

## Exergy, economic and enviro-economic analysis of single slope finned solar still with nano enhanced PCM

T R Sathish Kumar<sup>1\*</sup>, A T Navin Prasad<sup>2</sup> & A Vadivel<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, Sri Ramakrishna Engineering College, Coimbatore 641 022, Tamil Nadu, India

<sup>2</sup>Department of Mechanical Engineering, Velalar College of Engineering and technology, Erode 638 002, Tamil Nadu, India

\*E-mail: prof.tr.s@gmail.com

Received 19 October 2024; accepted 8 October 2025

Solar desalination is an eco-friendly technique for turning brackish water into fresh water. This study evaluated the performance of a single basin solar still utilizing different materials and configurations to assess their economic and environmental viability. The solar stills have been tested in four different cases: conventional solar still (CSS) with 2 cm water depth in the basin, solar still with fins only (SSWF), solar still with fins and phase change material (PCM), and solar still with fins and PCM enhanced with NiO<sub>2</sub> nanoparticles (SSWF+Nano PCM). The results indicated that the SSWF+Nano PCM configuration outperformed the others, exhibiting energy and exergy improvements of 52.89% and 27.63%, respectively, compared to CSS. Additionally, environmental-economic analysis revealed that SSWF+Nano PCM had lower net CO<sub>2</sub> emissions and higher carbon credits earned compared to CSS. Moreover, the cost of production and payback period for SSWF+Nano PCM are found to be more favourable compared to the other configurations.

**Keywords:** Carbon credit, Energy storage, Exergy, Fins, Nano PCM, Phase change material, Solar still

### Introduction

In our daily life, fresh drinking water is essential for cooking, drinking, farming, washing, etc. The most important serious factor is the scarcity of drinking water and tends to have more critical situation in future<sup>1</sup>. To reduce the fresh water scarcity in the world, many scientists are effectively doing research to give best solution. Solar distillation is one of the best approaches to reduce the fresh water scarcity by desalinating the water from oceans and seas. Solar still (SS) is the simplest, cheapest device and non-conventional energy process for producing the fresh drinking water. The authors reported that the main deficiency of the SS was lower in productivity, because of sometimes solar intensity found to be difficult during day hours<sup>2</sup>. Many research undergoing to enhance the efficiency of the SS by different modifications such as integration of energy storage unit, fins attachment, nanomaterials in phase change materials (PCM), different absorber plates, nano coating, cooling over glazing, glazing angle, different water depths, different SS designs, etc<sup>3-5</sup>.

Abdelgaied *et al.*<sup>6</sup> enhanced the performance of tubular solar still (TSS) by implementing circular and square hollow fins filled with PCM. The results revealed that the TSS with square shaped hollow fins

enhanced the yield by 33%, whereas the circular hollow fins showed the productivity enhancement by 47.2%. By integration of hollow circular fins with PCM enhanced the accumulated productivity to 90.1% when compared with traditional TSS. Hameed<sup>7</sup> evaluated the single slope SS with cooling over glass by continuous water spray and pulsed cooling such as 30s/30 min, 30 s/20 min, 30 s/10 min, 30 s/5 min and square cross section hollow fins to improve the productivity. The enhancement of the SS was found to be 10% for continuous spray, 13.3% for 30 s/30 min, 17.8% for 30 s/20 min, 36.2% for 30 s/10 min and 24.2% for 30 s/5 min, respectively. Panchal *et al.*<sup>8</sup> experimentally analyzed the SS with vertical and inclined fins. Authors investigated the SS using the waste wind chime pipes of length 2 cm used as fins both as vertical and inclined. From the investigation, it is found that the SS with inclined and vertical fins produced 2.375 and 2.322 L of water while conventional solar still (CSS) produced only 1.873 L. As a result, it is concluded that the productivity enhanced by 24.19% and 26.77% by using vertical and inclined fins and also stated that there is no significant difference when compared to CSS.

Sebaii *et al.*<sup>9</sup> investigated the single basin SS with finned basin made of various metals and nonmetals

like iron, aluminum, brass, stainless steel glass and mica, and stated that the fin material does not affect the productivity of the still and advised to construct the finned SS with glass or mica in order to avoid the corrosion when it contact with the salty water. Sebaïi *et al.*<sup>10</sup> enhanced the performance of the SS with the effect of fins. From the observation it is noticed that the yield of the finned SS improves with increase in height of the fins and also observed that the productivity falls when the fin number and fin thickness increased. Kumar *et al.*<sup>11</sup> investigated the CSS with fins made up of square pipes with three water depths such as 2 cm to 4 cm. The modified SS were integrated with thin layer of paraffin wax under the basin tray and also in the hollow spaces of the square pipe which acts as energy storage unit. The results revealed that the SS with fins increased the energy efficiency to 64% and fins cum energy storage unit increased the efficiency to 95%, respectively. The exergy efficiency was found to be 7% for CSS and 20% for SS with fins and energy storage unit which results in 74% raise in exergy efficiency during night time.

Dhivagar *et al.*<sup>12</sup> conducted a study on the performance of a single slope (SS) solar still using gravel coarse aggregate for sensible heat storage. The study found that the SS with 1 cm water depth achieved highest energy and exergy efficiency of about 32% and 4.7%, respectively, with a maximum productivity of 4.21 kg/m<sup>2</sup> per day over a 12 h period. The economic analysis revealed a cost of production of fresh water per litre as 0.0618 USD, a payback period of 4.3 months, and a reduction in CO<sub>2</sub> emissions of about 8.27 tons for 1 cm water depth. Mevada *et al.*<sup>13</sup> made modifications to the conventional single slope solar still (CSS) by adding fins, air-cooled condenser in zig-zag, and evacuated tubes, resulting in the modified solar still (MSS). The MSS achieved a higher productivity of 3.92 kg/m<sup>2</sup>, which was 73.45% higher than CSS. The economic analysis showed a cost of 0.013 USD/L for CSS and 0.015 USD/L for MSS. The authors also noted that the CO<sub>2</sub> mitigation was found to be lower for MSS compared to CSS.

