliance loss due to its poor condition is 20%, power required to be generated in power plant=1/((1-0.2)(1-0.4))=2.08 units. The mean value of carbon dioxide emission for unit kWh at source is about 0.96 kg if electrical energy is produced from coal (Sovacool 2008). In this

Fig. 2 Calculation flow chart for the performance analysis of CPSS
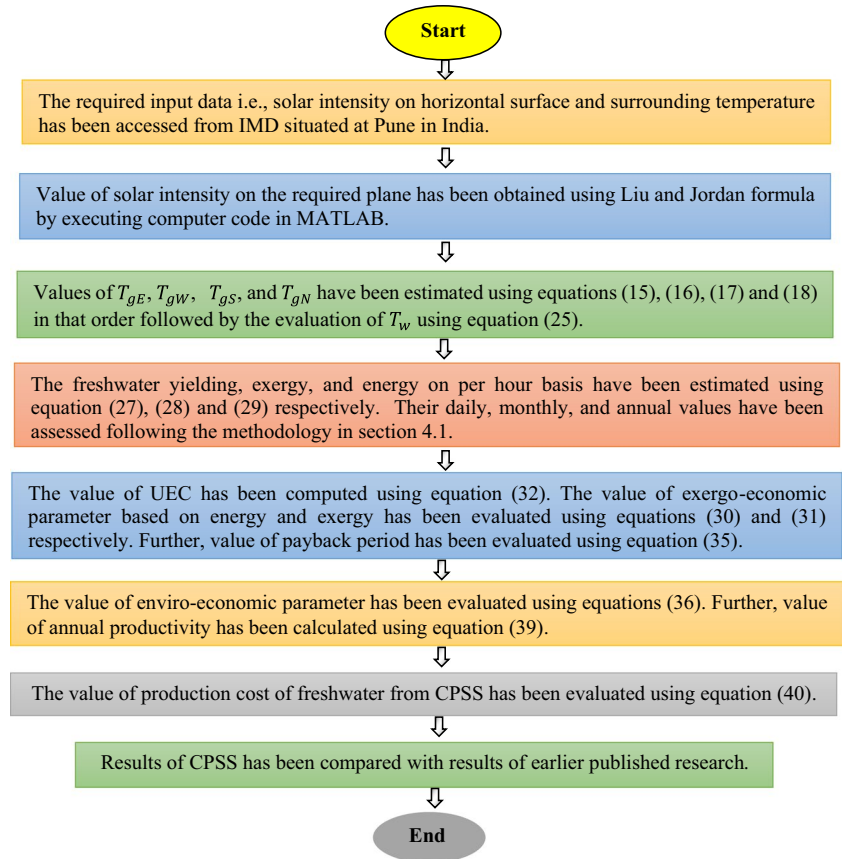
way, the value of carbon dioxide emission corresponding to 1 kWh electrical power consumption comes out to be $2.08 \times 0.96 = 2$ kg. The value of reduction in the amount of carbon dioxide for the entire life of CPSS in terms of ton of carbon dioxide can be estimated as

$$\left(\xi_{\text{carbon dioxide}}\right)_{\text{energy}} = \left[(\text{Annual energy output})(\text{Life of system}) - \text{Embodied energy}\right] \times (0.002) \tag{37}$$

$$\left(\xi_{\text{carbon dioxide}}\right)_{\text{exergy}} = \left[(\text{Annual exergy output})(\text{Life of system}) - \text{Embodied energy}\right] \times (0.002) \tag{38}$$

Annual productivity of CPSS

Productivity stands for the deep relationship that exists between output and input. The main objective of productivity estimation is to enhance the value of output as high as possible while keeping input as low as possible. International Labour Office (ILO 1979) defines the term productivity as effectiveness divided by efficiency. The annual productivity for CPSS can be defined as (ILO 1979)

$$\eta_{\text{p,annual}} = \frac{(\text{Annual freshwater output}) \times (\text{Selling price of freshwater})}{\text{UEC}} \times 100 \tag{39}$$

Production cost of freshwater from CPSS

The production cost of freshwater on annual basis can be estimated as the ratio of UEC and annual freshwater production and can be written as

$$\text{Cost of freshwater} = \frac{\text{UEC}}{\text{Annual freshwater production}} \times 100 \tag{40}$$

Methodology

The solution procedure for the estimation of relevant parameters of CPSS can be stated as follows:

Fig. 3 Dissimilarity of different temperatures and yield on per hour basis for an archetypal day of May for CPSS
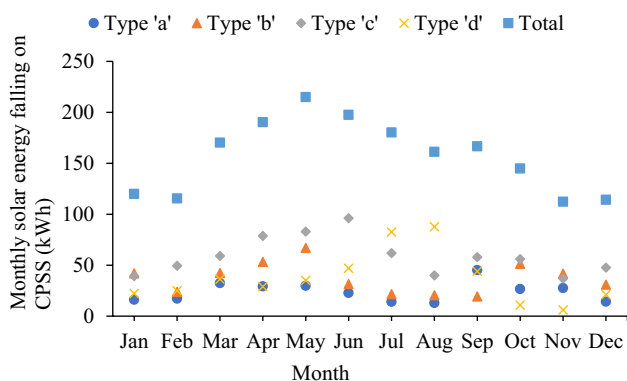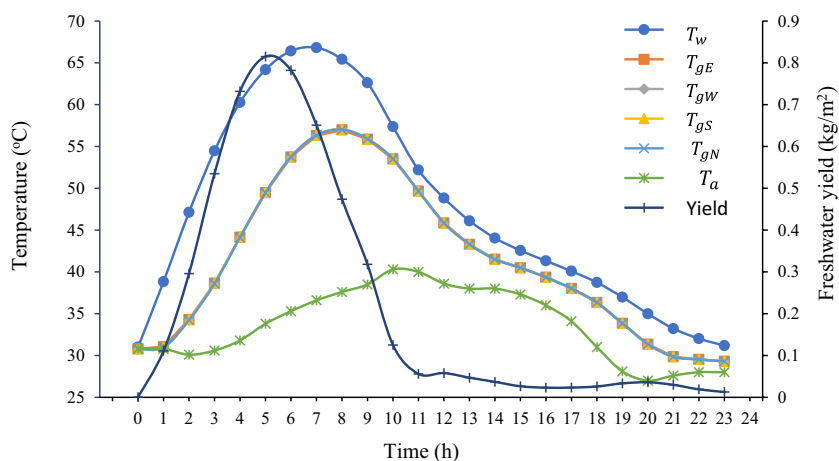
Fig. 4 Dissimilarity of monthly solar energy falling on CPSS
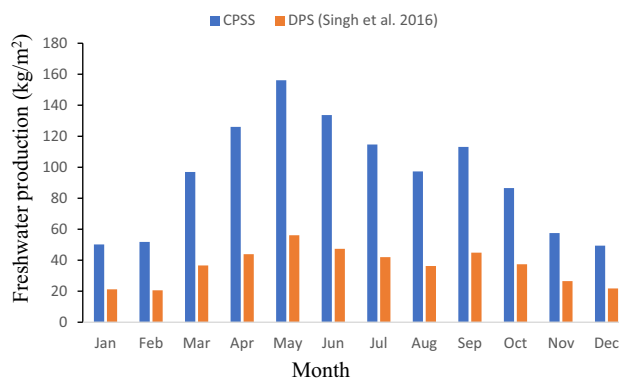
Fig. 6 Comparison of freshwater output of CPSS with DPS
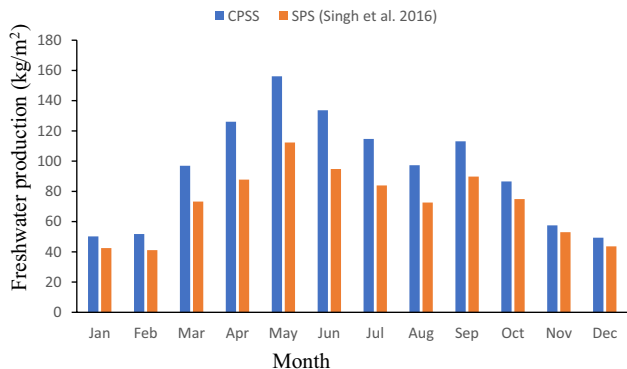
Fig. 5 Comparison of freshwater output from CPSS with SPS
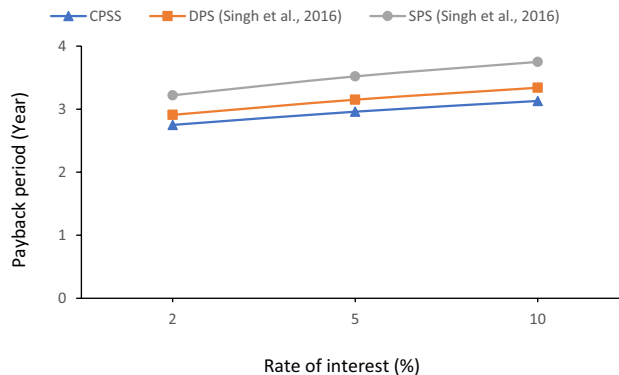
Fig. 7 Comparison of energy payback time of CPSS with DPS and SPS

