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Conference paper

Comparative Evaluation of Performance Parameters of Single Slope Solar Still with and without using Paraffin Wax

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ABSTRACT

The old methods for producing drinkable water have problems with electricity, maintenance, proper space, etc. To overcome these problems, researchers have switched to a solar still for producing water in an efficient way. In contrast to conventional solar stills, various researchers have been working to increase the distillate output while simultaneously lowering the price per liter of distillate output by incorporating a variety of efficient techniques, which include solar still design configurations, stills with solar collectors, diverse use of energy storage materials, and many more. Therefore, the present study aims at enhancing fresh water production by the use of paraffin wax as a phase-changing material (PCM), which first absorbs and retains heat in latent form during sunlight hours and later it provides same stored heat to the basin water and hence maintains the basin water temperature even during absence of sunshine hours when the intensity of solar radiation starts decreasing drastically. Also, the comparison of solar still with and without using paraffin wax is done based on energy efficiency, exergy efficiency, yield productivity, environmental analysis, economic analysis, and. It has been found that the maximum energy efficiency, exergy efficiency, and total yield for the still with & without using PCM are 93.7% & 88.9%, 6.61% & 3.41% and 1493ml &1155ml in a 24-hour study in Gorakhpur, India. The economic and environmental analysis shows that the setup with PCM has a 16.6% shorter payback period and 22.6% greater CO2 mitigation as compared to without using PCM, with the values as 6.05 months and 6.84 tons, respectively. This study can be extended through the utilization of various energy storage materials or changing the design parameters of the solar sill.

1. INTRODUCTION

Water is the primary necessity of life for all organisms living on Earth. Only 0.5% water is useful for drinking out of the available water. The population of living organisms is increasing day by day, which

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results in increasing water consumption. One should use different technologies for obtaining drinkable water without harming the ecosystem and resources. Currently, the most common method for cleaning the water in a household is reverse osmosis (RO), ultraviolet treatment, ozone treatment, etc (Arjunan et al., 2009). All these methods for purifying water rely on electricity for operation, where the cost and its generation, which contribute to global warming, pose significant concerns for the human population. are. From this perspective solar desalination emerges as the best option for purifying salty water to potable water by utilizing solar energy - safe, clean, environmentally friendly, and abundantly accessible—without the need for electricity. However, the productivity from solar stills is quite low and has been the subject of extensive research, and it continues to be pursued till a sufficient increment in yield productivity. Moreover, different techniques and methods such as modifications in still design, such as single slope, double slope, pyramidal shape, use of different solar collectors and reflectors, and also use of different energy storing materials such as nano-particles, phase change materials.

The most commonly used solar still for research purposes is the single slope solar still (SSSS) because of its simple construction and ease of certain modifications. Hameed et al. examined the design using numerical study on the functioning of SSSS by utilising different geometries of stainless steel in the basin absorber. The different designs were small-sized balls, large-sized balls, small horizontal cylinders, small vertical cylinders, large horizontal cylinders, large vertical cylinders, and cone-shaped geometries of stainless steel placed at the basin absorber. The author's results show that the maximum productivity was 4.013 kg/m^2 yield output from cone-shaped geometries (Hameed et al., 2023; Ramzy et al. 2023). An experiment was conducted by Al-Mezeini et al. (2023) using a single slope solar still (S) having an external mirror with water depths of 4cm, 5cm, and 7cm in which the maximum output was achieved at 4cm water depth having a yield output of 2.68 Litres/day with the efficiency of 30%.

To increase the performance, energy-storing materials should be used in SSSS, which can absorb the heat in daytime and the same can be released at nighttime. A.S Abdullah et al. (2023) have experimentally investigated SSSS with different modifications to conventional SSSS, such as a heating coil of copper, external and internal reflectors, external condenser, and nano-enhanced PCM. The authors have examined that the output yield was increased to 76%, 58%, 41% and 57% higher using internal and external reflectors, copper heating coil, PCM incorporated external condenser, respectively. Furqan et al. have reviewed different types of energy storage components such as nanomaterials, nanofluids, PCM enhanced with nanomaterials, PCM with porous materials, and PCM with heat pipes and found that all these materials enhance the output of the yield during off-sunshine hours and hence overall yield productivity leading to decreasing in the price rate of freshwater production (Jamil et al., 2023). Ali Fallahi et al. (2017) have experimented utilising various classifications of PCM. The authors have found that solid-solid PCM was better in contrast to solid-liquid PCM as solid-solid PCM has higher energy density, undergoes fewer volume changes, eliminates the problem of leakage, and hence avoids the need for encapsulation. Sampathkumar et al. (2023) et al. have carried out experiments for improving the SS performance using composite heat storage materials (PCM+Beach Sand), sensible (i.e. Beach sand) and latent (PCM-Paraffin Wax) heat storage materials. The author's findings were SS integrated with composite heat storage components has the highest thermal efficiency of 21.59% and yield output of 2.05 l/m^2, followed by SS with latent heat storage having thermal efficiency of 19.83% and yield output of 1.88 l/m^2, followed by SS with sensible heat storage having thermal efficiency of 14.92% and yield output of 1.42 l/m^2. Further, the PBP and CPL of fresh water from SS with composite heat storage is minimal.