From the literature, it is analyzed that the SS with fins, nanomaterials, energy storage unit and effective modifications improved the performance and production of distillate water with less CO<sub>2</sub> mitigation when compared with CSS. The current research work focused on enhancing the performance and efficiency

of the SS and also reducing the production cost and CO<sub>2</sub> emissions by fins, PCM and nanoparticles. The current research aims to increase the productivity and efficiency of the single slope solar still (SS) by integrating fin design and nano-enhanced phase change material (PCM).

## Experimental Section

### Methodology

The SS was designed and fabricated with basin made of aluminium material with thickness of 18 gauge and 0.5 m<sup>2</sup> area. In addition to that, the basin is incorporated with 32 square tubular fins with 20 mm x 20 mm x 50 mm in dimensions. The glazing condensation surface has made of toughened glass fixed at 12° inclination facing south, a value close to the latitude of the experimental location at Coimbatore (latitude 11° N, longitude 76°55' S). The outer casing of the SS is made with the dimension of 1050 mm x 550 mm in wood material. For insulation, thermocol is used with 2 cm thickness. Paraffin wax was utilized as an energy storage material in the thermal energy storage unit to store heat energy during the day. This stored heat energy was then used during non-sunshine hours to increase the yield of the SS. Nickel Oxide (NiO<sub>2</sub>) nanomaterial with 3% of weight were blended with PCM to improve the energy storage. Solar power meter, K-type thermocouples, temperature indicator and measuring jar are used during the experimentation. The experimentation is carried out for the following cases:

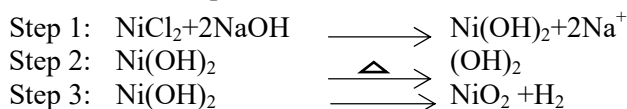
- (i) CSS - Conventional Solar Still (with 2 cm water depth)
- (ii) SSWF - Solar Still with Fins
- (iii) SSWF+PCM - Solar Still with Fins + PCM
- (iv) SSWF+PCM - Solar Still with Fins + Nano PCM

### Preparation of nickel oxide nanomaterial

Nickel oxide (NiO<sub>2</sub>) nanomaterial was synthesized using the precipitation method via a chemical synthesis approach. The process involved adding 1 g of Nickel(II) chloride (NiCl<sub>2</sub>) to 50 mL distilled water at a molar concentration of 0.1. A surfactant, in the form of 0.5 g in 10 mL distilled water at a 0.1 M concentration of PEG (polyethelglycol), was used to reduce the surface energy and reaction rate, and added to the precursor solution. Additionally, 0.05 g of sodium hydroxide, acting as the reducing agent, was added to 10 mL distilled water at a 0.1 M concentration and then to the precursor mixture drop by drop. The resulting 60 mL reaction mixture was

then transferred to a Teflon-lined autoclave. Subsequently, impurities were removed from the sample using an ultra-centrifuge and collected using a Whatman filter. The autoclave was then placed in a hot air oven at 100°C for 12 h before being moved to a box furnace for 6 h of heating and 6 h of cooling. Following this, the autoclave was allowed to air cool after being taken out from the oven. The prepared NiO<sub>2</sub> nanoparticles were then characterized, as shown in Fig. 1 and Fig. 2, which displays the XRD resultant graph for the prepared NiO<sub>2</sub> nanoparticles<sup>14</sup>. Furthermore, Table 1 and Table 2 represent the thermo-physical properties and crystallite size of nickel oxide (NiO<sub>2</sub>)<sup>14,15</sup>.

#### NiO<sub>2</sub> reaction steps



#### Experimental setup and working

The experiments were conducted with fabricated SS at 12° glazing angle which was faced towards the

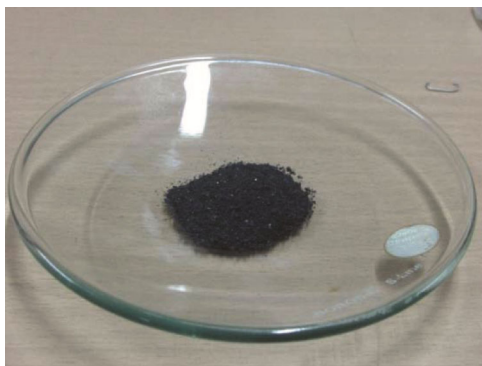


Fig. 1 — NiO<sub>2</sub> powder

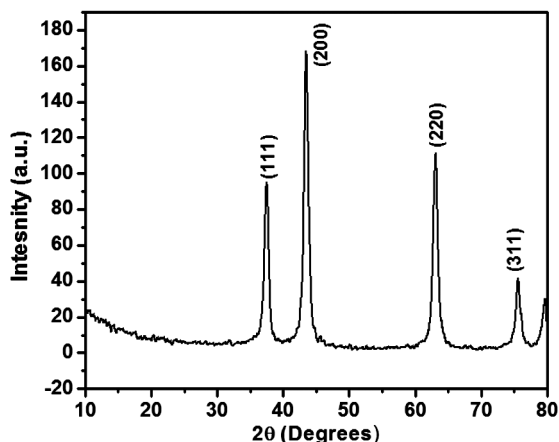


Fig. 2 — X-ray diffractogram of NiO<sub>2</sub>

south for the experimental location in order to receive more solar radiation. The basin tray was poured with brackish water with depth level of 2 cm. The brackish water is heated by solar radiation, causing it to evaporate. The vapour then hits the glazing surface, where it condenses and is collected in a measuring jar through the collecting channel. During this process, the salt content settles down in the basin. The experimentation was conducted from 9 h to 18 h for continuous four days. In day 1, CSS with 2 cm water depth, in day 2, SSWF, in day 3, SSWF+PCM and in day 4, SSWF+NanoPCM was investigated. The measurements of solar radiation intensity, hourly yield and temperatures are taken for every hour to evaluate the performance of the SS. Fig. 3 illustrates the diagrammatic view of SS with modifications, while Fig. 4 depicts the photograph of the experimental setup of the SS.