Step 1

The required input data, i.e. solar intensity on a horizontal surface and the surrounding temperature, has been accessed from IMD situated at Pune in India. The value of solar intensity on the required plane has been obtained using Liu and Jordan formula by executing computer code in MATLAB.

Step II

Values of condensing cover temperatures, i.e. T_{gE}, T_{gW}, T_{gS}, and T_{gN}, have been estimated using Eqs. (15), (16), (17), and (18) in that order followed by the evaluation of T_w using Eq. (25).
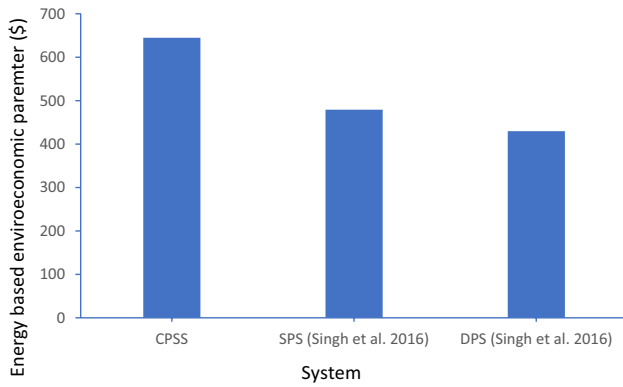
Fig. 8 Comparison of CPSS with basin-type PSSs

Step III

The value of freshwater production, exergy, and energy on per hour basis has been estimated using Eq. (27), (28), and (29), respectively, followed by the computation of daily, monthly, and annual freshwater production, exergy, and energy.

Step IV

The exergo-economic parameter on exergy and energy bases has been estimated using Eqs. (30) and (31), respectively. The payback period has been estimated using Eq. (35).

Step V

The enviro-economic parameter has been estimated using Eq. (36). Furthermore, annual productivity and production cost of freshwater have been computed using Eqs. (39) and (40), respectively.

A flow chart for better understanding the methodology followed for the performance analysis of CPSS is presented as Fig. 2.

Results and discussion

All required data along with relevant equation have been fed to MATLAB, and the output so obtained is presented in Figs. 3, 4, 5, 6, 7, and 8 and Tables 3, 4, 5, 6, 7, 8, 9, and 10. All four kinds of weather situations for each month of the year are taken to analyse the proposed system. All needed data, viz. solar intensity on a horizontal surface and surrounding temperature, are accessed from IMD Pune, India. From the solar intensity on a horizontal plane, the solar intensity on the inclined plane has been calculated using Liu and Jordan formula.

Figure 3 represents the dissimilarity of freshwater yielding and various temperatures, namely, water temperature, condensing surface temperatures, and surrounding temperature. In Fig. 3, the value 0 on horizontal axis represents 8:00 am and the value 24 on the same axis represents 8:00 am at the next day. From Fig. 3, one can observe that water temperature is higher than condensing surface temperature as per

Table 3 Computation of annual production of freshwater from CPSS

Month	Type 'a'			Type 'b'			Type 'c'			Type 'd'			Total monthly yield (kg)
	Daily yield (kg)	n	Monthly yield (kg)	Daily yield (kg)	n	Monthly yield (kg)	Daily yield (kg)	n	Monthly yield (kg)	Daily yield (kg)	n	Monthly yield (kg)	
Jan	2.56	3	7.68	2.48	8	19.81	1.40	11	15.39	0.81	9	7.31	50.19
Feb	2.95	3	8.86	3.13	4	12.53	1.79	12	21.51	0.99	9	8.90	51.80
Mar	3.92	5	19.60	4.42	6	26.51	2.66	12	31.87	2.37	8	19.00	96.97
Apr	5.07	4	20.27	5.34	7	37.39	3.55	14	49.77	3.72	5	18.62	126.05
May	5.53	4	22.12	5.49	9	49.42	5.03	12	60.37	4.04	6	24.24	156.14
Jun	5.36	3	16.07	5.64	4	22.54	4.68	14	65.49	3.29	9	29.57	133.67
Jul	4.86	2	9.71	4.98	3	14.93	4.05	10	40.49	2.91	17	49.55	114.69
Aug	4.23	2	8.46	4.56	3	13.67	3.52	7	24.62	2.66	19	50.52	97.27
Sep	4.59	7	32.15	4.59	3	13.76	3.95	10	39.50	2.77	10	27.67	113.08
Oct	3.39	5	16.93	3.17	10	31.69	2.47	13	32.11	1.96	3	5.87	86.60
Nov	2.57	6	15.43	2.19	10	21.88	1.45	12	17.36	1.44	2	2.87	57.54
Dec	2.24	3	6.73	2.06	7	14.43	1.58	13	20.49	0.97	8	7.73	49.39
Annual yield (kg)													1133.38