Nanofluids, along with PCMs can also be used to improve the efficiency of SSSS. Sangeetha et al. have reviewed the performance of DSSS with storage of thermal energy, i.e., PCM & nanofluids (NFs). The authors discovered that the integration of PCM and NFs into DSSS significantly increases the DSSS yield output (Sangeetha et al., 2023). PCM materials can be employed with solar stills to increase the performance during nighttime. Al-harahsheh et al. (2018) have studied on performance of SS augmented with PCM and external solar collectors for water desalination. The authors have found that using external solar collectors and PCM simultaneously with SS increases the overall yield output as it increases the yield in off-sunshine hours by utilizing stored latent energy. Further, the flow rates for water in solar collectors have a substantial impact on productivity. Jahanpanah et al. (2021) conducted an experimental study using low-temperature commercial salt hydrate PCM, which has a latent heat of 225 kJ/kg and a melting temperature of 28°C. Three test cases were examined: remaining PCM-free, remaining PCM-containing (3 kg), and remaining PCM-containing (6 kg). In every experiment, the operating temperature, hourly and cumulative productivities, and desalination efficiency were monitored and computed. Six kilogrammes of PCM were found to increase the desalination efficiency from 28.13% to 36.42%. Several solar desalination systems' operating performance has been examined by Mohammed et al. (2021) proposed with varying quantities of PCM (say 2kg, 4kg, 6kg) used at the stills basin and without PCM. The outcomes show that the yield output was maximum from SS employing 4kg of PCM than SS with 2kg and 4kg of PCM, respectively. Kumar et al. (2023) have studied the SSSS with three different modifications. In the first, there was no PCM, i.e., CSS; second, there was the use of inorganic PCM materials (say sodium acetate trihydrate); and third, employed nano-doped PCM (say 0.75% of MgO nano-particle doped in inorganic PCM). The experimental results evinced an increase in yield output by 45.23% and 26.63% higher than CSS using nano-doped inorganic PCM and inorganic PCM, respectively. Saad et al. (2024) have examined the melting temperature, specific heat, and latent heat of different types of PCM (say, Vaseline, Paraffin wax, and Soy Wax) and their effects on the performance of SSSS during the spring and summer seasons. The melting temperatures were 39℃, 67℃, and 52℃for Soy Wax, Vaseline, and Paraffin wax, respectively. The author's results demonstrate that productivity was increased by 51.91% and 124.74% for Soy wax, 45.72% and 110.68% for Vaseline, and 43.35% and 103.18% for Paraffin wax in summer and spring conditions, respectively. Patel et al. (2021) assessed the efficiency of an active SSSS in conjunction with several kinds of solar collectors, such as parabolic trough and flat-plate models. The authors found that the argumentation of solar collectors, i.e., flat plate collectors and parabolic trough collectors, increases the yield productivity by 415% and 115% in the winter and summer seasons, respectively, as these collectors increase the heat transfer rates and hence increase productivity. Kumar et al. (2021) have performed an experiment to increase the productivity of conventional SSSS using PCM and nano-enhanced PCM. The author's experimental evidence shows that with the use of nano-enhanced PCM, the productivity was increased to 67.07%, while from only using PCM, the productivity was 51.22%. Sujit Kumar et al. (2022) have carried out an experiment comparing energy, exergy efficiencies, and distillate output for different setups- Conventional SSSS, SSSS integrated with PCM, SSSS integrated with PCM and solar air heater at different water depths of 3cm, 6cm, 9cm, 12cm, and 15cm. The authors found that at a water depth of 3 cm, the hourly energy, exergy, and distillate production were at their highest when SSSS was combined with PCM and a solar air heater. Hemmatian et al. (2024) examine the effect on water production under conditions of low solar irradiation intensity by PCM placed inside a thermosyphon heat pipe and two filling ratios of 50% and 100% to SS for pulsing heat pipe evacuated tubes. The experimental results show that SS with a heat pipe has an energy efficiency of 19.4% while that of SS with a pulsating heat pipe has an energy efficiency of 20.3%. Khan et al. (2019) have an experimental investigation on the performance of SSSS with and without using Bitumen as PCM under Bangladesh weather conditions. It was found by the authors that the efficiency with PCM increased to 17 % while that without PCM was 13.6%. Further, the yield output per hour was 123 ml/m^2 and 110 ml/m^2 with and without PCM, respectively. Tiwari et al. (2023) have carried out experimental work with the aim of enhancing the productivity of SS. The authors have analyzed three different models of SS-CSS, CSS with PCM placed under a basin liner, and CSS with PCM placed inside a copper tube at the basin. The experiments were carried out at a water depth of 6cm for all three setups. The author's results reveal there was an increase the efficacy of solar stills utilizing PCM, but the highest increase was in CSS with PCM placed under the basin.

After having a thorough review of previous research works, fewer studies have been conducted in single slope solar stills at Gorakhpur, Uttar Pradesh (Longitude- 83.37°E, Latitude 26.76°N), where the average daily solar radiation is 400-700 W/m^2 (according to profileSOLAR). Thus, the specific novelty of the present study is to examine the performance parameters, such as energy, exergy, environmental, and economic, of a SSSS using paraffin wax as PCM (i.e., latent energy storage) and comparing them without using PCM. Further, it also aims at investigating the effectiveness of the use of Paraffin wax as PCM alone in single slope solar sills at Gorakhpur, Uttar Pradesh.

2. MATERIALS AND METHODOLOGY

2.1 Experimental Setup

The current work involves investigating the performance (such as energy, exergy, economics, and environmental) for 2 different setups: 1. Conventional solar still (CSS) without PCM, and 2. Conventional solar still (CSS) with PCM. Here, paraffin wax is used as a PCM because of its easy availability, low cost, and suitable melting temperature range. Paraffin wax is put inside a rectangular box as a latent heat storage material and kept inside the basin of CSS with PCM. Both setups were similar in structure (i.e. Single slope), and dimension, having a basin area of 1 m x 1 m, an inclination angle of 26.76°, a glass cover thickness of 3 mm, front and back heights of 16 cm and 97 cm respectively, an inclined height of 110 cm, and GI sheets with a thickness of 0.6 mm, and aluminum absorber sheet was painted with black dye for both setups. However, three rectangular boxes of dimensions length-74 cm x breadth-4.4 cm x height-2.2 cm were used to store PCM (Paraffin Wax) at the basin absorber inside CSS with PCM. The insulation thermocol of thickness 4mm has been used for retaining maximum heat inside the solar stills for both setups. In addition, K-type thermocouple wires have been used for measuring the temperature at various locations inside solar stills for both setups. Further, the water condensed at the inner glass is made to flow through the glass slope and is collected in a beaker. Later, the water collected in the beaker is measured using a measuring cylinder. The complete schematic picture of the experimental setup is shown in Figure 1. Table 1 represents the thermophysical properties of paraffin wax.

Fig 1. Schematic picture of the experimental setup illustrating various parts.

Table 1. Properties of Paraffin Wax

Melting Point	Specific Heat	Density	Thermal Conductivity	Latent heat	Boiling Point
331 K	2.48 kJ/kg	910 kg/m^3	0.22 W/mK	210 kJ/kg	643 K

2.2 Instrumentation and Accuracy

Different types of instruments were used to find out different parameters of the solar still (SS), like temperature, wind velocity, solar radiation, and ambient temperature. K-type of thermocouple wire was used to measure the temperature at various locations inside the SS, including the absorber, basin water, inner glass temperature, and PCM. To obtain precise temperatures at various locations, each thermocouple wire was connected to a digital multi-point temperature indicator. The amount of radiation coming from the sun was measured using a solar power meter. An anemometer was used to measure the wind velocity (BTH 401). Using a measuring flask, the yield productivity from solar stills was determined. The detailed technical specifications of various instruments are given in Table 2.