#### Efficiency analysis

The hourly efficiency of the SS is evaluated by using the flowing relation with the variables such as solar radiation intensity ( $I_s$ ) and hourly productivity ( $m_{\text{water}}$ )

$$\eta_{\text{hourly}} = \frac{m_{\text{water}} \times h_{\text{vw}}}{A \times S_{\text{ri}}} \quad \dots (1)$$

Where,

$m_{\text{water}}$  = hourly productivity of the SS (kg/m<sup>2</sup>),  
 $h_{\text{vw}}$  = latent heat of evaporation of water (J/kg),

Table 1 — Thermo-physical properties of Nickel Oxide

| Property             | Nickel oxide            |
|----------------------|-------------------------|
| Chemical Formula     | NiO <sub>2</sub>        |
| Nickel               | 78.6 %                  |
| Mass of Oxygen       | 21.39 %                 |
| Molar Mass           | 74.71 g/mol             |
| Appearance           | Black crystalline solid |
| Refractive Index     | 2.1818                  |
| Solubility in water  | Negligible              |
| Melting              | 1955 °C                 |
| Density              | 6.66 g/cm <sup>3</sup>  |
| Specific Heat        | 603 J/kgK               |
| Thermal conductivity | 46.024 W/mK             |

Table 2 — NiO<sub>2</sub> Crystallite size

| d-spacing | Crystallite size (Å) |
|-----------|----------------------|
| 2.39757   | 161.111500           |
| 2.08052   | 164250700            |
| 1.47350   | 153.255400           |
| 1.25788   | 232.699800           |

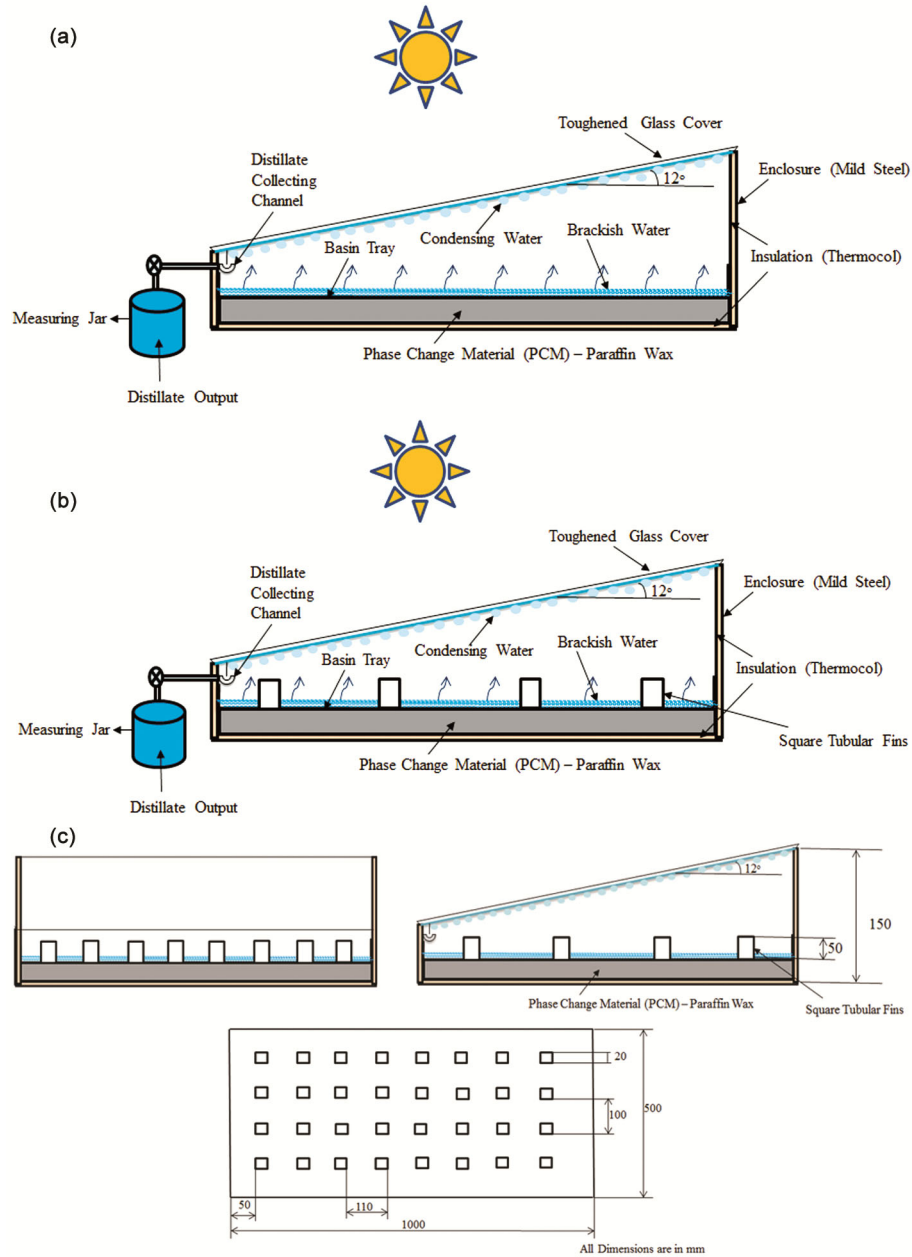


Fig. 3 — Diagrammatic view of SS with modifications – (a) SS with PCM, (b) SS with fins and PCM and (c) fins arrangements in basin liner of SS

$A$  = area of the basin ( $m^2$ ), and  
 $S_{ri}$  = solar radiation intensity  $W/m^2$ .

The daily efficiency of the SS was determined by (Kumar *et al.*<sup>16</sup>):

$$\eta_{daily} = \frac{\sum m_{water} \times h_{vw}}{A \times \sum S_{ri}} \quad \dots (2)$$

To determine the theoretical instantaneous efficiency of the SS, the following correlations are used.

The convective heat transfer coefficient  $h_{ctc}$  between glass surface and water surface in the basin of the SS is given as

$$h_{ctc} = 0.884 \left( T_w - T_i + \frac{(P_w - P_i) T_w}{268900 - P_w} \right)^{1/3} \quad \dots (3)$$

Where,

$T_w$  = temperature of the water in the basin (K),

$T_i$  = temperature of the glazing inner surface (K),

and

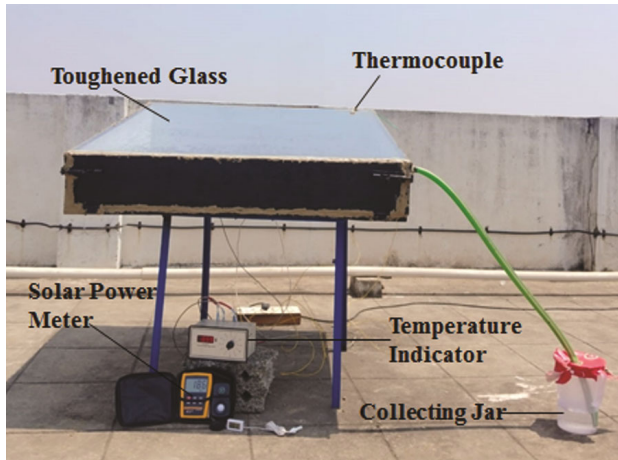


Fig. 4 — Photograph of SS - experimental setup

$P_w$  &  $P_i$  = saturation partial pressures for corresponding basin water temperature and glazing inner surface temperature.

