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Comparison between double slope solar still and fourfold slope solar still: energy, exergy, exergoeconomic, and enviroeconomic evaluation

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ABSTRACT

This paper proposes a single basin fourfold slope solar still, which includes a fourfold slope glass cover plate used for solar heat collection and steam condensation. In order to show the efficiency of the fourfold slope solar still, comparative experiments are conducted under the winter climate conditions in Hangzhou for testing the operational performance of a double slope type solar still (DOSS) and the fourfold slope still (FOSS), so as to make a comparative analysis between them. Results show that the productivity of the fourfold slope still is 19.51% higher than that of the double slope still, and the fourfold slope solar still enhances the average hourly energy efficiency by 31.11%. According to the energy method, the energy payback time values of the fourfold slope solar still and double slope solar still are 64.88 months and 75.42 months respectively. According to the environmental parameter method, FOSS and DOSS reduce 5.47 tons and 4.58 tons of CO_2 respectively. The corresponding values based on the exergy environment parameters are 0.21 and 0.18 tons of CO_2, respectively. The fourfold slope solar still has a more obvious emission reduction function than the double slope solar still. The cost of the distilled water of the fourfold slope solar still is 0.28 RMB/kg, and the cost of the double slope solar still is 0.30 RMB/kg. In addition, the environmental and economic parameters of the fourfold slope still and double slope still are 79.29$ (561.37RMB) and 66.35$ (469.76RMB), respectively. While, the corresponding values based on the exergoenvironmental parameter are 3.05$ (21.59RMB) and 2.56$ (18.12RMB), respectively. From the analysis of exergoeconomic and exergoenvironmental parameters, the fourfold slope single basin solar still appears to be more effective.

Key words: energy and exergy, exergoeconomic and environmental parameters, fourfold slope, solar distillation, water treatment

HIGHLIGHTS

- A novel solar still with fourfold slope is developed and evaluated.
- Fourfold slope single basin solar still increases the still's productivity by about 19.51%.
- Fourfold solar still enhances the average hourly energy efficiency by 31.11%.
- Fourfold still mitigates more CO_2 compared to a conventional one based on energy and exergy.
- Fourfold solar still's enviroeconomic and exergoenvironmental parameters are 79.29$ and 3.05$.

NOMENCLATURE

h_{cw} Convective heat transfer coefficient from water to glass cover W/m^2 °C
h_{rw} Radiative heat transfer coefficient from water to glass cover W/m^2 °C
h_{ew} Evaporative heat transfer coefficient from water to glass cover W/m^2 °C
ΔT Temperature difference between water and inner side of glass cover °C
I Solar intensity W/m^2
α_w Absorbance of the water %
q_e Evaporative heat transfer rate W/m^2
q_c Convective heat transfer rate W/m^2
q_r Radiative heat transfer rate W/m^2
Q_{cw} Convective heat transfer from water to glass cover W
T_w Temperature of water °C

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T_g Temperature of inner side of glass cover °C
C_v Specific heat of humid air J/kg °C
ρ_v Mass density of vapor kg/m^3
ρ_g Density of vapor at glass temperature kg/m^3
ρ_w Density of vapor at water temperature kg/m^3
T_v Vapor temperature °C
H_{fg} Latent heat of vaporization J/kg
P_w Saturated vapour pressure on water surface Pa
P_g Saturated vapour pressure on inner glass surface Pa
q_{rw} Radiative heat transfer rate from water to glass cover W/m^2
σ Stefan–Boltzmann constant 5.6697×10^{-8} W/(m^2·K^4)
m_{ew} Hourly theoretical distillate yield kg/hr
q_{ew} Evaporative heat transfer rate from water to glass cover W/m^2
A_w Surface area of water m^2
t Time interval s