Table 2. Technical Specifications of Measuring Devices

Instrument	Accuracy	Range
Thermocouple (K-type)	± 0.1 °C	0–200 °C
Multi-point digital temperature indicator	± 1 °C	0–200 °C
Measuring Flask	± 1ml	0-1000 ml
Anemometer	± 0.1 m/s	0.2-20 m/s
Solar Power Meter	±10 W/m^2	0-1999 W/m^2

3. MATHEMATICAL FORMULATION

This experimental work was carried out at the MED, MMMUT, Gorakhpur (Longitude- 83.37°E, Latitude 26.76°N) in 1st week of October. Both configurations were orientated southward to optimize sunlight absorption, and the water depth of 2 cm throughout the day. Furthermore, the variation of temperatures at different locations inside the SS and atmospheric conditions were observed at an interval every 30 min from 7:00 AM to 7:00 AM the next day (24-hour cycle).

3.1 Energy Analysis

The mathematical model highlights the complete performance of the system by calculating thermal performance metrics, including energy efficiency, economic, and environmental analysis. Energy efficiency is defined as the ratio of output to input energy. Here, latent heat from the condensation of water vapour to produce fresh water is the output energy, and the output is condensed, evaporated fresh water (Khan et al., 2019; Surapaju et al., 2023). In contrast, input energy is the intensity of the sun's radiation that strikes the basin's surface. The following formulas are used to determine the daily energy efficiency:

$$\eta_{energy} = \frac{\sum m_w \times L}{\sum I_{t(s)} \times A_s} \tag{1}$$

Where $\sum m_w$ = Total amount of distillate per day in kg/m^2 and can be calculated as (Fallahi et al., 2017):

$$m_w = \frac{hev{,}wgi \times (Tw - Tgi)}{L} \tag{2}$$

L= Latent Heat of Evaporation of fresh water at temperature Tw, and are determined from equation (3) (Abdullah et al., 2023; Fallahi et al. 2017):

$$L = 3161500 - (2407.41 \times T_w) \text{ J/Kg} \tag{3}$$

where T_w is in °C.

The evaporative heat transfer coefficient (h_{ev}) is calculated by Dunkel's relations, which are given in equation (4) (Fallahi et al. 2017).

$$h_{\mathrm{ev,w-gi}} = 0.016273 \times hcw \times \left(\frac{Pw - Pgi}{Tw - Tgi}\right) \tag{4}$$

The heat transfer coefficient from the convection heat transfer (hcw) is determined using equation (5) (Fallahi et al., 2017; Ramzy et al. 2023):

$$h_{\mathrm{cw-gi}} = 0.884\left[(Tw - Tgi) + \frac{(Pw - Pgi)(Tw + 273.15)}{268900 - Pw}\right]^{\frac{1}{3}} \tag{5}$$

The two important parameters, P_w and P_{gi}, are calculated using the following relations (Fallahi et al., 2017; Ramzy et al. 2023):

$$P_w = exp\left[25.317 - \left(\frac{5144}{Tw + 273}\right)\right] \tag{6}$$

$$P_{gi} = exp\left[25.317 - \left(\frac{5144}{Tgi + 273}\right)\right] \tag{7}$$

3.2 Exergy Analysis

Exergy refers to the maximum amount of usable energy that can be extracted from a system before it attains a dead state, characterized by a decrease of kinetic and potential energy, as well as the equalization of temperature and pressure with the surrounding environment. It plays a crucial role in improving the SS performance. Its definition is a fraction of output exergy (i.e., the exergy of water evaporation in SS) to input exergy (i.e., the exergy of the sun’s radiation intensity).

The exergy efficiency can be computed as (Abdullah et al., 2023; Fallahi et al., 2017):

$$\eta_{exergy} = \frac{\sum \text{Exergy}_{out}}{\sum \text{Exergy}_{in}} \tag{8}$$

Where,

$$\sum Exergy_{out} = \sum Exergy_{evap} = m_w \times L \times \left[1 - \left(\frac{Ta+273}{Tw+273}\right)\right] \tag{9}$$

$$\sum Exergy_{in} = \sum Exergy_{sun} = A_s \times \sum I_{t(s)} \times \left[1 - \left(\frac{4}{3} \times \left(\frac{T_a+273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a+273}{T_s}\right)^4\right)\right] \tag{10}$$

Where T_s = 5700 K

3.3 Economic Analysis

Economic analysis is used to check whether the existing system is cost-effective, compatible, and sustainable in comparison to a typical working system (Anika et al., 2024). The different parameters of economic analysis for different stills are calculated using the following equation (Fallahi et al., 2017; Kumaravel et al., 2024):

$$\text{FAC} = \text{CRF} \times \text{CC} \tag{11}$$

$$\text{CRF} = \frac{\text{i}(\text{i}+1)^{\text{n}}}{(\text{i}+1)^{\text{n}} - 1} \tag{12}$$

Where i = annual bank interest rate (assumed as 8%) and n = life span of SS in years (assumed as 10 years)

$$\text{ASV} = \text{SFF} \times \text{SV} \tag{13}$$

$$\text{SFF} = \frac{i}{(i+1)^n - 1} \tag{14}$$

$$\text{salvage value (SV)} = 0.2 \times \text{CC} \tag{15}$$

$$\text{AMC} = 0.10 \times \text{FAC} \tag{16}$$

$$\text{TAC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{17}$$

$$\text{CPL} = \frac{\text{TAC}}{\text{Pd}} \tag{18}$$

Where P_d = Annual distillate produced from Solar stills operated for 300 clear sunny days.

The payback period assesses the duration required to make up the capital expenditure invested in designing any system. This parameter is crucial for assessing the system's feasibility. The smaller the pay-back period of the system, the higher the feasibility. Whereas a higher pay-back period decreases the feasibility of the system. The pay-back period for a current solar desalination system is calculated using equations (Kumar et al., 2023; Kumaravel et al. 2024):

$$PBP = \frac{\ln\left(\frac{m \times SP}{m \times SP - (CC \times AMC) \times i}\right)}{\ln(1+i)} \tag{19}$$

Where m is the annual yield (Kg) obtained from SS and SP is the selling price of water.