The evaporative heat transfer coefficient  $h_{etc}$  from basin water surface to the glazing surface is given as follows<sup>11,17</sup>;

$$h_{etc} = 0.016273 h_{ctc} \left( \frac{P_w - P_i}{T_w - T_i} \right) \quad \dots (4)$$

The theoretical instantaneous efficiency of the SS is determined by using the equation (Kumar *et al.*<sup>17</sup>);

$$\eta_{theoretical} = \frac{h_{etc} (T_w - T_i)}{S_{ri}} \quad \dots (5)$$

#### Exergy analysis

The useful work extracted from the system is determined by the exergy analysis. The imperfections of the system can be effectively determined by using the exergy analysis. With the intensity of solar radiation, the exergy efficiency of the SS is given as the exergy ratio of output to input based on SS yield.

$$\eta_{Exergy} = \frac{Exergy_{output}}{Exergy_{input}} = \frac{Exergy_{evap}}{Exergy_{sun}} \quad \dots (6)$$

The exergy output of the SS can be determined by utilizing the following equation<sup>16,18</sup>:

$$Exergy_{output} = Exergy_{evap} = \frac{m_{water} \times h_{vw}}{3600} \left( 1 - \frac{T_a + 273}{T_w + 273} \right) \quad \dots (7)$$

Where,

$T_a$  = ambient temperature (K).

The exergy input of the SS can be determined using the following equations.<sup>16,18,19</sup>:

$$Exergy_{input} = Exergy_{sun} = A \times h_{vw}(t) \left[ 1 - \frac{4}{3} \left( \frac{T_a}{T_w} \right) + \frac{1}{3} \left( \frac{T_a}{T_{sun}} \right)^4 \right] \quad \dots (8)$$

Where,

$Exergy_{sun}$  = energy input through solar insolation to SS ( $W/m^2$ ),

$h_f(t)$  = intensity of incident solar radiation ( $W/m^2$ ), and

$T_{sun}$  = sun outer surface temperature (K) and taken as 6000 K.

#### Economic analysis

In this study, an economic analysis was conducted to determine the cost of water per liter and the payback period.

The first annual cost (FAC) is determined by using the following equation<sup>20</sup>:

$$FAC = (CRF) \times (F) \quad \dots (9)$$

Where,

CRF - capital recovery factor, and

F - capital cost of the SS

The capital recovery factor (CRF) is determined by using following equation<sup>21</sup>:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \dots (10)$$

Where,

i - annual rate of interest on SS investment (%), and

n - total number of operative years of the SS.

The value of i is taken as 12 % per year and n value is taken as 10 years respectively.

The sinking fund factor (SFF) and the annual salvage value (ASV) can be calculated using following equation<sup>22,23</sup>.

$$SFF = \frac{i}{(1+i)^n - 1} \quad \dots (11)$$

$$ASV = (SFF) \times S \quad \dots (12)$$

Where,

S - salvage value of the SS, taken as 20% of the total investment of the SS.

The total annual cost (TAC) of the SS is determined by using the following equation<sup>24,25</sup>:

$$TAC = (FAC) + (AMC) - (ASV) \quad \dots (13)$$

AMC - Annual Maintenance Cost

The market cost of the water produced by the SS per year is given by

$$\text{Market cost of the water per year} = Q \times \text{Market cost of water per litre} \quad \dots (14)$$

The annual maintenance cost is calculated by Eq. 15<sup>24</sup>:

$$\text{AMC} = 0.15 \times \text{FAC} \quad \dots(15)$$

Where,

Q –average annual production of water from the SS in liters.

In this present study, the market cost of water per liter is taken as 0.2\$.

The annual cost of the water production of the SS per liter,

$$\text{Annual cost of yield per liter} = \frac{\text{TAC}}{Q} \quad \dots (16)$$

The net earnings through the production of water from the SS per year are given by

$$\text{Net earnings per year} = \text{Market cost of yield per year} - \text{AMC} \quad \dots (17)$$

The payback period of the SS is determined using the expression<sup>24</sup>:

$$\text{Paybackperiod}(in\text{day}) = \frac{\text{Investments}}{\text{Net earnings}} \quad \dots (18)$$

The annual fresh water production was calculated for 270 days.

#### Enviro-economic analysis

An enviro-economic analysis was conducted to calculate carbon dioxide (CO<sub>2</sub>) mitigation and carbon credits earned (CCE). The CO<sub>2</sub> emissions from fossil fuel combustion in power plants are calculated to be 1.58 kg/kWh<sup>26</sup>.

To determine the enviro-economic analysis the following equation was used<sup>27,28,29</sup>:

$$\text{CO}_2 \text{ emissions of the SS (kg)} = E_{\text{input}} \times 1.58 \quad \dots(19)$$

The annual energy output is calculated by

$$AE_{\text{output}} = \frac{M_{\text{water}} \times h_{\text{vw}}}{3600} \quad \dots(20)$$

Where,

$M_{\text{water}}$  = fresh water yield for 270 days, and  
CO<sub>2</sub> mitigation during the lifetime of the SS in kg

$$= AE_{\text{output}} \times n \times 1.58 \quad \dots(21)$$

Table 3 — Properties of Paraffin Wax (PCM)

| Property                     | Phase change material (PCM) – Paraffin wax |
|------------------------------|--|
| Meting Point                 | 56 °C                                      |
| Latent heat of melting       | 226 kJ/kg                                  |
| Thermal Conductivity         | 0.24 W/mK                                  |
| Density @ Solid Phase        | 818 kg/m <sup>3</sup>                      |
| Density @ Liquid Phase       | 760 kg/m <sup>3</sup>                      |
| Specific heat @ Solid Phase  | 2.9 kJ/kgK                                 |
| Specific heat @ Liquid Phase | 2.5 kJ/kgK                                 |

Net CO<sub>2</sub> emission (NCEM) of SS for the 10-year lifetime is calculated by:

$$\text{NCEM} = \frac{(\text{AE}_{\text{output}} \times n - E_{\text{input}}) \times 1.58}{1000} \quad \dots (22)$$

Where,

n =SS life time and it is assumed as 10 years.