1. INTRODUCTION

With the rapid development of global economy and industrialization, human demand for water resources is increasing, and the utilization of water resources is unreasonable (Ostad-Ali-Askari & Shayannejad 2020). The total amount of water on the earth is constant, but the total amount of fresh water resources is limited. The severity of water shortage varies in different countries and regions. As a country lacking in fresh water, most of China's large and medium-sized cities are in a state of water shortage. High salinity brackish water (salt content greater than 10 g/L) such as surface water and shallow well water are the main drinking water resources in western China (Sun *et al.* 2020). Meanwhile, western China is blessed with the most abundant solar energy resources (the annual total solar radiation is about 5,850–8,400 MJ/m^2) (Fang *et al.* 2018). Therefore, exploring clean energy to meet the needs of human development is the only way to improve the water utilization. Because of this, the major scientific and technological projects of the Xinjiang region of China put forward a new method for obtaining condensed water resources and crystal salt from brackish water by the solar thermal method. It provides new ideas and scientific basis for the economic and effective utilization of brackish water, so as to improve saline alkali land in southern Xinjiang. Also, harmless discharge can be realized. Furthermore, the research and development into small and medium-sized devices for brackish water desalination can be implemented.

Desalination projects play an increasingly important role in meeting the demand for fresh water. According to the previous studies (Ostad-Ali-Askari *et al.* 2017, 2020; Ostad-Ali-Askari & Shayannejad 2021), there are some mainstream water treatment methods. Solar desalination methods include solar multi effect distillation, solar reverse osmosis, solar electrodialysis, solar falling film evaporation, solar humidification and dehumidification. These technologies are based on alternative energy sources such as biomass, wind, solar, geothermal or industrial waste heat. However, there are many deficiencies in desalination technology, including high cost, low efficiency of the heat collection system, high maintenance cost of the desalination system, and mismatch between the solar heat collection system and desalination system. As such, seeking a desalination technology with simple system, low cost, low operating temperature and high yield will be the focus of future research. The improved solar still is a new efficient water treatment technology that can solve the above problems. Such solar still are simple to manufacture, and easy to maintain. Then, the cost of solar stills is very low, and the still can match with other systems. Some researchers have improved the traditional solar desalination device. Mohamed (Mohamed *et al.* 2019a) conducted a thermal economic study to assess the performance and productivity of the solar distillation system, by using natural fine stone (black basalt) as a porous absorber. The results showed that the output of their solar energy distillers was higher than that of conventional ones. Kabeel (Kabeel *et al.* 2019) proposed a new solar energy distiller with internal reflector and composite black gravel phase change material for heat storage. The static water yield of the solar still with composite black gravel phase change material was increased by 37.55%. Mohamed (Mohamed *et al.* 2019b) has carried out an experimental study on the effect of heat transfer and mass transfer on the static thermodynamic properties of solar stills by using porous absorbers. The results show that the exergy efficiency of a solar still with 1 cm, 1.5 and 2 cm fine stone particle sizes was 65, 104.4 and 123% higher than that of the stone-free distiller. Yousef *et al.* (2019) carried out three cases of solar still to evaluate the efficiency of energy and exergy of the single slope still. Case (1) is a traditional still, case (2) is the pin fins (hollow cylindrical) assisted still and case (3) is the steel wool fibers used still. The calculated data showed that the energy efficiencies for the three cases are 42%, 45.5%, and 52.5% respectively. The exergy efficiencies for the case (2) and (3) are enhanced by 14% and

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23%. Layek (2018) tried to improve the efficiency of the energy and exergy of the single slope solar still by using three absorber materials. The black color of the solution of ink and dye is used in the basin and the film of the photocopier is used on the surface of the water. The results revealed that the energy efficiencies for the three absorber materials are 41.3%, 43.42%, and 45.79% respectively. Also, the exergy efficiencies for the three absorber materials are 5.91%, 6.34%, and 7.10%. Kabeel *et al.* (2020) conducted experiments on the modified pyramid type solar still to evaluate the efficiency and productivity of the still and the normal pyramid type still. They tested three cases of the pyramid still in the same environmental situations in Egypt. The results showed that the energy efficiencies for the three test cases are 32.2%, 45.9%, and 64.3%. The production values for the three test cases are 4.02 L/day, 5.75 L/day and 8.1 L/day respectively. Jani & Modi (2019) investigated the energy efficiency and productivity of two similar double slope solar stills using circular and square hollow fins. The calculated data showed that the energy efficiency of the still was improved by 54.19%, 38.91%, and 62.24% for circular fins over the square fins at different levels of water depths. The water yield was improved by 54.22%, 38.49% and 43.86% for the circular finned still over the square finned still at the 1, 2 and 3 cm levels of water. Kaviti *et al.* (2021) attached the truncated conic fins to the double sloped solar still, then energy and exergy efficiency analysis was carried out at the 1 cm, 2 cm, and 3 cm levels of water depth and compared with a conventional still. The truncated conic fins were made of aluminum and were 18 in number, having a height of 50 mm and diameter of 30 mm. The maximum energy efficiencies obtained for truncated conic fin solar stills were 54.11% at 1 cm, 45.52% at 2 cm, and 33.12% at 3 cm. The maximum exergy efficiencies obtained for the truncated conic fin solar still improved by 6.20% at 1 cm, 10.52% at 2 cm, and 14.51% at 3 cm over the conventional still.