Table 4 Evaluation of annual exergy gain for CPSS

Month	Type 'a'			Type 'b'			Type 'c'			Type 'd'			Total monthly exergy (kWh)
	daily exergy (kWh)	n	monthly exergy (kWh)	daily exergy (kWh)	n	monthly exergy (kWh)	daily exergy (kWh)	n	monthly exergy (kWh)	daily exergy (kWh)	n	monthly exergy (kWh)	
January	0.12	3	0.35	0.11	8	0.88	0.04	11	0.49	0.02	9	0.16	1.87
February	0.13	3	0.39	0.14	4	0.57	0.06	12	0.68	0.02	9	0.18	1.82
March	0.17	5	0.87	0.21	6	1.27	0.09	12	1.09	0.08	8	0.60	3.83
April	0.23	4	0.91	0.25	7	1.74	0.13	14	1.76	0.14	5	0.69	5.09
May	0.24	4	0.94	0.23	9	2.11	0.20	12	2.44	0.14	6	0.84	6.33
June	0.24	3	0.71	0.26	4	1.04	0.19	14	2.68	0.11	9	0.95	5.38
July	0.23	2	0.45	0.24	3	0.71	0.17	10	1.69	0.10	17	1.66	4.51
August	0.20	2	0.41	0.23	3	0.69	0.15	7	1.05	0.10	19	1.83	3.97
September	0.21	7	1.44	0.21	3	0.62	0.16	10	1.60	0.09	10	0.88	4.54
October	0.14	5	0.71	0.13	10	1.29	0.08	13	1.10	0.05	3	0.16	3.26
November	0.10	6	0.59	0.08	10	0.76	0.04	12	0.43	0.04	2	0.07	1.85
December	0.08	3	0.25	0.07	7	0.52	0.05	13	0.63	0.02	8	0.16	1.57
Annual exergy gain (kWh)													44.01

Table 5 Cost of CPSS

Item	Description
Cost of CPSS (Rs.)	15000
Maintenance cost (Rs.)	1500
Salvage value considering inflation rate as 4% (Rs.)	4865
Life of the system (year)	30

the expectation. The difference in these two temperatures is responsible for the production of freshwater from CPSS. The average value of solar intensity as well as atmospheric temperature has been used for the estimation of various parameters reported in this work. The variation in water temperature and condensing surface temperature corresponds to the variation in solar intensity. The maximum value of solar intensity occurs at 12:00 noon, whereas the maximum value of water temperature occurs at 2:00 pm. The reason is that water takes some time to increase its temperature after receiving solar intensity.

The computation of annual freshwater output from CPSS has been presented in Table 3. The methodology for the estimation has been discussed in analysis section. One can observe from Table 3 that the value of monthly freshwater output is highest in May and minimum in December. The value of monthly freshwater output is maximum in May because May falls in the summer season, and solar intensity is maximum in May as evident from Fig. 4. Data used for evaluating solar energy falling on CPSS has been presented in Tables 11, 12, 13, 14, 15, and 16 in Appendix 2. The value of monthly production of freshwater is minimum in December because December falls in the winter season, and hence, solar intensity is comparatively poor.

The output (freshwater production) obtained for the proposed system has been compared with earlier published results of basin-type passive solar stills, and they have been presented in Figs. 5 and 6, respectively. It has been observed from Figs. 5 and 6 that the production of freshwater is higher for CPSS than SPS as well as DPS in each month of the year. The reason being that the CPSS uses the solar intensity from all directions, viz. east, west, south, and north. Also, the shading effect is less in CPSS as compared to SPS and DPS. The annual freshwater production for CPSS is higher by 23.28% and 31.36% than SPS and DPS, respectively, due to less shading effect in the case of CPSS.

The computation of annual exergy output from CPSS at 0.025 m water depth and 30° inclination angle of the condensing cover has been presented in Table 4. It has been observed from Table 4 that the value of monthly exergy output is maximum in May due to favourable climatic as it falls in the summer season. Furthermore, the value of monthly exergy output is minimum in December due to unfavourable climatic situations in December as it falls in winter season.

The cost of CPSS has been presented in Table 5, and the estimation of UEC for the CPSS has been presented in Table 6. One can observe from Table 6 that UEC is the

Table 6 Estimation of UEC for CPSS

Life of system (year)	Rate of interest (%)	Present value (Rs.)	Maintenance cost (Rs.)	Salvage value (Rs.)	Capital recovery factor (fraction)	Sinking fund factor (fraction)	UEC (Rs.)
30	2	10000	1200	3243	0.0446	0.0246	411.21
30	5	10000	1200	3243	0.0651	0.0151	666.75
30	10	10000	1200	3243	0.1061	0.0061	1147.16

Table 7 Estimation of annual productivity and cost of producing freshwater

UEC (Rs.)	Annual yield (kg)	Annual exergy (kWh)	cost of water (Rs./kg)	Selling price of water (Rs.)	Annual productivity (%)	Exergo-economic parameter (kWh/Rs.)
411.21	1133.38	44.01	0.36	5	1378.10	0.107
666.75	1133.38	44.01	0.59	5	849.93	0.063
1147.16	1133.38	44.01	1.01	5	493.99	0.038

Table 8 Estimation of exergo-economic parameter for CPSS

Rate of interest (%)	UEC (Rs.)	Annual energy (kWh)	Annual exergy (kWh)	Energy-based exergo-economic parameter (kWh/Rs.)	Exergy-based exergo-economic parameter (kWh/Rs.)
2	411.21	755.59	44.01	1.84	0.107
5	666.75	755.59	44.01	1.13	0.063
10	1147.16	755.59	44.01	0.66	0.038

Table 9 Comparison of CPSS with basin-type PSS on the basis of cost of water, yearly productivity, and exergo-economic parameter at a 5% rate of interest and 30-year lifetime

Types of system	Annual energy (kWh)	Cost of water (Rs./kg)	Annual productivity (%)	Exergy-based exergo-economic parameter (kWh/Rs.)	Energy-based exergo-economic parameter (kWh/Rs.)
CPSS	755.59	0.59	849.93	0.063	1.13
SPS [46]	579.71	0.67	475.36	0.059	0.63
DPS [46]	518.59	0.67	496.97	0.057	0.66

lowest corresponding to a 2% rate of interest which is minimum. The estimation of annual productivity using Eq. (39) and the production cost of freshwater from CPSS using Eq. (40) have been presented in Table 7. One can observe from Table 7 that the value of yearly productivity is higher than 100% which represents the feasibility of CPSS.

The estimation of exergo-economic parameter at 0.025 m water depth for CPSS has been presented in Table 8. The evaluation of exergo-economic parameter for CPSS has been done on both energy and exergy bases. Values of exergo-economic parameters are minimum at a 10% rate of interest because the value of UEC is maximum at a 10% rate of interest. Furthermore, values of exergo-economic parameters are maximum at a 2% rate of interest because the value of UEC is minimum at a 2% rate of interest. The life of the system has been considered as 30 years.