By using net CO<sub>2</sub> emission with market price, the carbon credit earned (CCE) is evaluated as:

$$\text{CCE} = \text{NCEM} \times \text{Cost of CO}_2 \text{ traded per ton} \quad \dots(23)$$

(At present, the carbon dioxide mitigation price is calculated 20 \$ per ton approximately)

## Results and Discussion

From the literature studies, the SS modifications with fins and thermal energy storage (TES) has enhanced the productivity of fresh water and thus improved the overall efficiency. The experimental analysis was conducted for the cases CSS, SSWF, SSWF+PCM and SSWF+ Nano PCM. The performance, economic and enviro-economic analysis was evaluated and compared. Table 3 represents the properties of Paraffin wax<sup>17</sup> which is used as PCM to store heat energy from solar radiation and used as energy storage unit. The specific heat, thermal conductivity and density of aluminium are 896 J/kg K, 167 W/m K and 2700 kg/m<sup>3</sup>, respectively<sup>30</sup>.

#### Productivity and efficiency

The comparison of hourly and cumulative productivity with respect to time for CSS, SSWF, SSWF+PCM and SSWF+Nano PCMis shown in Fig. 5 and 6, respectively. From the investigation, it is noticed that the SS with fins and nano PCM enhanced the productivity even after sunshine hours. This is due to the heat captured during daytime which was being utilised after sunshine hours. It results in increase in the nocturnal productivity. The SSWF+NanoPCM produces better productivity when compared to other

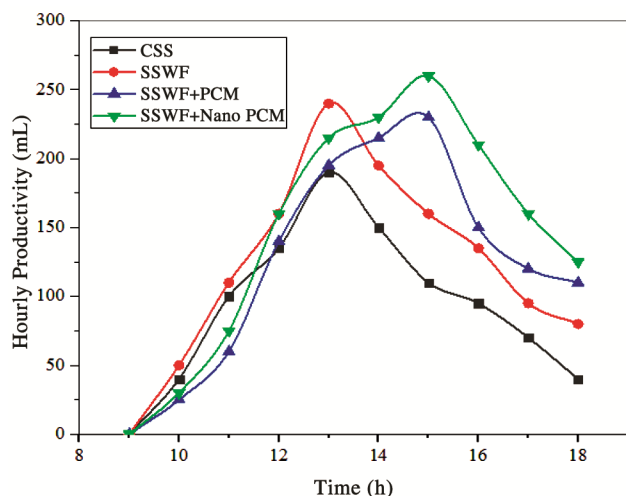


Fig. 5 — Comparison of time Vs hourly productivity for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

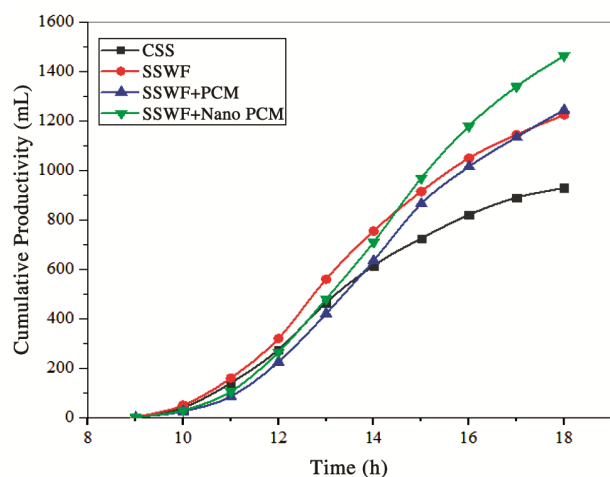


Fig. 6 — Comparison of time Vs cumulative productivity for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

cases, as the modified stills with PCM results in enhancement in productivity, due to the energy capture in the TES unit during the day time. The nocturnal productivity of SSWF, SSWF+PCM and SSWF+Nano PCM was determined around 1.3, 3.1 and 3.2 times respectively. As shown in Fig. 7, the nocturnal productivity for the CSS, SSWF, SSWF+PCM and SSWF+Nano PCM are found to be 290, 370, 890 and 920, respectively.

Fig. 8 shows the comparison of hourly efficiency with respect to time for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM. Due to decline of solar intensity radiation after 15.00 h, the hourly efficiency of CSS started to decrease. The forenoon session, the hourly efficiency of SS with fins, with and without PCM was noticed to be lower than other cases, as the significant

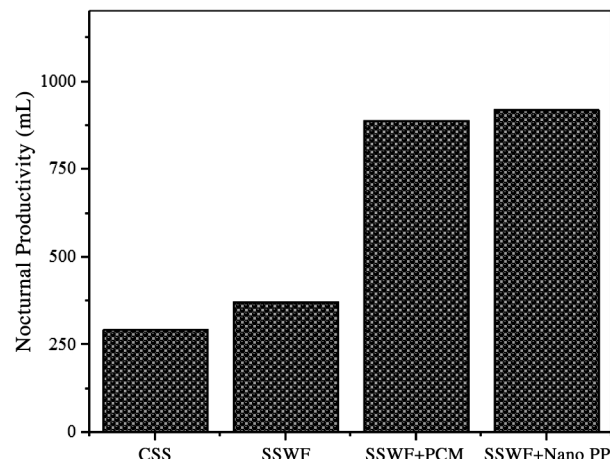


Fig. 7 — Nocturnal productivity for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