3.4 Environmental analysis

Promoting the use of solar- desalination technology helps to lower carbon emissions in the atmosphere (Abdel-Aziz et al., 2023). This study's environmental analysis aims to forecast how much CO_2 emissions will be reduced as a result of using this technology (Shatar et al., 2023).

An average power-producing station releases 980 g CO_2/kW of CO_2 into the atmosphere when it generates electricity. Nevertheless, taking into account 40% losses from distribution and about 20% losses from inefficient domestic devices, the total CO_2 per kWh is calculated to be 2 kg. Thus, the annual CO_2 emission by solar distillers can be stated as

$$CO_2 \text{ emission per year} = \frac{E_{in} \times 2}{n} \tag{20}$$

$$CO_2 \text{ emission in total life Span (tons)} = \frac{E_{in} \times 2}{1000} \tag{21}$$

Over the lifetime of the system, the quantity of carbon dioxide that is reduced may be represented as CO2 mitigation.

$$CO_2 \text{ mitigation (tons)}, \left(\vartheta_{co_2}\right) = \frac{E_{en,out} \times n \times 2}{1000} \tag{22}$$

Where E_{en}, out is termed as the output energy from the solar desalination system per year.

3.5 Enviro-economic analysis

Promoting the use of solar desalination technology helps to lower carbon emissions in the atmosphere (Suraparaju et al., 2023). This study's environmental analysis aims to forecast how much CO_2 emissions will be reduced as a result of using this technology (Singh & Kumar, 2024):

$$\text{Net } CO_2 \text{ mitigation (tons)} = \left(\frac{\left(\left(E_{en,out} \times n\right) - E_{in}\right) \times 2}{1000}\right) \tag{23}$$

The emissions of 1 ton of CO_2 or another greenhouse gas (GHG) are known as carbon credits. 14.5 dollars per ton of CO_2 is the assumed trade price. As a result, the system's carbon credit acquired over its lifetime can be expressed as follows. CO_2 generated and released per kWh is 0.96 kilogram (Sovacool, 2008).

Carbon Credit Earned (CCE) = Carbon Credit × Monetary value per ton.

$$\text{CCE (USD)} = \left(\frac{\left((E_{en,out} \times n) - E_{in}\right) \times 2}{1000}\right) \times USD/co_2 \qquad (24)$$

Where E_{in} and n stand for embodied energy and the system's overall lifespan in years, respectively. Embodied energy is defined as the energy used at every stage of production. These phases include resource extraction and processing, manufacturing, transportation, and product distribution; they do not include the energy needed to operate and dispose of building materials (Rajaseenivasan & Srithar, 2016).

4. RESULTS AND DISCUSSIONS

The whole experimental work was completed in two successive days in October 2024 because of the lower chances of deviation in atmospheric conditions for both experiments, i.e., with and without using PCM. For a simple illustration of the results, CSS and CSSP are termed as CSS without PCM and CSS with PCM, respectively. For both configurations, readings are obtained every half hour for 24 hours. All readings were taken three times to maintain accuracy in readings during the experimentation. The experiment on CSS without PCM was performed on day 1, while the experiment on CSS with PCM was performed on day 2. In addition, energy, exergy, economic, and environmental parameters were evaluated and analysed for both setups.

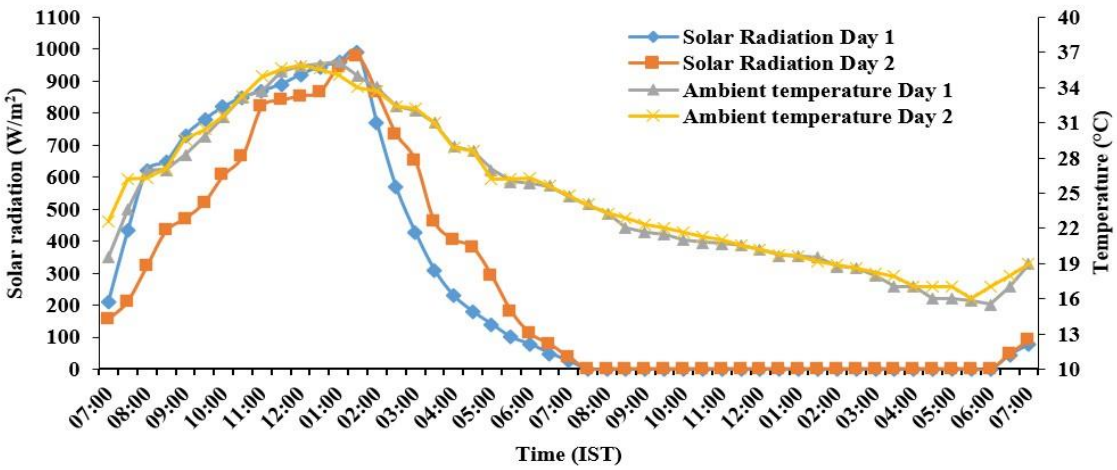


Fig 2. Variation of ambient temperature and solar radiation for day 1 and day 2

"Figure (2)" illustrates how the ambient temperature and solar radiation vary with time for two successive days of experimentation on a half-hourly basis over 24 hours. Maximum sun radiation was found. at 1:30 PM for day 1 as well as day 2 with solar intensity of 990 and 978 W/m^2, respectively, after which it decreases. The maximum values of ambient temperature for day 1 and day 2 were 35.8 and 35.9°C, respectively. The average solar radiation during sunshine hours and average ambient temperature for day 1 were 541.76 W/m^2 and 24.7°C, respectively, while for day 2, these values were 514.76 W/m^2 and 25°C, respectively, as shown in "Figure (3)".

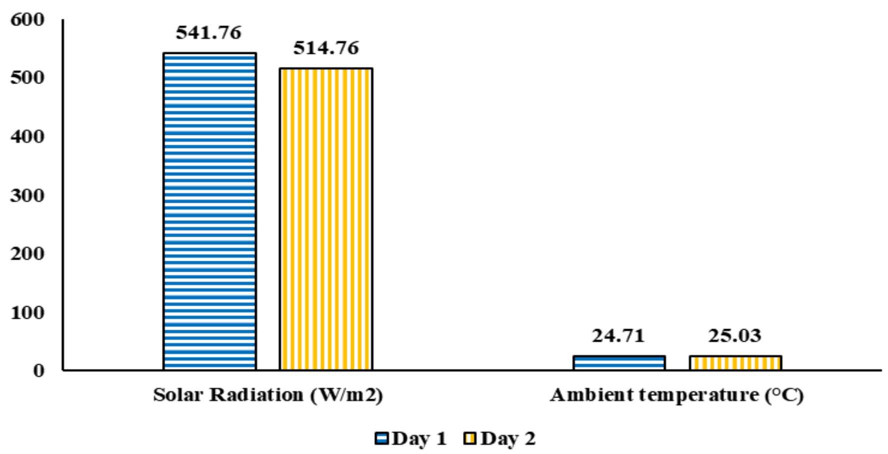


Fig 3. Average values of ambient condition for day 1 and day 2.