According to the above review, the two motivation points of the present study are: (1) Maximize the solar energy storage. (2) Enhance the distillated water yield. So, we will present in our research the effect of inclined glass shape on the solar still performance, and the novelty points of the research are:

(1) Estimate the distilled water production performance.
(2) Make a comparison between the fourfold slope solar still and double slope solar still, and point out the law of temperature variation inside the stills.
(3) Apply the energy, exergy, exergoeconomic, and enviroeconomic parameters to evaluate the effect of fourfold slope on the solar still.
(4) Using solar energy to desalinate brackish water is of great significance to alleviate water pollution in Xinjiang, China. The single basin fourfold slope solar still in this paper can be used for fresh water distillation, and it is a pure physical device with high energy utilization rate and high yield of distilled water.

2. MATERIALS AND METHODS

2.1. Design of fourfold slope solar still

The fourfold slope solar still (FOSS) device is described in detail according to the attached schematic figure and design concept, so that the purpose and effect of the fourfold slope solar still will become more clear. The structure diagram of the fourfold slope solar still is shown in Figure 1(b). One side of the fourfold slope of the FOSS can be opened and closed. When it is open, the saline water will be poured into the evaporation chamber. When it is closed, the chamber will be completely sealed up. The four surfaces of the glass cover plate are all transparent, so the sunrays can enter the evaporator

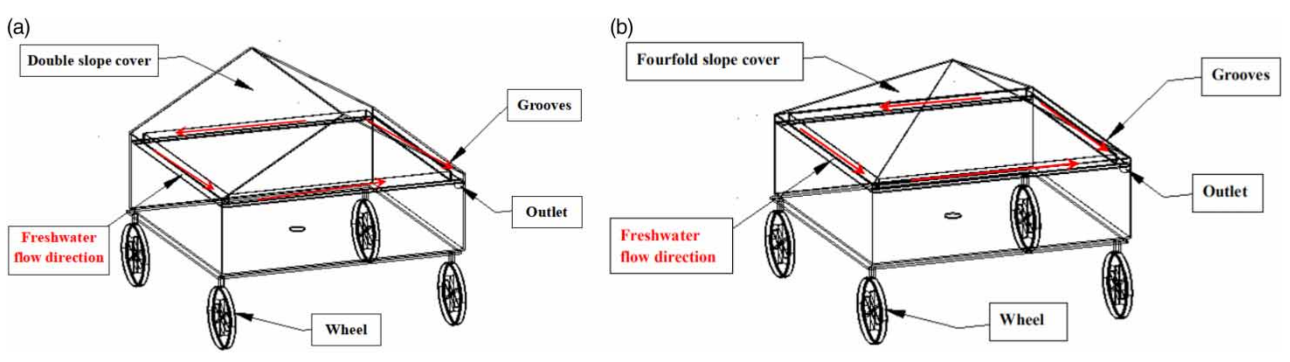

Figure 1 | Structure diagram of solar stills with double slope cover and fourfold slope cover.

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chamber through the top. After the heat-insulation treatment around the FOSS's walls, it can effectively collect and preserve the sunrays and solar heat, and then make the saline water in the chamber absorb heat. The steam rises and condenses under the action of temperature difference and pressure difference at the fourfold slope glass cover plate. The four water collecting grooves are located in the four walls of the evaporator chamber, which are connected with each other, showing a spiral upward trend, so that the water droplets flowing down the wall can be completely collected. Finally, under the action of gravity, the water droplets slide down the water collecting grooves and enter into the outlet hole. The outlet hole is connected with the outside to send the distilled water into the water collecting bottle.