The comparison of CPSS with basin-type PSS based on the production cost of freshwater, yearly productivity, and exergo-economic parameter has been presented in Table 9. One can observe from Table 9 that the value of the production cost of freshwater from CPSS is lower than basin-type PSS by 13.56% because annual freshwater production is higher in the case of CPSS due to a lower shading effect. The value of yearly productivity for CPSS is higher by 44.07% and 41.53% than SPS and DPS, respectively, due to higher value of annual freshwater production and lower value of UEC because of less material requirement in the case of CPSS. The exergy-based exergo-economic parameter is higher for CPSS by 6.35% and 9.52%, respectively, because the value of UEC is lower due to less material requirement in the case of CPSS. The energy-based exergo-economic parameter is higher for CPSS by 44.25% and 41.59%,

Table 10 Computation of enviro-economic parameter for CPSS

Element	Density (kg/m^3)	Mass (kg)	Specific energy (kWh/kg)	Embodied energy (kWh)
GRP body	1700	10.17	25.64	260.76
Glass condensing cover	2500	11.54	8.72	100.63
Others	-	-		73.40
Total embodied energy for CPSS (kWh)				434.79
Annual freshwater production (kg)				1133.38
Annual energy output (kWh)				755.59
Life of system (year)				30.00
Net energy available considering whole life of system (kWh)				22232.81
Annual exergy produced from the system (kWh)				44.01
Net exergy available considering whole life of system (kWh)				885.51
Carbon dioxide credited based on energy (*t*)				44.47
Carbon dioxide credited based on exergy (*t*)				1.77
Energy-based enviro-economic parameter ($)				644.75
Exergy-based enviro-economic parameter ($)				25.68

respectively, because the value UEC is lower due to less material requirement in the case of CPSS. Also, the energy output is higher by 23.37% and 31.36% than SPS and DPS, respectively, due to less shading effect in the case of CPSS.

Figure 7 represents the comparison of the payback period of CPSS with DPS and SPS considering the selling price of freshwater as Rs. 5 per kg. The rate of interest has been considered as 2%, 5%, and 10%. The payback period for CPSS has been estimated to be 2.75 years, 2.91 years, and 3.22 years at rates of interest as 2%, 5%, and 10%, respectively. The minimum payback period is 2.75 years because the rate of interest is minimal. The higher the rate of interest, the higher will be the payback period because a higher rate of interest increases the cost of production of freshwater. The payback period for SPS and DPS has been estimated based on the data accessed from Singh et al. (2016a, 2016b). The payback period for CPSS is lower than DPS and SPS by 7.63% and 13. 82%, respectively.

The evaluation of enviro-economic parameter for CPSS at 0.025 m water depth and 30-year lifetime has been presented in Table 10. The calculation has been performed taking both energy and exergy bases. The estimation of embodied energy for CPSS has also been carried out and shown in Table 10. One can observe from Table 10 that value energy-based enviro-economic parameter has been obtained as $644.75 and the exergy-based enviro-economic parameter has been obtained as $25.68. The value of exergy-based enviro-economic parameter is lower than the value of the energy-based parameter because exergy signifies the quality of energy, and due to this reason, the value of exergy is very lower than energy.

The comparison of the energy-based enviro-economic parameter of CPSS with basin-type PSSs at 0.025 m water depth has been presented in Fig. 8. One can see in Fig. 8 that the value of the energy-based enviro-economic parameter of CPSS is higher by 25.68% and 33.36% than SPS and DPS, respectively. It occurs due to higher energy output and lower embodied energy in the case of CPSS. The embodied energy is lower due to lower material requirements in the case of CPSS. The energy output is higher in the case of CPSS due to less shading effect than basin-type PSS.

Conclusions

A new approach of thermal modelling for conical passive solar still has been discussed, wherein the condensing surface has been divided into four equal parts and energy balance equations for different components of the system have been written followed by expressing unknown parameters in terms of known parameters with the help of computational and mathematical concepts. Furthermore, the required parameters of CPSS have been evaluated, and obtained results have been compared with the earlier research reported in the literature. Based on the present work, the following conclusions have been drawn:

i. The annual freshwater production for CPSS at 0.025 m water depth is higher by 23.28% and 31.36%, respectively, than SPS and DPS. The production of freshwater for CPSS is lower by 13.56% than basin-type passive solar still.

ii. The energy-based exergo-economic parameter for CPSS at 0.025 m water depth is higher by 44.25% and 41.59%, respectively, than SPS and DPS. The exergy-based exergo-economic parameter for CPSS at 0.025 m water depth is higher by 6.35% and 9.52%, respectively, than SPS and DPS.

iii. The values of payback time vary from 2.75 to 3.22 years corresponding to the variation in the rate of interest from 2 to 10%. Furthermore, the energy payback time for conical passive solar still is less by 7.64% and 13.83% than DPS and SPS, respectively.

iv. The value of annual productivity for CPSS at 0.025 m water depth is higher by 44.07% and 41.53% for conical than SPS and DPS, respectively. Also, the value of productivity for CPSS is more than 100% for all cases which represent the feasibility of the proposed system.

v. The values of energy-based and exergy-based enviro-economic parameters have been obtained as $644.75 and $25.68, respectively. Furthermore, the energy-based enviro-economic parameter is 25.68% and 33.36% higher for conical passive solar still than SPS and DPS, respectively.

Appendix 1

$A_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wW} T_a + 2A_g^2 h_{1g} h_{EW} T_a + A_g^2 h_{1g} I_{SE} \dot{\alpha}_g$
$\qquad + A_b A_g h_{1wW} I_{SE} \dot{\alpha}_g + A_g^2 h_{EW} I_{SE} \dot{\alpha}_g$
$\qquad\qquad + A_g^2 h_{EW} I_{SW} \dot{\alpha}_g$

$A_2 = A_b A_g h_{1wE} h_{1g} + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wE} h_{EW} + A_b A_g h_{1wW} h_{EW}$

$B_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wE} T_a + 2A_g^2 h_{1g} h_{EW} T_a + A_g^2 h_{1g} I_{SE} \dot{\alpha}_g + A_b A_g h_{1wE} I_{SW} \dot{\alpha}_g + A_g^2 h_{EW} I_{SW} \dot{\alpha}_g$
$\qquad\qquad + A_g^2 h_{EW} I_{SW} \dot{\alpha}_g$

$B_2 = A_b A_g h_{1wW} h_{1g} + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wE} h_{EW} + A_b A_g h_{1wW} h_{EW}$

$C_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wN} T_a - 2A_g^2 h_{1g} h_{NS} T_a + A_g^2 h_{1g} I_{SS} \dot{\alpha}_g$
$\qquad + A_b A_g h_{1wN} I_{SS} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g$
$\qquad\qquad - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g$

$C_2 = A_b A_g h_{1wS} h_{1g} + A_b^2 h_{1wN} h_{1wS} - A_b A_g h_{1wN} h_{NS} - A_b A_g h_{1wS} h_{NS}$