"Figure (4)" shows the variation of inner glass, basin, water, and ambient temperatures change over time for CSS without PCM. It clearly shows that all the temperatures are greater than the ambient temperature at all times. In the morning, when the sun's radiation encounters the glass cover first thereby increases its temperature rapidly till 9:30 AM. Basin temperature and water temperature also get increased till 1:30 PM, after which they start decreasing till the next morning, and then again increase. This is because of the variation of solar radiation, which is increasing till 1:30 PM and decreasing onwards. The inner glass temperature of the SS plays a role in the evaporation and condensation of water inside the solar still. Initially, it increased with an increase in solar radiation till 10:30 AM and then decreased onwards. This is an indication of the start of water collection through the evaporation and condensation of water inside the SS. A larger temperature differential between the inner glass and water causes basin water to absorb more heat and gather more water. In next morning, the temperatures increase because of solar radiation.

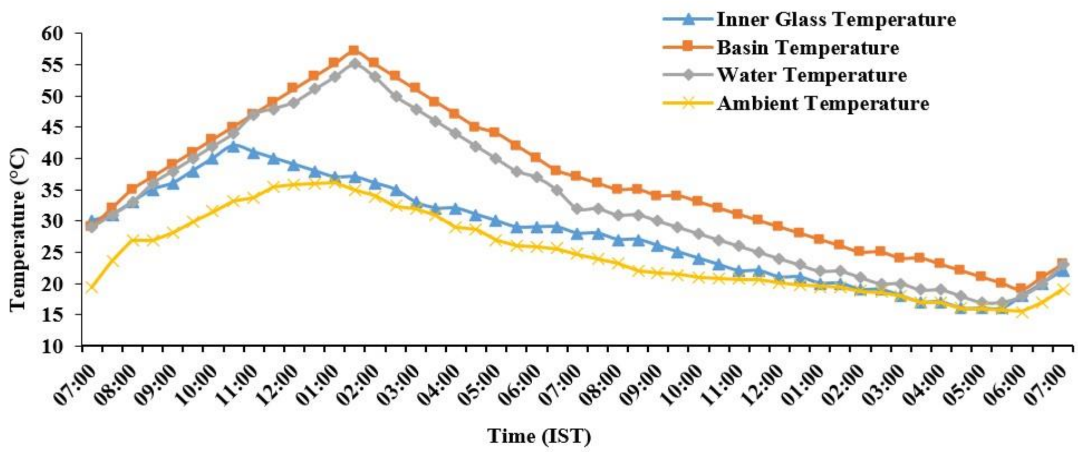


Fig. 4. Variation of various temperatures with time for CSS without PCM.

"Figure (5)" demonstrates how inner glass, basin, water, PCM, and ambient temperatures vary throughout the daytime for CSS with PCM. Similar to CSS without PCM, all the temperatures are greater than the ambient temperature at all times. However, the main difference between the variation of temperatures in basin water and inner glass for CSS without PCM and CSS with PCM occurs during off-sunshine hours. For CSS with PCM, the water temperature is greater than the basin temperature till 02:00 PM because water is taking heat from the basin as well as solar radiation, and the basin is releasing heat to water as well as PCM. After 02:00 PM, water just absorbs basin heat, while PCM returns the absorbed heat to the basin. This causes water and interior glass temperature differences greater compared to CSS without PCM, resulting in more water collection through CSS with PCM. The temperature of PCM is greater than all temperatures during evening and nighttime, which shows its effectiveness in applications of solar energy.

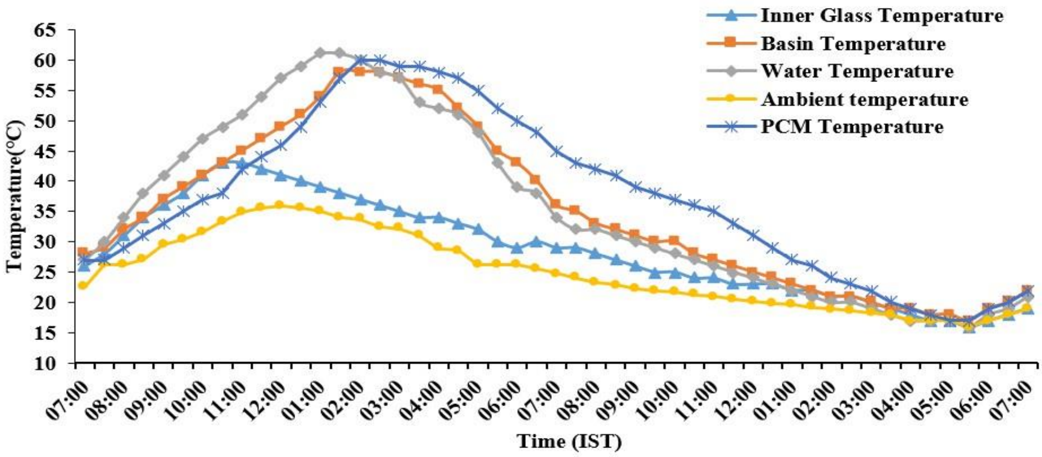


Fig 5. Variation of various temperatures with time for CSS with PCM.