The advantages of the device are as follows: the fourfold slope glass cover plate can receive solar heat on all sides, and the collected solar heat is higher than that of conventional solar still. In addition, the fourfold water collecting groove is used to collect fresh water, and four interconnected water collecting grooves with spiral upward trend are installed in the four walls of FOSS to realize the efficient collection of fresh water, avoiding the loss of distilled water. Also, the FOSS is movable, and it is easy to repair, maintenance, etc.

2.2. Experimental test scenario

The models of FOSS (fourfold slope single basin solar still) and DOSS (double slope single basin solar still) were tested to assess their performance. Based on the innovative points, this research combined the solar still with multiple slope structure, proposing a new type of solar still (FOSS) to improve the efficiency of evaporation. Design concept of the FOSS: the incident sunrays were transmitted through the glass cover with fourfold slope, and the fourfold slope's area is far bigger than that of conventional solar still, to allow more sunrays to locate on the blackened liner. Then the steam pressure and temperature in the cavity were greater than the outside, hence the steam was condensed on the inside surface of the fourfold slope. Figure 2 indicates the actual test rig of FOSS and DOSS. The experiments were tested in winter time of Hangzhou city, China (Latitude 30.3°N, Longitude 120.2°E), and the location map of the study area is shown in Figure 3.

The basin areas of FOSS and DOSS are all 0.25 m^2. The solar stills are all made of glass material. The thickness of glass is 5 mm. The depth of brackish water is always 5 cm. The bottom of the still is painted black for maximum absorption of solar heat (see in Figure 2). The glass cover is fixed on the still's walls and properly sealed to prevent vapor leakage from the still. The distilled water is collected by the measuring jar. Experiments were carried out from 9.00 a.m. to 22.00 p.m. during January of 2021 in Hangzhou. The temperatures, solar intensity, and distilled water yield were measured for every one hour. The device in the upper left corner of Figure 2 is the double slope solar still, and the device in the upper right corner of Figure 2 is the fourfold slope solar still. We arranged temperature probes on the two devices respectively. The temperature probes

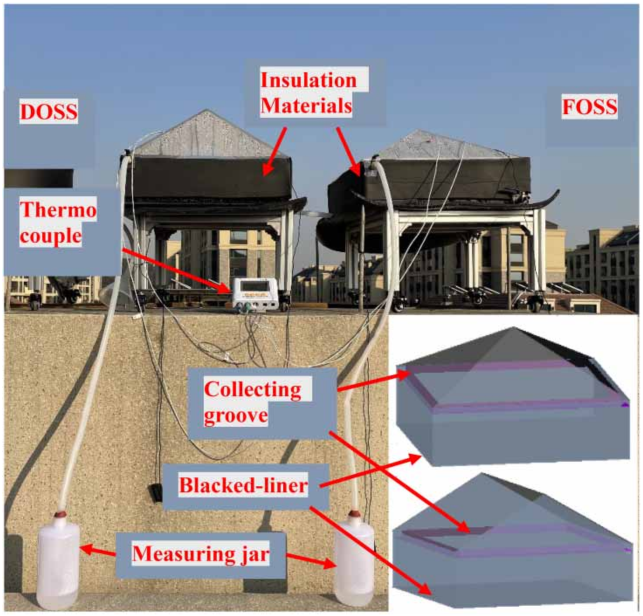

Figure 2 | Photograph of experimental test rig of FOSS and DOSS.