$D_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wS} T_a - 2A_g^2 h_{1g} h_{NS} T_a + A_g^2 h_{1g} I_{SN} \dot{\alpha}_g$
$\qquad + A_b A_g h_{1wS} I_{SN} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g$
$\qquad\qquad - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g$

$D_2 = A_b A_g h_{1wN} h_{1g} + A_b^2 h_{1wN} h_{1wS} - A_b A_g h_{1wN} h_{NS} - A_b A_g h_{1wS} h_{NS}$

$P_1 = A_b A_g h_{1wE} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wE} h_{1wW}$
$\qquad + A_b A_g h_{1wW} h_{1g} + A_b A_g h_{1wE} h_{EW}$
$\qquad + 2A_g^2 h_{1g} h_{EW} + A_b A_g h_{1wW} h_{EW}$

$P_2 = A_b A_g h_{1wN} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wN} h_{1wS}$
$\qquad + A_b A_g h_{1wS} h_{1g} - A_b A_g h_{1wS} h_{NS}$
$\qquad - 2A_g^2 h_{1g} h_{NS} - A_b A_g h_{1wN} h_{NS}$

$I_e = -\left(A_g^2 h_{1g} I_{SE} \dot{\alpha}_g + A_b A_g h_{1wW} I_{SE} \dot{\alpha}_g + A_g^2 h_{EW} I_{SE} \dot{\alpha}_g + A_g^2 h_{EW} I_{SW} \dot{\alpha}_g \right)$

$I_w = -\left(A_g^2 h_{1g} I_{SW} \dot{\alpha}_g + A_b A_g h_{1wE} I_{SW} \dot{\alpha}_g + A_g^2 h_{EW} I_{SE} \dot{\alpha}_g + A_g^2 h_{EW} I_{SW} \dot{\alpha}_g \right)$

$I_s = -\left(A_g^2 h_{1g} I_{SS} \dot{\alpha}_g + A_b A_g h_{1wN} I_{SS} \dot{\alpha}_g - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g \right)$

$I_n = -\left(A_g^2 h_{1g} I_{SN} \dot{\alpha}_g + A_b A_g h_{1wS} I_{SN} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g \right)$

$U_e = \left(A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wW} + 2A_g^2 h_{1g} h_{EW} \right)$

$U_w = \left(A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wE} + 2A_g^2 h_{1g} h_{EW} \right)$

$U_s = \left(A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wN} - 2A_g^2 h_{1g} h_{NS} \right)$

$U_n = \left(A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wS} - 2A_g^2 h_{1g} h_{NS} \right)$

$E = \left(\dfrac{h_{ewgE} I_e + h_{ewgW} I_w}{P_1} + \dfrac{h_{ewgS} I_s + h_{ewgN} I_n}{P_2} \right) \left(\dfrac{A_b}{4} \right)$

$F_1 = \left(\dfrac{h_{1wE} U_e + h_{1wW} U_w}{P_1} + \dfrac{h_{1wS} U_s + h_{1wN} U_n}{P_2} \right) \left(\dfrac{A_b}{4} \right)$

$h_{ewE} = 0.016273\, h_{cwgE} \left[\dfrac{P_w - P_{gE}}{T_w - T_{gE}} \right]$

(Cooper 1973)

$h_{ewgW} = 0.016273\, h_{cwgW} \left[\dfrac{P_w - P_{gW}}{T_w - T_{gW}} \right]$

(Cooper 1973)

$h_{ewS} = 0.016273\, h_{cwgS} \left[\dfrac{P_w - P_{gS}}{T_w - T_{gS}} \right]$

(Cooper 1973)

$h_{ewgN} = 0.016273\, h_{cwgN} \left[\dfrac{P_w - P_{gN}}{T_w - T_{gN}} \right]$

(Cooper 1973)

$h_{cwgE} = 0.884 \left[(T_w - T_{gE}) + \dfrac{(P_w - P_{gE})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$

(Dunkle 1961)

$h_{cwgW} = 0.884 \left[(T_w - T_{gW}) + \dfrac{(P_w - P_{gW})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$

(Dunkle 1961)

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

(Dunkle 1961)

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

(Dunkle 1961)

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

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

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

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

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

$$h_{EW} = 0.034 \times 5.67 \times 10^{-8} \left[\left(T_{gE} + 273 \right)^2 + \left(T_{gW} + 273 \right)^2 \right] \left[T_{gE} + T_{gW} + 546 \right]$$

$$h_{NS} = 0.034 \times 5.67 \times 10^{-8} \left[\left(T_{gN} + 273 \right)^2 + \left(T_{gS} + 273 \right)^2 \right] \left[T_{gN} + T_{gS} + 546 \right]$$

Appendix 2

Table 11 Average hourly radiations (W/m^2) for type 'a' weather situation for New Delhi

Solar radiation	Month▶ Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8 am	132.99	180.29	266.77	368.14	406.31	436.67	367.36	333.59	277.96	168.75	121.46	93.12
	9 am	355.56	403.58	488.94	588.48	608.84	637.22	587.04	528.54	501.30	364.58	316.04	275.27
	10 am	554.69	594.44	671.21	767.81	776.26	802.22	737.27	674.49	682.04	565.28	485.35	443.25
	11 am	680.73	729.39	804.33	888.32	897.98	915.00	831.71	820.20	809.07	694.45	609.97	565.87
	12 pm	726.74	786.02	866.93	941.01	956.82	951.67	881.48	868.18	869.07	761.80	664.01	621.83
	1 pm	733.85	792.03	869.28	944.12	950.51	946.11	896.53	807.83	855.19	756.25	657.45	618.39
	2 pm	656.08	728.58	803.15	878.68	886.62	882.78	820.60	766.67	779.81	686.11	587.37	553.31
	3 pm	500.00	584.23	665.33	746.90	761.37	765.56	753.24	658.08	656.48	543.75	454.17	426.19
	4 pm	311.46	391.22	483.01	568.30	580.81	611.67	569.68	477.78	483.89	362.50	274.62	253.97
	5 pm	106.42	178.23	264.10	348.61	372.48	420.00	373.15	305.81	270.19	152.08	84.09	68.78
Diffuse	8 am	52.60	73.30	94.23	122.47	117.68	123.89	109.03	86.62	100.00	44.44	42.80	36.37
	9 am	86.28	105.82	123.02	139.54	137.12	149.44	141.44	100.00	124.81	68.75	61.36	53.31
	10 am	107.29	126.08	142.20	159.40	153.28	157.22	171.07	155.30	140.93	119.45	77.15	60.19
	11 am	121.53	137.36	154.11	174.84	166.67	158.89	205.09	176.26	151.67	137.50	109.60	81.61
	12 pm	126.39	141.31	153.21	180.39	174.24	167.78	218.75	189.65	152.41	147.92	141.67	142.46
	1 pm	136.63	145.07	153.21	181.78	177.02	185.00	219.68	201.26	160.00	154.17	136.36	141.27
	2 pm	128.30	138.35	151.12	177.45	175.76	180.56	204.86	197.48	164.26	142.36	131.82	119.18
	3 pm	110.94	123.84	136.54	163.24	165.66	176.11	179.63	172.72	150.74	121.53	114.77	105.03
	4 pm	90.28	101.52	116.35	146.08	154.29	142.78	149.54	128.28	123.15	93.06	88.01	78.84
	5 pm	41.84	63.98	85.74	115.36	133.08	116.11	110.42	93.69	91.30	59.72	43.05	37.43
Beam	8 am	80.38	106.99	172.54	245.67	288.64	312.78	258.33	246.97	177.96	124.31	78.66	56.75
	9 am	269.27	297.76	365.92	448.94	471.72	487.78	445.60	428.54	376.48	295.83	254.67	221.96
	10 am	447.40	468.37	529.01	608.41	622.98	645.00	566.20	519.19	541.11	445.83	408.21	383.07
	11 am	559.20	592.03	650.21	713.48	731.31	756.11	626.62	643.94	657.41	556.95	500.38	484.26
	12 pm	600.35	644.71	713.73	760.62	782.58	783.89	662.73	678.53	716.67	613.89	522.35	479.37
	1 pm	597.22	646.95	716.08	762.34	773.48	761.11	676.85	606.57	695.19	602.08	521.09	477.12
	2 pm	527.78	590.23	652.03	701.23	710.86	702.22	615.74	569.19	615.56	543.75	455.56	434.13
	3 pm	389.06	460.39	528.79	583.66	595.71	589.45	573.61	485.36	505.74	422.23	339.39	321.16
	4 pm	221.18	289.69	366.67	422.22	426.51	468.89	420.14	349.50	360.74	269.44	186.62	175.13
	5 pm	64.58	114.25	178.37	233.25	239.40	303.89	262.73	212.12	178.89	92.36	41.04	31.35