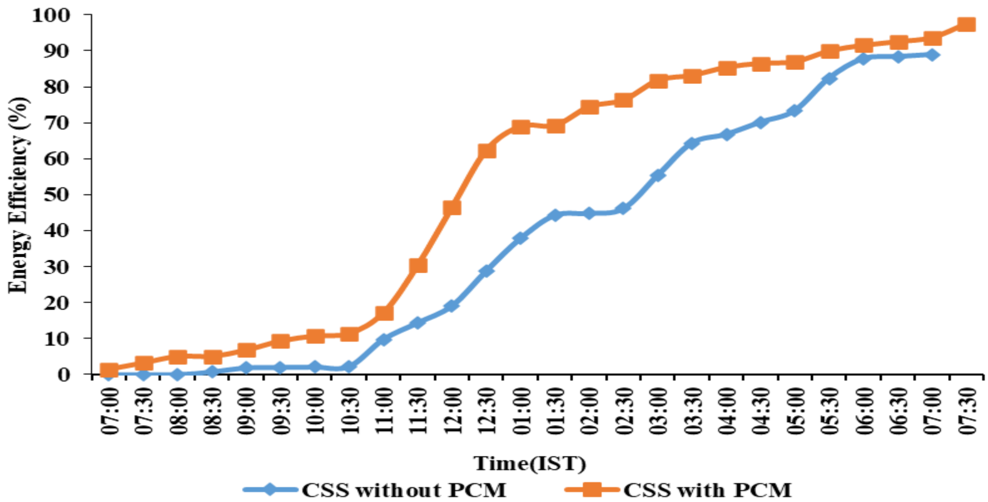


Fig. 6. Variation of energy efficiency with time for CSS without PCM and CSS with PCM

"Figure (6)" compares both systems' energy efficiency till evening. The graph illustrates the variation of energy efficiency for CSS without PCM and CSS with PCM. It is seen clearly that energy efficiency is found to be zero at the start when the inner glass temperature exceeds that of the water. But when water temperature exceeds the inner glass temperature, the efficiency for energy increases gradually. The sudden increment in energy efficiency starts at 10:30 AM for both setups when the collection of evaporated water is started. This is because of the increase in heat absorption by water and the greater differences between the inner glass and water temperature. CSS with PCM has higher energy efficiency than CSS without PCM at all times because of its uniform heat distribution towards the water. The maximum values of energy efficiency for both setups, i.e., CSS without PCM and CSS with PCM, were found to be 88.9% and 93.7%, respectively. However, the average energy efficiency for CSS with PCM is 50.15% which is 23.15% greater than the energy efficiency of CSS without PCM, which is 40.89%.

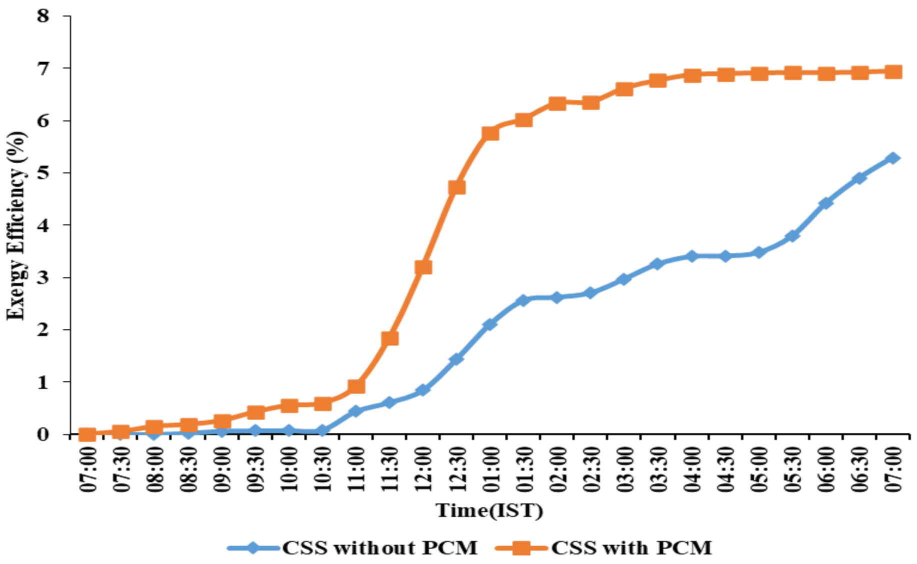


Fig 7. Variation of exergy efficiency with time for CSS without PCM and CSS with PCM.

“Figure (7)” illustrates the change in exergy efficiency for both configurations, i.e., CSS without PCM and CSS with PCM, over time until the evening. Here, the graph indicates that the exergy efficiency for both configurations is on the rise over time. The exergy efficiency is found to be zero before 9:30 AM when the temperature of the inner glass exceeds that of the water. But when water temperature exceeds the temperature of the inner glass due to solar radiation, the exergy efficiency increases gradually. The sudden increment can be seen after 10:30 AM because more useful heat is absorbed by water. CSS with PCM has a higher exergy efficiency than CSS without PCM at all times because of its uniform useful heat distribution towards the water. The maximum values of exergy efficiency for both CSS without PCM and CSS with PCM were 3.41% and 6.61%, respectively. Average exergy efficiency for CSS with PCM is 42.8% greater than that of CSS without PCM, with the values as 3.30% and 1.88%, respectively.

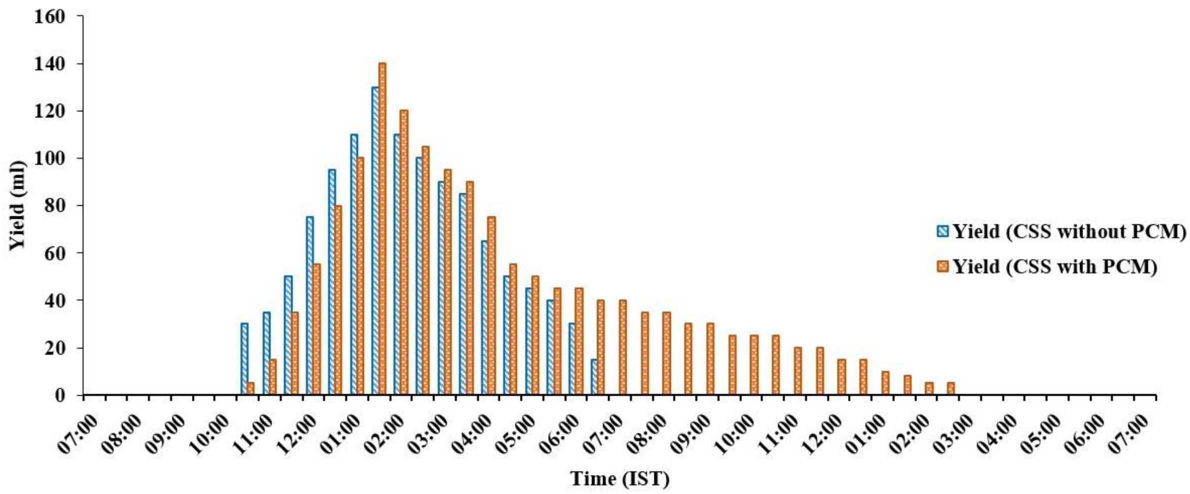


Fig 8. Variation of yield of water with time for setups CSS without PCM and CSS with PCM