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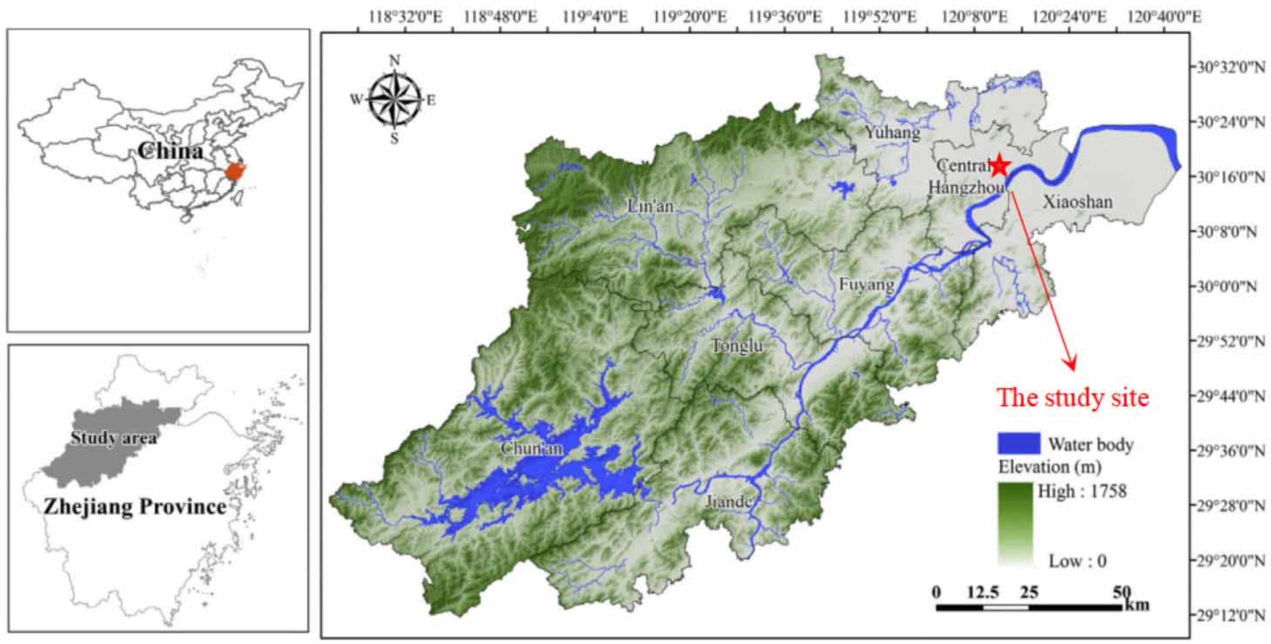

Figure 3 | Location map of the study area.

measure the glass cover plate temperature, water body temperature, bottom plate temperature and ambient temperature. These probes are integrated and displayed on the white device of the thermocouple in Figure 2. The plastic bottle indicated in the figure is a measuring jar, which can read the liquid level to know the weight of freshwater. The lower right corner of Figure 2 shows the design drawings of the two devices to show the internal features. The collecting groove is used to collect fresh water, and four interconnected water collecting grooves with spiral upward trend are installed in the four walls of the solar stills to realize the efficient collection of fresh water, avoiding the loss of distilled water.

The results of uncertainty analysis of the measurements are presented in Table 1, including solar intensity, temperature, and distilled water yield. The uncertainty is assessed according to Mohamed *et al.* (2019a), and the calculation is shown in Equation (1).

$$W_R = \left[\left(\frac{\partial R}{\partial X_1}W_1\right)^2 + \left(\frac{\partial R}{\partial X_2}W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n}W_n\right)^2\right]^{1/2} \quad (1)$$

where W_R is the uncertainty W_1, W_2, W_3, ….. W_n are the uncertainties in the independent variables.

The heat transfer process of the fourfold slope solar still is shown in Figure 4. The solar intensity is expressed by I, and the solar irradiance through the glass cover of the distiller is represented by φI. The solar irradiance absorbed by the water body is $\alpha_w \varphi I$, in which the absorptivity of water is α_w. When the water body is heated enough to cause evaporation, the heat passes through evaporation, convection and radiation (evaporation heat transfer qe, convection heat transfer qc, and radiation heat transfer qr). The cooling process is in the upper part of the cavity of the fourfold slope solar still of Figure 4. Due to the temperature difference and pressure difference inside and outside the tilted glass, the hot steam begins to condense during the