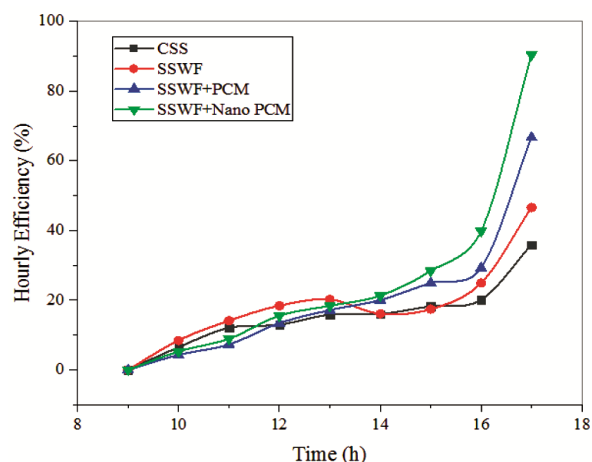


Fig. 8 — Comparison of time Vs hourly efficiency for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

amount of heat from solar radiation was stored and used by SS when solar radiation gets declined. Fig. 9 shows the overall efficiency for the CSS, SSWF, SSWF+PCM and SSWF+Nano PCM. Percentage Increase in Productivity Efficiency (%) for SSWF, SSWF+PCM and SSWF+Nano PCM are found to be 19.98, 40.99 and 46.93, respectively. The percentage increase in daily productivity are 30.74, 75.00 and 95.49 for SSWF, SSWF+PCM and SSWF+Nano PCM, respectively. It is noticed that the SSWF+Nano PCM results in higher with 95.40% when compared to CSS. The overall efficiency are 28.07%, 35.08%, 47.57% and 52.89% for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM, respectively.

#### Exergy efficiency

Fig. 10 shows the exergy efficiency comparison for CSS (11.86), SSWF (15.70), SSWF+PCM (21.76) and

SSWF+Nano PCM (21.63) with respect to time. Due to the destruction of large amount of exergy, it is found that exergy efficiency is lesser. During day time, the PCM absorbs heat energy and after sunshine hours the SS with and without PCM result in increase in exergy efficiency. The heat exchange occurs between the PCM and basin water, while the PCM undergoes a phase change and thus it results in production of fresh water even after sunshine hours and better enhancement in nocturnal productivity. For the cases SSWF+PCM and SSWF+Nano PCM, the exergy efficiency is found to be on higher side. The highest exergy efficiency was found to be 27.63% for SSWF+Nano PCM.

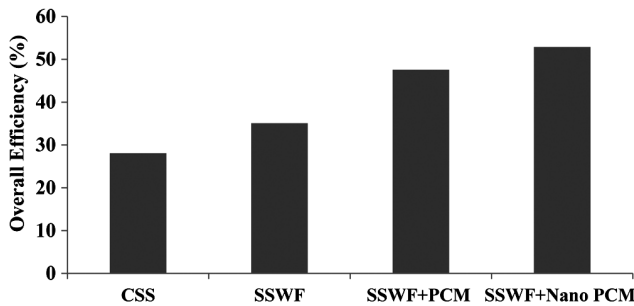


Fig. 9 — Overall efficiency for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

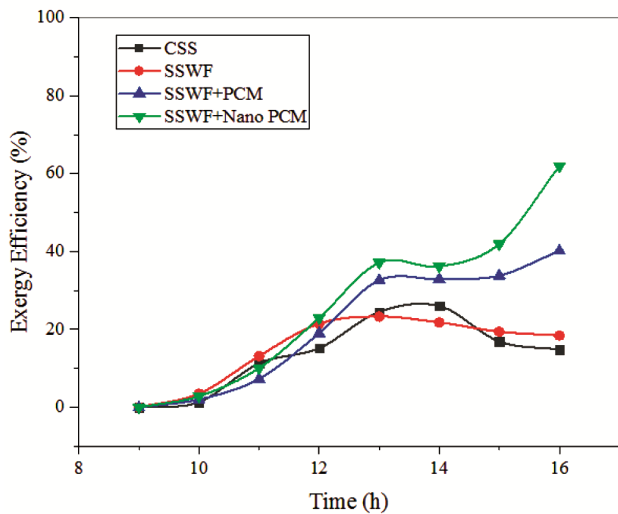


Fig. 10 — Comparison of time Vs exergy efficiency for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

**Water – glass temperature difference**

Fig. 11 shows the comparison of the water – glass temperature difference with respect to time and solar radiation for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM. During forenoon session, the difference in temperature for the modified cases is observed high as compared to CSS, this is due to the significant amount of heat is captured and stored by PCM. A sharp decline is observed for the CSS and SSWF, when the solar radiation gets declined. Due to the retrieval of heat from the PCM, the SS with fins and TES showed the higher temperature difference. Thus, it helps in continuing the basin water temperature on higher side due to the latent heat source from the PCM after sunshine hours.

**Economic analysis**

For all the cases, annual cost of water per liter and payback period was determined<sup>31</sup> and the results were represented in the Table 4. The FAC, AMS and TAC were higher when compared with CSS, because it is due to the incorporation of fins and PCM. Due to modifications by implementing fins and TES, the annual cost of water was found to be slightly lesser than CSS. For the modified SS, the net earnings per year could be increased and turn down the payback period.

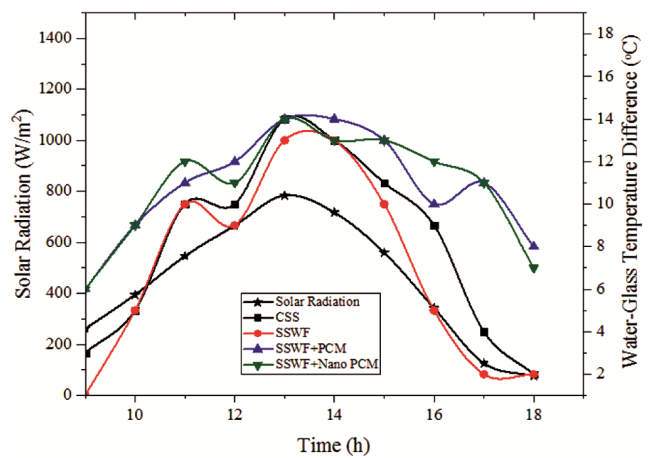


Fig. 11 — Comparison of time Vs water – Glass Temperature Difference for CSS, SSWF, SSWF+PCM and SSWF+Nano PCM