“Figure (8)” represents the yield productivity of distillate water (ml) for both setup arrangements with time for 24-hour study. The yield productivity was zero till 10:30 AM for both setups because the inner glass temperature was higher compared to the water temperature, and hence, evaporation did not occur during these periods. However, the yield productivity of both setups increases with an increase in the sun's radiation intensity from 10:30 AM and reaches a maximum at 01:30 PM. After that, yield productivity decreases as the sun's radiation intensity decreases. From 10:30 AM to 01:00 PM, the yield production from CSS without PCM is higher than CSS with PCM because at starting, PCM as well as water take heat from the absorber sheet of CSS with PCM while for setup CSS without PCM, only water takes heat from the absorber sheet for the same amount of solar radiation. However, the yield productivity from CSS with PCM is quite high even in off-sunshine periods as compared to CSS without PCM because the latent heat from paraffin wax has increased. The maximum yield was 140ml and 130ml at 01:30 PM within half an hour for both, i.e., CSS without PCM and with PCM, respectively, while the total yield from CSS without PCM and CSS with PCM was 1155ml and 1493ml, respectively.

The capital cost and cost of maintenance are two important factors that determine the cost of distillate produced from different setups. The capital cost includes the cost of materials used during fabrication of setups such as GI Sheet, glass, PCM, PVC pipe, sealant, and labour costs. The maintenance cost includes the cleanliness of the formation of scales at the still basin, dust accumulation on the glass cover, etc. The fabrication cost, i.e., capital cost in USD ($) for CSS without PCM and CSS with PCM were 45.34$ and 50.43$. Assuming 8% interest rate for 10 years for both setups, various economic parameters can be calculated by equations 12-19. Annual maintenance cost and salvage value have been considered as 10% of fixed annual cost and 20% of capital cost, respectively. Considering 300 days in a year as sunny days, the production of water for CSS without PCM and CSS with PCM was found as 1.26 kg/m2 and 1.89 kg/m2, respectively. 15.9% less cost per liter is found for CSS with PCM in contrast to CSS without PCM, with the values 0.0169$ and 0.0196$, respectively. Irrespective of CPL, the PBP for CSS with PCM is 16.6% less than that of CSS without PCM, which makes it feasible for use.

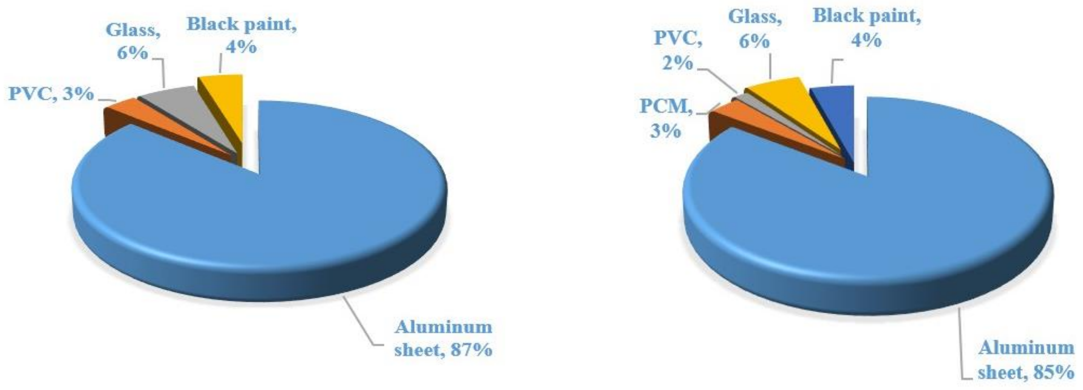
Table 3. Various economic factors with corresponding values for CSS without PCM and CSS with PCM

Parameter	**Values**	
	CSS without PCM	CSS with PCM
Interest Rate (*i*)	8 %	8 %
Life span (*n*)	10 years	10 years
Capital cost (CC) ($)	45.34	50.43
Capital Recovery Factor (CRF)	0.15	0.15
Fixed annual cost (FAC) ($)	6.75	7.51
Annual Maintenance Cost ($)	0.675	0.751
Sinking Fund Factor	0.069	0.069
Salvage value ($)	9.068	10.086
Annual Salvage value ($)	0.6259	0.6962
Total Annual cost (TAC) ($)	6.80	7.57
Production Periods	300 days	300 days
Production Per Day/m^2	1.26 kg/m^2	1.89 kg/m^2
Cost per liter (CPL) ($)	0.0196	0.0169
Payback period (PP) (Months)	7.06	6.05

Embodied energy is an important factor for evaluating the environmental parameters of an experimental setup because it is the energy that occurs during the production of the material used in each component. Table 3 lists the embodied energies of each solar still component. The total embodied energy for CSS without PCM and CSS with PCM is 487.96 kWh and 504.29 kWh, respectively. The percentage of embodied energy of each component for CSS without PCM and CSS with PCM is shown in 9(a) and 9(b), respectively. These figures show that aluminium sheet used for absorbers in setups has the maximum percentage of embodied energy. There is not much difference between the two setups because the same setup is used for experiments, except for the PCM in CSS with PCM.

Table 4. Embodied energy of various components used in CSS without PCM and CSS with PCM

Component	**Material**	**Total Weight**	**Embodied energy (kWh/kg)**	**Embodied energy (kWh) CSS without PCM**	**Embodied energy (kWh) CSS with PCM**
Frame	Aluminum sheet	8	55.28	429.84	429.84
PCM	Paraffin Wax	1.6	10.20	_	16.32
Water outlet	PVC	0.4	18.9	7.56	7.56
Basin cover	Glass	1.6	17.87	28.59	28.59
Coating	Black paint	0.9	24.40	21.96	21.96
Total embodied energy				**487.96 kWh**	**504.29 kWh**



(a) **(b)**

Fig 9. Distribution of embodied energy for different components used in CSS (a) without PCM, (b) with PCM

Carbon emissions are related to the lifecycle of each component of solar still setups. Upon analysis, it has been found that aluminum sheets are the main contributor of Carbon emissions for both setups, with the value as 0.085968 tons among the total carbon emissions of CSS without PCM and CSS with PCM as 0.097 and 0.100 tons, respectively. Other components make a small contribution to carbon emissions for both setups.