Table 1 | The uncertainty analysis in this research

Instrument	Variable	Accuracy	Range	Uncertainty
Thermocouple (L93-5)	Temperature (°C)	±0.1 °C	0–200 °C	2.56 °C
Pyranometer (TRM-2)	Solar intensity (W/m^2)	±10 W/m^2	0–2,000 W/m^2	6.66 W/m^2
Graduated cylinder (Common model)	Distilled water (ml)	±2 ml	0–1,000 ml	2.05 ml

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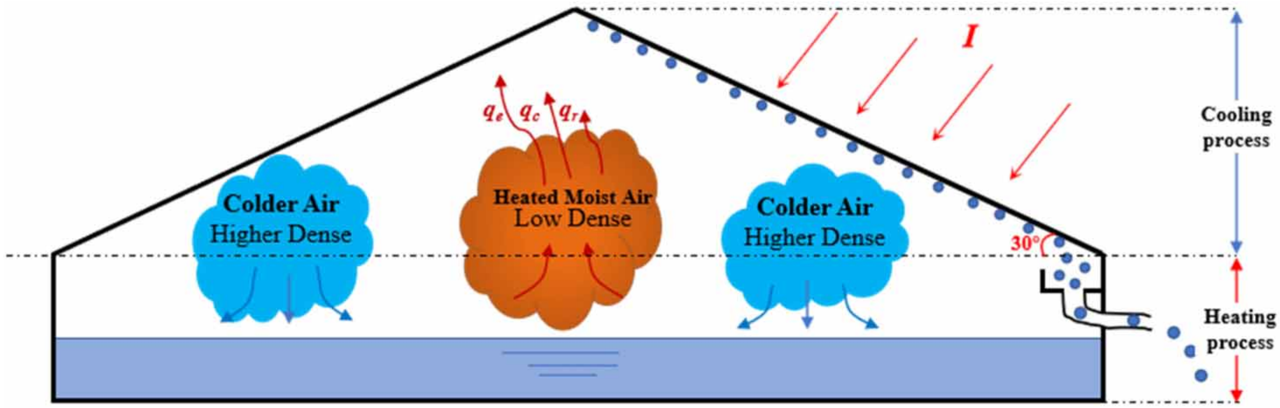

Figure 4 | Schematic diagram of heat transfer process of solar still of FOSS.

cooling process. Therefore, the cooling mechanism we studied is to increase the temperature difference between the brackish water and the glass cover, to improve the fresh water productivity of the solar still. The main purpose of FOSS is to concentrate sunlight on the bottom basin of the distiller through the fourfold slope cover.

The convective heat transfer rate from water to glass surface is described as (Mohamed *et al.* 2019a):

$$q_{cw} = h_{cw}(T_w - T_g) \tag{2}$$

where h_{cw} refers to convective heat transfer coefficient, T_w is the basin water temperature, T_g is the temperature of the glass cover, and the subscript g represents the glass cover.

A semi-empirical formula for the calculation of h_{cw} was first proposed by Dunkle, which is as follows (Dunkle 1961):

$$h_{cwd} = 0.884\left[(T_w - T_g) + \frac{(P_w - P_g)}{2.689 \times 10^5 - P_w}(T_w + 273)\right]^{1/3} \tag{3}$$

where P_w is saturated vapour pressure on the water surface, P_g is saturated vapour pressure on the inner glass cover.

h_{ew} can be evaluated as (Dumka *et al.* 2019):

$$h_{ew} = 1.6273 \times 10^{-2} \cdot h_{cw} \cdot \frac{P_w - P_g}{T_w - T_g} \tag{4}$$

When the temperature of the basin water is higher than the temperature of the glass cover, radiative heat transfer occurs and the heat is transferred from basin water to glass cover. The formula for radiative heat transfer can be expressed as:

$$q_{rw} = h_{rw}(T_w - T_g) \tag{5}$$

where q_{rw} is the radiative heat transferred from basin water to glass cover, and the subscript r represents radiation. h_{rw} is the radiative heat transfer coefficient.

The radiative heat transfer coefficient in the evaporation cavity is calculated by the Duffle-Beckman formula (Duffle & Beckman 1991):

$$h_{rw} = \varepsilon_{\text{eff}}\sigma\left((T_w + 273)^2 + (T_g + 273)^2\right)(T_w + T_g + 2 \times 273) \tag{6}$$

where ε_{eff} is the effective emissivity, σ is the Stefan–Boltzmann constant, which is $5.6697 \times 10^{-8}\ \text{W}/(\text{m}^2 \cdot \text{K}^4)$.