Table 12 Average hourly radiations (W/m^2) for type 'b' weather situation for New Delhi

Solar radiation	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8 am	119.58	186.67	300.45	413.11	439.11	433.34	398.66	366.89	277.34	260.00	153.11	86.66
	9 am	332.50	425.84	540.22	635.55	641.34	641.34	592.22	551.78	499.78	442.00	332.22	280.22
	10 am	516.25	609.59	733.78	808.89	794.45	794.45	751.11	713.55	687.55	598.00	470.89	456.45
	11 am	650.41	752.50	872.45	936.00	898.45	912.89	840.66	832.00	788.66	693.34	574.89	580.66
	12 pm	708.75	813.75	933.11	999.55	947.55	999.55	936.00	881.11	837.78	728.00	606.66	629.78
	1 pm	723.33	822.50	938.89	982.22	936.00	996.66	907.11	881.11	860.89	702.00	563.34	635.55
	2 pm	650.41	758.33	869.55	901.34	852.22	912.89	837.78	808.89	800.22	615.34	491.11	566.22
	3 pm	498.75	603.75	713.55	751.11	722.22	808.89	707.78	687.55	667.34	465.11	352.45	424.66
	4 pm	315.00	408.33	522.89	557.55	540.22	635.55	554.66	505.55	462.22	283.11	193.55	228.22
	5 pm	110.84	183.75	288.89	332.22	340.89	416.00	352.45	317.78	265.78	98.22	86.66	63.55
Diffuse	8 am	52.75	84.99	119.58	134.17	204.16	198.33	192.67	170.00	104.84	133.17	107.67	28.34
	9 am	102.57	143.60	160.42	166.25	247.92	250.83	229.50	218.17	144.50	187.00	158.67	99.16
	10 am	123.09	167.04	180.83	186.67	274.17	277.08	283.34	252.16	204.00	212.50	192.67	133.17
	11 am	149.46	181.69	201.25	201.25	297.50	297.50	320.17	260.67	226.66	232.34	212.50	155.84
	12 pm	155.32	190.49	204.16	215.84	300.42	300.42	340.00	277.66	240.83	238.00	218.17	170.00
	1 pm	161.18	190.49	207.08	215.84	300.42	335.41	328.66	280.50	232.34	232.34	206.84	172.83
	2 pm	155.32	181.69	198.33	210.00	297.50	315.00	311.67	252.16	223.83	218.17	201.16	161.50
	3 pm	128.94	158.25	177.91	201.25	271.25	291.67	291.83	232.34	204.00	184.17	170.00	136.00
	4 pm	96.71	123.09	154.58	175.00	239.17	274.17	243.67	218.17	170.00	141.67	121.83	99.16
	5 pm	46.88	70.34	110.84	125.41	189.59	207.08	198.33	178.50	133.17	70.83	48.16	51.00
Beam	8 am	66.83	101.68	180.86	278.94	234.95	235.00	206.00	196.89	172.5	126.83	45.44	58.33
	9 am	229.94	282.24	379.80	469.31	393.42	390.50	362.72	333.61	355.28	255.00	173.55	181.05
	10 am	393.17	442.55	552.95	622.22	520.28	517.36	467.77	461.39	483.55	385.50	278.22	323.27
	11 am	500.95	570.81	671.19	734.75	600.95	615.39	520.50	571.33	562.00	461.00	362.39	424.83
	12 pm	553.43	623.26	728.95	783.72	647.14	699.14	596.00	603.44	596.95	490.00	388.50	459.78
	1 pm	562.15	632.01	731.81	766.38	635.58	661.25	578.44	600.61	628.56	469.66	356.50	462.73
	2 pm	495.09	576.64	671.22	691.34	554.72	597.89	526.11	556.73	576.39	397.17	289.94	404.72
	3 pm	369.81	445.50	535.64	549.86	450.97	517.22	415.95	455.22	463.34	280.94	182.44	288.67
	4 pm	218.29	285.25	368.31	382.55	301.05	361.39	311.00	287.39	292.21	141.44	71.73	129.05
	5 pm	63.95	113.41	178.05	206.81	151.30	208.92	154.12	139.28	132.61	27.39	38.50	12.55

Table 13 Average hourly radiations (W/m^2) for type 'c' weather situation for New Delhi