Table 4 — Results of Economic Analysis

| Type of solar still | Capital cost (USD) | Annual cost of water per liter (USD) | Net earnings per year (USD) | Payback period (days) |
|---------------------|--------------------|--------------------------------------|-----------------------------|-----------------------|
| CSS                 | 71.94              | 0.08645                              | 63.97                       | 416.69                |
| SSWF                | 86.33              | 0.07935                              | 83.84                       | 346.85                |
| SSWF+PCM            | 103.11             | 0.07080                              | 112.55                      | 288.49                |
| SSWF+Nano PCM       | 113.90             | 0.07001                              | 125.77                      | 277.45                |

Table 5 — Embodied energy breakdown of components in the SS

| Solar still components           | Basin plate | Frame body | Cover  | Insulation | Water Condensati on Tube | Fins   | PCM          | Nano Particles   | Embodied energy (Ein) in MJ | Embodied energy (Ein) in KWh |
|----------------------------------|-------------|------------|--------|------------|--------------------------|--------|--------------|------------------|-----------------------------|------------------------------|
| Materials                        | AL          | Plywood    | Glass  | Thermocol  | Plastic (PVC)            | AL     | Paraffin Wax | NiO <sub>2</sub> | -                           | -                            |
| Weight (kg)                      | 5.5         | 19         | 7.2    | 0.5        | 0.4                      | 4.35   | 15           | 0.9              | -                           | -                            |
| Specific embodied energy (MJ/kg) | 749.4       | 18         | 15.9   | 117        | 18.7                     | 749.4  | 26.2         | 200              | -                           | -                            |
| CSS                              | 1815        | 342        | 114.48 | 230.55     | 7.48                     | -      | -            | -                | 2509.51                     | 697.09                       |
| SSWF                             | 1815        | 342        | 114.48 | 230.55     | 7.48                     | 1435.5 | 393          | -                | 4338.01                     | 1205.00                      |
| SSWF+PCM                         | 1815        | 342        | 114.48 | 232.55     | 7.48                     | 1435.5 | 393          | -                | 4340.01                     | 1205.56                      |
| SSWF+Nano PCM                    | 1815        | 342        | 114.48 | 233.55     | 7.48                     | 1435.5 | 393          | 180              | 4521.01                     | 1255.84                      |

Table 6 — Results of enviro-economic analysis

| Solar Still   | Annual Yield (kg) | Embodied energy, E <sub>input</sub> (kWh) | Annual energy output, E <sub>output</sub> (kWh) | CO <sub>2</sub> emission for a lifetime (kg) | CO <sub>2</sub> mitigation for a lifetime (ton) | Net CO <sub>2</sub> mitigation for a lifetime (ton) | Carbon credit earned (USD) |
|---------------|-------------------|---|---|--|---|---|----------------------------|
| CSS           | 329.4             | 697.09                                    | 219.6   | 1101.40                                      | 3.47  | 2.37  | 47.37                      |
| SSWF          | 430.65            | 1205.00                                   | 287.1   | 1903.91                                      | 4.54  | 2.63  | 52.65                      |
| SSWF+PCM      | 576.45            | 1205.56                                   | 384.3   | 1904.78                                      | 6.07  | 4.17  | 83.34                      |
| SSWF+Nano PCM | 643.95            | 1255.84                                   | 429.3   | 1984.22                                      | 6.78  | 4.80  | 95.97                      |

### Enviro-economic analysis

Table 5 shows the embodied energy calculated for the various components of SS<sup>29,32,33</sup>. The enviro-economic result analysis was represented in the Table 6. It is noticed that the addition of fins and TES with nano particles has increased the embodied energy of the modified SS.

### Conclusion

The single slope SS were incorporated with fins, PCM and nano particles. The SS basin material was made up of aluminium material and PCM with and without nano particles were investigated in this research. Based on the observations noticed from the experimental work, performance analysis, economic analysis and enviro-economic analysis are derived in the conclusions. The modified SS has enhanced the daily productivity of SSWF, SSWF+PCM and SSWF+Nano PCM by 30.74%, 75% and 95.49%, respectively. It is noticed that the presence of TES has improved the energy storage efficiency and it is being utilised after sunshine hours. During day time, the SS productivity was decreased due to the presence of TES and but the stored heat is utilized after sunshine hours, thus it increases the nocturnal productivity by 1.3, 3.1 and 3.2 times for SSWF, SSWF+PCM and SSWF+Nano PCM and results higher in overall

productivity of the SS. The overall efficiency has enhanced by 35.08%, 47.57% and 52.89 for SSWF, SSWF+PCM and SSWF+Nano PCM, respectively. The SS with fins and nano PCM has reduced the cost of yield water and also payback period when compared to CSS. The net CO<sub>2</sub> mitigations during its lifetime and carbon credit earned were determined as 4.80 tons and 95.97 USD for SSWF+ Nano PCM. Thus, SS with aluminium fins and NiO<sub>2</sub>PCM have enhanced the overall performance.

### Conflict of interest

The authors declare no conflict of interest.

### References

- Hussen H M, Younes M M, Alawee W H, Abdullah A S, Mohammed S A, Atteya T E, Abbas F & Omara Z M, An experimental comparison study between four different designs of solar stills, *Case Stud Therm Eng*, 44 (2023) 102841.
- Nehar L, Rahman T, Tuly S S, Rahman M S, Sarker M R & Beg M R, Thermal performance analysis of a solar still with different absorber plates and external copper condenser, *Groundw, Sustain Dev*, 17 (2022) 100763.
- Kumar R, Mukhtar A, Yasir A S, Eldin S M, Musa D A, Rocha C M, Le B N & Ghalandari M, Simultaneous applications of fins and nanomaterials in phase change materials: A comprehensive review, *Energy Rep*, 10 (2023) 1028.