Evaporative heat transfer refers to a form of forced heat transfer that occurs during the evaporation process when water (liquid phase) changes into vapor (gas phase). Once the basin water in the still absorbs heat and evaporates into water vapor, the heat in the water body is transmitted to the air through the gas-liquid interface, and then the heat is carried to

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the glass cover by the flowing air. Due to that, hot air encounters the cold glass cover, water vapor will exotherm and condense into distilled water. Thereafter, theoretical distillate yield can be written as (Dumka *et al.* 2019):

$$m_{ew} = \frac{q_{ew} A_w t}{H_{fg}} \tag{7}$$

$$q_{ew} = h_{ew}(T_w - T_g) \tag{8}$$

where m_{ew} is the hourly theoretical distillate yield, q_{ew} is the heat transfer per unit area, A_w is the liquid surface area, H_{fg} is the latent heat of vaporization, t is the time interval, h_{ew} is the evaporative heat transfer coefficient.

2.3. Theoretical method and mathematical formula

2.3.1. Energy efficiency

For the solar still, the energy efficiency can be expressed by:

$$\eta_{\text{th}} = \frac{\sum P_d \times H_{fg}}{A_{ex} \times \sum I(t) \times 3{,}600} \tag{9}$$

where H_{fg} is the latent heat of vaporization of water (J/kg), P_d is the gathered freshwater yield (kg), A_{ex} is the exposure area of FOSS (m^2), and I is the solar intensity (W/m^2).

2.3.2. Exergy efficiency

According to Elshamy & El-Said (2018), the exergy efficiency of solar still can be defined as the ratio of the exergy output of evaporated water to the exergy input of solar irradiance, which is determined by:

$$\eta_{ex} = \frac{\dot{E}_{x,\text{evap}}}{\dot{E}_{x,\text{sun}}} \tag{10}$$

where $\dot{E}_{x,\text{sun}}$ is input of solar irradiance, and $\dot{E}_{x,\text{evap}}$ is exergy output.

The hourly exergy output of FOSS is given by:

$$\dot{E}_{x,\text{evap}} = \frac{H_{fg}\,\dot{m}_{ew}}{3{,}600}\left[1 - \left(\frac{T_a + 273}{T_w + 273}\right)\right] \tag{11}$$

where T_w is the brackish water temperature (°C), T_a is the ambient temperature (°C), and $\dot{m}_{ew}$ is the distilled water (kg/hr).

The exergy input of $\dot{E}_{x,\text{sun}}$ can be determined by:

$$\dot{E}_{x,\text{sun}} = A_{ex} I(t)\left[1 - \frac{4}{3}\left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3}\left(\frac{T_a + 273}{T_s}\right)^4\right] \tag{12}$$

where T_s is the sun temperature of 5,600 K.

2.3.3. Energy payback time

Energy payback time (EPBT) is determined by the following equations:

$$(EPBT)_{en} = \frac{E_{\text{in}}}{E_{en,\text{out}}} \tag{13}$$

$$(EPBT)_{ex} = \frac{E_{\text{in}}}{E_{ex,\text{out}}} \tag{14}$$

where, E_{in} is the embodied energy, $E_{en,\text{out}}$ is the total energy output of the solar still, and $E_{ex,\text{out}}$ expresses the total exergy output of FOSS.