Solar radiation	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8 am	71.11	117.78	197.78	288.89	361.11	358.33	333.33	297.50	261.25	195.83	66.66	66.66
	9 am	235.55	284.45	366.66	453.34	566.67	555.56	530.67	490.00	456.53	365.56	206.66	216.00
	10 am	360.00	420.00	513.34	582.22	708.33	727.78	642.66	597.50	617.50	496.11	333.34	365.34
	11 am	457.78	522.22	613.34	677.78	841.67	816.67	744.00	700.00	691.39	587.50	415.55	482.67
	12 pm	515.55	562.22	664.45	724.45	894.44	833.33	778.67	702.50	730.97	624.06	444.45	544.00
	1 pm	515.55	562.22	662.22	720.00	872.22	861.11	762.66	702.50	752.09	608.39	453.34	522.66
	2 pm	462.22	506.66	602.22	664.45	805.56	763.89	722.67	630.00	712.50	514.39	406.66	448.00
	3 pm	353.34	384.45	497.78	564.45	666.67	688.89	602.67	540.00	575.28	383.83	313.34	341.34
	4 pm	217.78	266.66	353.34	420.00	513.89	538.89	469.33	430.00	414.30	229.77	177.78	200.00
	5 pm	71.11	111.11	188.89	233.34	322.22	333.33	280.00	282.50	255.97	73.11	62.22	58.67
Diffuse	8 am	64.16	91.66	134.44	187.50	215.28	277.77	205.84	239.58	169.30	130.56	63.89	45.84
	9 am	146.66	161.94	192.50	236.11	291.66	350.70	263.89	290.70	239.58	172.22	137.36	122.22
	10 am	195.56	201.66	229.16	277.77	336.80	378.47	295.55	348.20	300.28	205.56	185.28	171.12
	11 am	220.00	232.22	241.38	305.55	392.36	416.66	345.70	370.55	313.05	230.56	223.61	226.12
	12 pm	226.12	244.44	253.62	319.45	440.97	434.03	387.91	376.95	367.36	241.67	245.97	250.56
	1 pm	226.12	241.38	268.88	326.39	440.97	423.61	366.80	367.36	364.17	236.11	258.75	247.50
	2 pm	210.84	247.50	259.72	322.91	378.47	402.78	340.41	351.39	345.00	213.89	230.00	235.28
	3 pm	180.28	213.88	232.22	284.73	333.34	385.41	321.95	316.25	303.47	188.89	191.67	189.44
	4 pm	122.22	168.06	189.44	246.53	319.45	347.22	263.89	277.92	255.55	141.67	140.55	125.28
	5 pm	51.94	85.56	128.34	177.09	253.47	246.53	184.72	207.64	198.05	63.89	61.89	61.16
Beam	8 am	6.95	26.11	63.33	101.39	145.84	80.56	127.49	57.92	91.95	65.27	2.77	23.60
	9 am	88.89	122.51	174.16	217.22	275.01	204.86	266.78	199.30	216.95	193.34	69.31	102.78
	10 am	164.44	218.34	284.17	304.45	371.53	349.31	347.11	249.30	317.22	290.55	148.06	209.44
	11 am	237.78	290.00	371.95	372.23	449.31	400.01	398.30	329.45	378.34	356.94	191.95	276.66
	12 pm	289.44	317.78	410.83	405.00	453.47	399.31	390.75	325.56	363.61	382.39	198.47	316.11
	1 pm	289.44	320.84	393.34	393.61	431.25	437.50	395.86	335.15	387.92	372.28	194.59	296.94
	2 pm	251.39	259.16	342.50	341.54	427.08	361.11	382.26	278.61	367.50	300.50	176.66	231.39
	3 pm	173.06	170.56	265.56	279.72	333.33	303.48	280.72	223.75	271.81	194.94	121.67	166.12
	4 pm	95.56	98.61	163.89	173.47	194.44	191.67	205.44	152.08	158.75	88.10	37.22	83.05
	5 pm	19.17	25.55	60.55	56.25	68.75	86.80	95.29	74.86	57.91	9.22	1.67	3.05

Table 14 Average hourly radiations (W/m^2) for type 'd' weather situation for New Delhi

Solar radiation	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8 am	51.20	94.30	169.75	266.75	304.12	235.12	262.50	208.47	155.00	110.84	63.88	54.45
	9 am	140.11	188.61	331.42	441.89	503.44	350.12	397.50	358.89	287.50	237.66	184.00	176.95
	10 am	237.11	247.89	479.61	600.86	623.56	454.88	515.00	440.70	425.00	375.66	273.44	272.22
	11 am	301.78	291.00	552.36	716.72	702.78	595.44	587.50	530.41	557.50	488.12	375.66	356.61
	12 pm	379.92	369.14	590.08	773.30	761.56	672.12	605.00	572.64	585.00	503.44	444.66	397.45
	1 pm	379.92	412.25	627.80	757.14	764.12	682.34	615.00	588.47	585.00	511.12	477.88	405.61
	2 pm	328.72	374.53	568.53	689.78	621.00	631.22	517.50	562.09	530.00	454.88	424.22	359.34
	3 pm	261.36	299.08	463.45	541.58	529.00	536.66	445.00	496.11	442.50	339.88	337.34	239.55
	4 pm	161.67	204.78	307.17	425.72	426.78	426.78	347.50	348.34	350.00	237.66	198.33	141.55
	5 pm	45.80	88.92	161.67	239.80	255.56	281.12	232.50	195.28	187.50	113.75	66.44	52.72
Diffuse	8 am	48.16	90.67	147.33	207.85	236.17	169.56	215.96	177.50	127.20	107.34	49.58	52.50
	9 am	107.67	150.16	229.50	261.95	342.14	251.31	298.08	257.38	224.83	195.42	116.67	140.00
	10 am	175.66	204.00	297.50	321.74	372.42	360.31	377.16	340.20	310.63	280.00	145.83	186.67
	11 am	221.00	229.50	351.33	387.22	429.94	405.72	438.00	375.71	405.30	335.41	207.08	227.50
	12 pm	246.50	269.17	357.00	404.30	466.28	454.17	441.04	396.41	414.17	364.58	256.66	262.50
	1 pm	255.00	289.00	374.00	432.78	466.28	481.42	431.91	428.96	402.34	332.50	306.25	303.33
	2 pm	240.83	272.00	328.66	387.22	399.67	448.11	386.29	402.34	360.92	282.91	277.08	291.67
	3 pm	187.00	204.00	303.16	333.12	372.42	393.61	358.92	346.13	295.84	259.58	239.17	207.08
	4 pm	138.83	150.16	212.50	298.96	314.89	330.03	276.79	266.25	266.25	224.58	196.78	122.50
	5 pm	42.50	82.17	144.50	205.00	230.11	260.39	197.71	162.71	174.54	104.78	64.17	51.50
Beam	8 am	3.03	3.64	22.42	58.90	67.94	65.55	46.55	30.96	27.79	3.50	14.30	1.95
	9 am	32.44	38.44	101.92	179.94	161.30	98.80	99.42	101.51	62.66	42.25	67.33	36.95
	10 am	61.44	43.89	182.10	279.12	251.14	94.57	137.84	100.49	114.37	95.66	127.61	85.56
	11 am	80.77	61.50	201.03	329.50	272.84	189.72	149.50	154.70	152.20	152.70	168.58	129.11
	12 pm	133.42	99.98	233.08	369.00	295.28	217.94	163.95	176.23	170.83	138.86	188.00	134.95
	1 pm	124.92	123.25	253.80	324.37	297.83	200.92	183.09	159.51	182.66	178.61	171.63	102.28
	2 pm	87.89	102.52	239.86	302.55	221.33	183.11	131.21	159.75	169.08	171.97	147.14	67.67
	3 pm	74.36	95.08	160.28	208.46	156.58	143.05	86.08	149.98	146.67	80.30	98.17	32.47
	4 pm	22.84	54.61	94.67	126.76	111.89	96.75	70.70	82.09	83.75	13.08	1.56	19.05
	5 pm	3.30	6.75	17.17	34.80	25.45	20.73	34.78	32.57	12.95	8.97	2.28	0.78