CO_2 mitigation is a parameter of environmental analysis that examines how much equivalent CO_2 emissions can be reduced (Zhenyu et al., 2019). This factor is related to the yearly production of water from the solar stills along with their lifetime. Total CO_2 mitigation for CSS without PCM and CSS with PCM has been found as 5.29 and 6.84 tons, respectively, which indicates that CSS with PCM has 22.6% greater CO_2 mitigation as compared to CSS without PCM. Net or effective CO_2 mitigation can be found by subtracting carbon emissions from the CO_2 mitigation. Hence, the net CO_2 mitigation for CSS without PCM and CSS with PCM has been found as 5.20 tons and 6.83 tons, respectively. Carbon credits are a grant for reducing carbon emissions using renewable energy systems. For CSS without PCM and CSS with PCM, net carbon credits were 75.51$ and 99.16$, respectively, which indicates economic, environmental viability, and feasibility for using CSS with PCM, i.e., a solar still with PCM for water production.

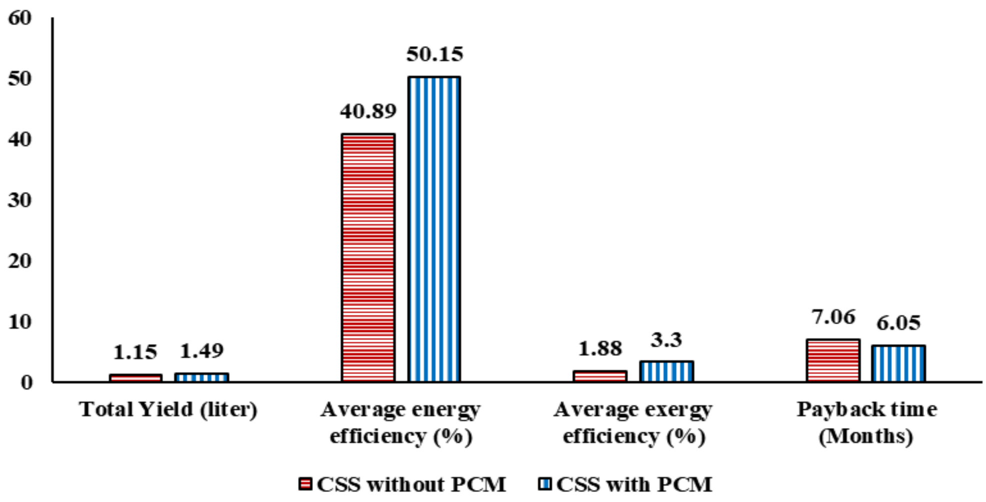


Fig 10. Overall comparison of various performance parameters for both setups

Since there is little difference between the ambient conditions of two consecutive days of experiments, the performance parameters can be compared for both setups. Figure 11 shows the comparative analysis of performance parameters for CSS without PCM and CSS with PCM, which indicates that CSS with PCM, has higher yield production, average energy efficiency, and average exergy efficiency, while less payback time as compared to CSS without PCM. This is an indication of the economic, and environmental feasibility of the use of a solar still using PCM in Gorakhpur, Uttar Pradesh, India, for producing water.

Table 5. Comparison between the current study and previous studies.

S.No	Configuration	References	Yield (L/m²·day)	Efficiency
1.	Single Slope Solar stills with low temperature PCM	Marayam Jahanpanah et al. (2021)	0.450	36.42 %
2.	Single slope basin still + PCM	Mohammed et al. (2021)	1.22	41.2 %
3.	Single-slope still + paraffin wax + preheater (PCM only)	Jothilingam et al. (2024)	1.19	46.8 %
4.	Single slope solar stills with paraffin wax as PCM only	Current study	1.49	50.15 %

5. CONCLUSION

In this experimental research work, the energy, exergy, and economic analysis have been carried out for two different setups, i.e., CSS without PCM and CSS with PCM. The following findings are from the experimental analysis of the two setups.

- As the intensity of solar radiation rises, so do energy and exergy efficiency of both configurations. However, energy and exergy efficiencies of CSS with PCM increase rapidly from 4:00 PM as compared to CSS without PCM, even when the sun's radiation intensity decreases. It is due to the implementation of latent heat storage material in CSS with PCM that is responsible for sustaining an increased temperature gradient.

- CSS with PCM has 23.15% and 42.8% greater average energy efficiency and exergy efficiency as compared to CSS without PCM.
- The daily yield from CSS with PCM is 22.8% higher in water production compared to CSS without PCM, yielding 1.49 liters/m² per day.
- The cost per liter of distillate output from CSS without and with were 0.019$ and 0.016$, while the payback periods at the lifetime of 10 years are 7.05 months and 6.05 months, respectively.
- CSS with PCM has greater CO_2 mitigation and carbon credits as compared to CSS without PCM, with the values of 6.83 tons and 99.16$, respectively.

Overall, it can be concluded that using PCM in SS is technically, economically, and environmentally feasible for water production. This study can be further extended to analyze the performance parameters of solar stills using other energy storing materials like nanoparticles, sand, a combination of PCM with nanoparticles at different weight percentages of nanoparticles.

ABBREVIATIONS

CSS	Conventional Solar Stills
CSSP	Conventional Solar Stills with PCM
SS	Solar still
USD	US Dollars

NOMENCLATURE

AC	Annual cost	I(t)	Intensity of sun's radiation (W/m^2)
AMC	Annual maintenance cost	L	Latent heat of Evaporation (J/kg)
As	Area of Solar Stills	m	Hourly distillate (kg)
ASV	Annual salvage value	PBP	Payback period
CC	Capital cost	PCM	Phase Change Materials
Cp	Specific heat (J/kg K)	P_g	Partial pressure of inner glass surface N/m^2
CPL	Cost per Liter	P_w	Partial pressure of water vapor at basin (N/m^2)
CRF	Capital Recovery Factor	SFF	Sinking Fund factor
E	Energy (W)	T_a	Ambient temperature (°C)
E_x	Exergy (W)	T_{gi}	Temperature at inner glass (°C)
FAC	Fixed Annual cost	T_s	Sun temperature (K)
h	Heat transfer coefficient (W/m^2 K)	T_w	Basin water temperature (°C)
$h_{cw,}$	Convective heat transfer coefficient (W/m^2K)	η_{energy}	Energy efficiency (%)
h_{ew}	Evaporative heat transfer coefficient (W/m^2 K)	η_{exe}	Exergy efficiency (%)

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