- 4 Abdullah A S, Essa F A, Panchal H, Alawee W H & Elsheikh A H, Enhancing the performance of tubular solar stills for water purification: A comprehensive review and comparative analysis of methodologies and materials, *Results Eng*, 30 (2023) 101722.
- 5 Abdullah A S, Panchal H, Alawee W H & Omara Z M, Methods used to improve solar still performance with generated turbulence for water desalination-detailed review, *Results Eng*, 5 (2023) 101251.
- 6 Abdelgaied M, Zakaria Y, Kabeel A E & Essa F A, Improving the tubular solar still performance using square and circular hollow fins with phase change materials, *J Energy Storage*, 38 (2021) 102564.
- 7 Hameed H G, Experimentally evaluating the performance of single slope solar still with glass cover cooling and square cross-section hollow fins, *Case Stud Therm Eng*, 40 (2022) 102547.
- 8 Panchal H, Mevada D, Sadasivuni K K, Essa F A, Shanmugan S & Khalid M, Experimental and water quality analysis of solar stills with vertical and inclined fins, *Groundw Sustain Dev*, 11 (2020) 100410.
- 9 El-Sebaei A A & El-Naggar M, Year round performance and cost analysis of a finned single basin solar still, *Appl Therm Eng*, 110 (2017) 787.
- 10 El-Sebaei A A, Ramadan M R, Aboul-Enein S & El-Naggar M, Effect of fin configuration parameters on single basin solar still performance, *Desalination*, 365 (2015) 15.
- 11 Kumar S T R, Jegadheeswaran S & Chandramohan P, Performance investigation on fin type solar still with paraffin wax as energy storage media, *J Therm Anal Calorim*, 136 (2019) 101.
- 12 Dhivagar R, Mohanraj M, Hidouri K & Belyayev Y, Energy, exergy, economic and enviro-economic (4E) analysis of gravel coarse aggregate sensible heat storage-assisted single-slope solar still, *J Therm Anal Calorim*, 145 (2021) 475.
- 13 Mevada D, Panchal H & Sadasivuni K K, Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis, *Case Stud Therm Eng*, 27 (2021) 101217.
- 14 Navinprasad A T, Prakash R, Yoganandh J, Meenakshipriya B & Ramakrishnan K, Experimental investigation of nickel oxide nanomaterials with n-pentane diesel blends in compression ignition engine, *IOP Conf Ser: Mater Sci Eng*, 1070 (2021) 012126.
- 15 Puspitasari P, Permanasari A A, Shaharun M S & Tsamroh D I, Heat transfer characteristics of NiO nanofluid in heat exchanger, *AIP Conf Proc*, 2228 (2020) 030023.
- 16 Kumar S T R & Jegadheeswaran S, Experimental investigation on finned solar still with enhanced thermal energy storage, *J Therm Sci Eng Appl*, 14 (2022) 091001.
- 17 Modi K V, Patel U N, Patel S J, Patel J N & Patel S R, Efficacy of partially and fully submerged circular cross-section metal hollow-fins and black cotton cloth wick-segments on a single-basin dual-slope solar still, *J Clean Prod*, 344 (2022) 131059.
- 18 Tiwari G N, Dimri V & Chel A, Parametric study of an active and passive solar distillation system: energy and exergy analysis, *Desalination*, 242 (2009) 1.
- 19 Tuly S S, Islam M S, Hassan R, Das B K & Sarker M R, Investigation of a modified double slope solar still integrated with nanoparticle-mixed phase change materials: energy, exergy, exergo-economic, environmental, and sustainability analyses, *Case Stud Therm Eng*, 37 (2022) 102256.
- 20 Abdullah A S, Hadj-Taieb L, Hikal M M, Omara Z M & Younes M M, Enhancing a solar still's performance by preheating the feed water and employing phase-change material, *Alex Eng J*, 77 (2023) 395.
- 21 Modi K V & Modi J G, Influence of wick pile of jute cloth on distillate yield of double-basin single-slope solar still: Theoretical and experimental study, *Sol Energy*, 205 (2020) 512.
- 22 Dhivagar R & Kannan K G, Thermodynamic and economic analysis of heat pump-assisted solar still using paraffin wax as phase change material, *Environ Sci Pollut Res Int*, 29 (2022) 3131.
- 23 Shahdabadi R S, Mortazavi A, Lotfi P, Shakib S E & Ghafurian M M, Boosting stepped solar still system efficiency with affordable natural energy absorbers, *Case Stud Therm Eng*, 52 (2023) 103666.
- 24 Dhivagar R & Mohanraj M, Performance improvements of single slope solar still using graphite plate fins and magnets, *Environ Sci Pollut Res Int*, 28 (2021) 20499.
- 25 Prakash O, Ahmad A, Kumar A, Chatterjee R, Chattopadhyaya S, Sharma S, Sharma A, Li C & Tag-Eldin E M, Performance analysis, and economic-feasibility evaluation of single-slope single-basin domestic solar still under different water-depths, *Energies*, 15 (2022) 8517.
- 26 Dwivedi V K & Tiwari G N, Thermal modeling and carbon credit earned of a double slope passive solar still, *Desalin Water Treat*, 13 (2010) 400.
- 27 Dhivagar R, Mohanraj M & Belyayev Y, Performance analysis of crushed gravel sand heat storage and biomass evaporator-assisted single slope solar still, *Environ Sci Pollut Res Int*, 46 (2021) 65610.
- 28 Thavamani J & Kumar P, Experimental investigation on the performance improvement of double-slope solar still by different shapes of the channel integration, *Environ Sci Pollut Res Int*, 17 (2023) 49450.
- 29 Suraparaju S K & Natarajan S K, Experimental investigation of single-basin solar still using solid staggered fins inserted in paraffin wax PCM bed for enhancing productivity, *Environ Sci Pollut Res Int*, 28 (2021) 20330.
- 30 Puthiyaveetil N, Renil T K, Unnikrishnakurup S, Prabhakar K P, Padmanabham G, Rajagopal P & Balasubramaniam K, Numerical model and experimental validation for online monitoring of cold metal transfer joining of aluminium to galvanized steel, *J Adv Manuf Technol*, 104 (2019) 4365.
- 31 Mevada D, Panchal H & Sadasivuni K K, Investigation on evacuated tubes coupled solar still with condenser and fins: Experimental, exergo-economic and exergo-environment analysis, *Case Stud Therm Eng*, 27 (2021) 101217.
- 32 Yousef M S, Hassan H & Sekiguchi H, Energy, exergy, economic and enviroeconomic (4E) analyses of solar distillation system using different absorbing materials, *Appl Therm Eng*, 150 (2019) 30.
- 33 Thulasimani N P, Jayaraman Y & Ramalingam S K, Exergo and enviro-economic analysis of thermal energy storage assisted finned solar still, *Proc Inst Mech Eng C*, 238 (2024) 11338.