Table 15 Surrounding temperature for an archetypal day in each month of the year for New Delhi climate

Month▶ Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
12 am	7.80	10.00	15.10	28.40	36.00	32.10	30.20	27.00	28.00	24.90	19.00	13.00
1 am	7.30	9.80	14.20	27.60	34.10	27.10	28.00	25.50	27.10	23.00	19.10	10.00
2 am	6.60	9.60	14.00	26.00	31.00	25.20	26.20	25.30	26.00	21.10	17.00	9.20
3 am	5.00	8.30	13.30	24.20	28.10	24.10	24.00	25.00	26.90	21.00	16.00	8.50
4 am	4.00	8.00	13.10	24.00	27.00	24.00	25.00	24.60	25.00	19.00	15.00	7.00
5 am	5.30	8.10	14.10	24.00	27.60	25.00	26.50	24.60	26.00	20.00	15.40	9.00
6 am	6.40	9.00	15.50	25.50	28.00	26.90	26.20	24.00	26.10	19.50	16.30	9.30
7 am	6.80	9.20	15.70	25.10	30.80	26.60	26.10	24.10	27.50	20.10	16.20	9.50
8 am	7.90	9.20	15.80	25.00	30.80	26.50	26.10	24.30	27.90	21.00	17.00	9.60
9 am	7.90	9.10	15.90	25.00	30.80	26.30	26.10	24.30	27.90	21.00	16.70	9.10
10 am	7.90	8.90	15.90	25.00	30.10	26.30	26.20	24.30	27.90	20.50	16.50	8.90
11 am	6.60	8.80	15.80	25.10	30.60	26.50	26.30	24.30	28.30	20.50	16.00	8.70
12 pm	6.40	8.90	16.60	25.90	31.80	27.30	26.60	24.40	28.90	22.70	16.20	9.40
1 pm	7.70	11.40	19.90	27.60	33.80	29.90	28.00	25.50	30.60	25.00	20.50	13.10
2 pm	10.60	15.10	22.80	30.30	35.30	31.40	28.40	25.60	32.30	28.30	25.00	16.80
3 pm	13.00	18.30	26.20	31.70	36.60	32.20	29.30	26.00	33.50	30.50	27.60	19.30
4 pm	15.00	20.10	27.00	33.20	37.60	33.60	30.40	26.40	33.90	31.60	28.50	20.90
5 pm	16.50	21.60	28.90	34.40	38.50	34.30	32.20	27.10	35.50	32.70	29.60	21.70
6 pm	17.00	22.20	25.30	35.30	40.30	34.20	33.80	28.30	36.00	34.00	30.20	20.00
7 pm	15.80	20.70	24.20	34.20	40.00	34.20	33.00	28.00	35.00	32.30	27.00	18.00
8 pm	14.10	19.60	21.10	32.30	38.60	34.10	32.60	27.30	32.00	30.00	25.10	17.00
9 pm	12.90	18.30	20.30	30.00	38.00	34.00	32.40	27.00	29.20	28.10	23.00	15.00
10 pm	10.20	15.20	18.20	29.30	38.00	35.00	31.50	27.50	28.10	27.20	21.00	14.50
11 pm	8.20	13.50	15.00	29.00	37.30	35.00	31.20	27.20	28.00	26.00	19.10	14.20

Table 16 Number of various types of days in each month of the year for New Delhi climate

Type of days	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
a	3	3	5	4	4	3	2	2	7	5	6	3
b	8	4	6	7	9	4	3	3	3	10	10	7
c	11	12	12	14	12	14	10	7	10	13	12	13
d	9	9	8	5	6	9	17	19	10	3	2	8

Nomenclature Symbols

A_g: area of condensing cover, m²; A_b : area of basin, m²; C_w: specific heat capacity of water, J/kg-K; $F_{CR, i, n}$: capital recovery factor, fraction; $F_{SR, i, n}$: sinking fund factor, fraction; h_{rwgE}: radiative HTC from water surface to condensing cover facing east, W/m²-K; h_{rwgW}: radiative HTC from water surface to condensing cover facing west, W/m²-K; h_{rwgS} : radiative HTC from water surface to condensing cover facing south, W/m²-K; h_{rwgN} : radiative HTC from water surface to condensing cover facing north, W/m²-K; h_{cwgE}: convective HTC from water surface to condensing cover facing east, W/m²-K; h_{cwgW}: convective HTC from water surface to condensing cover facing west, W/m²-K; h_{cwgS} : convective HTC from water surface to condensing cover facing south, W/m²-K; h_{cwgN} : convective HTC from water surface to condensing cover facing north, W/m²-K; h_{ewgE} : evaporative HTC from water surface to condensing cover facing east, W/m²-K; h_{ewgW}: evaporative HTC from water surface to condensing cover facing west, W/m²-K; h_{ewgS} : evaporative HTC from water surface to condensing cover facing south, W/m²-K; h_{ewgN}: evaporative HTC from water surface to condensing cover facing north, W/m²-K; I_{SE}: solar radiation impinging on glass cover facing east, W/m²; I_{SW}: solar radiation impinging on glass cover facing west, W/m²; I_{SN} : solar radiation impinging on glass cover facing north, W/m²; I_{SS} : solar radiation impinging on glass cover facing south, W/m²; h_{EW} : radiative HTC between east and west condensing surfaces, W/m²-K; h_{NS}: radiative HTC between south and north condensing surfaces,

W/m^2-K; M_w: mass of water in the basin, kg; t: time, s; T_w: temperature of water in the basin, °C; T_{wo}: temperature of water in the basin at t = 0, °C; T_a: ambient temperature, °C; T_{gE}: condensing cover temperature facing east, °C; T_{gW}: condensing cover temperature facing west, °C; T_{gS}: condensing cover temperature facing south, °C; T_{gN}: condensing cover temperature facing north, °C; r: rate of interest, %; L: latent heat, J/kg; n: number of clear days; l: life of the system; $\dot{Ex}_{hourly}$: hourly exergy output from conical PSS, kWh; S: number of sunshine hours

Greek

$\xi_{carbon\ dioxide}$: reduction in the emission of carbon dioxide; $\acute{\alpha}_g$: absorptivity of condensing cover, fraction; $\acute{\alpha}_w$: absorptivity of water mass, fraction; $\eta_{p,\ annual}$: annual productivity, %; γ: ratio of daily diffuse to daily global irradiation

Abbreviations

CPSS: conical passive solar still; *CF*: annual cash flow, Rs.; *DPS*: double slope passive solar still; *EHTC*: equivalent heat transfer coefficient, W/m^2-K; *HTC*: heat transfer coefficient, W/m^2-K; *PSS*: passive solar still; *SPS*: single slope passive solar still; *UEC*: uniform end-of-year annual cost, Rs.

Declarations

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