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2.3.4. Economic analysis

Economic performances of FOSS and DOSS can be estimated according to Elshamy & El-Said (2018). The maintenance cost of FOSS and DOSS will rise with years. As such, 10% of net present cost is defined as maintenance cost. The calculation process can be expressed as:

$$\mathrm{SFF} = \frac{i}{(1+i)^n - 1} \tag{15}$$

$$\mathrm{CRF} = (\mathrm{SFF}) \times (1+i)^n \tag{16}$$

$$\mathrm{FAC} = \mathrm{P} \times (\mathrm{CRF}) \tag{17}$$

$$\mathrm{S} = 0.2 \times \mathrm{P} \tag{18}$$

$$\mathrm{ASV} = (\mathrm{SFF}) \times \mathrm{S} \tag{19}$$

$$\mathrm{AMC} = 0.10 \times \mathrm{FAC} \tag{20}$$

$$\mathrm{AC} = \mathrm{FAC} + \mathrm{AMC} - \mathrm{ASV} \tag{21}$$

$$\mathrm{CPL} = \frac{\mathrm{AC}}{M} \tag{22}$$

where P is the present capital cost of FOSS or DOSS; i is the interest per year, which is assumed as 12% in this research; n is the number of life years, which is assumed as 20 years. CRF is the capital recovery factor, FAC is fixed annual cost, SFF is sinking fund factor, ASV is annual salvage value, M is average annual productivity, AC is annual cost, AMC is annual maintenance operational cost of FOSS or DOSS. CPL is cost of distilled water per liter, dividing the annual cost of the system (AC) by the annual yield of the solar still (M).

2.3.5. Exergoeconomic analysis

An exergoeconomic analysis identifies the location, magnitude and sources of thermodynamic inefficiencies and costs in an energy conversion system. This information is used for improving the thermodynamics and the economic performance and for comparing various systems. A conventional exergy-based analysis does not consider the interactions among the components of a system or the real potential for improving the system. These shortcomings can be addressed and the quality of the conclusions obtained from an exergoeconomic evaluation is improved, when for each important system component the values of exergy destruction and costs are split into endogenous/exogenous and avoidable/unavoidable parts. We call the analyses resulting from such splittings advanced exergy-based analyses. The paper demonstrates how an advanced exergoeconomic analysis provides the user with information on the formation processes of thermodynamic inefficiencies and costs and with suggestions for their minimization.

Exergoeconomic analysis is an exergy-based economic evaluation for analyzing the performance of desalination devices. The exergoeconomic calculation is expressed by:

$$R_{g,en} = \frac{E_{en,\mathrm{out}}}{AC} \tag{23}$$

$$R_{g,ex} = \frac{E_{ex,\mathrm{out}}}{AC} \tag{24}$$

where $R_{g,en}$ and $R_{g,ex}$ are exergoeconomic parameters.

2.3.6. Environmental analysis

The device in this study is helpful to control carbon emission to the environment. The average carbon dioxide emissions from the power plant to the environment are about 980 g CO_2/kW. However, considering the 40 percent loss caused by distribution and transmission and about 20 percent of the loss caused by inefficient household instruments, the total amount of carbon dioxide per kilowatt hour is about 2 kg (Rashidi *et al.* 2018). Therefore, the annual reduction of carbon dioxide in

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tons of solar stills is set as follows:

$$\Phi_{en,CO_2} = \frac{E_{en,\text{out}} \times n \times 2}{1{,}000} \tag{25}$$

where Φ_{en,CO_2} is the environmental parameter, $E_{en,\text{out}}$ is the energy output from the solar still per annum.

The amount of CO_2 mitigated per year in tons from solar stills considering the exergy approach is expressed by:

$$\Phi_{ex,CO_2} = \frac{E_{ex,\text{out}} \times n \times 2}{1{,}000} \tag{26}$$

where Φ_{ex,CO_2} is the exergoenvironmental parameter, $E_{ex,\text{out}}$ is the total exergy output from the solar still per annum.

2.3.7. Enviroeconomic analysis

The enviroeconomic calculation is in accordance with the price of CO_2 emitted over the lifespan of the solar still and can be expressed by:

$$Z_{en,CO_2} = z_{CO_2} \times \Phi_{en,CO_2} \tag{27}$$

$$Z_{ex,CO_2} = z_{CO_2} \times \Phi_{ex,CO_2} \tag{28}$$

where Z_{en,CO_2} and Z_{ex,CO_2} are the enviro-economic parameters, z_{CO_2} is the international carbon price that is taken as 14.5$ per ton of CO_2 (Yousef & Hassan 2020).

2.4. Experimental procedure

The experimental work procedures were carried out as the following procedures in order:

(1) Before doing any experimental measurements, the experiment was prepared carefully where the hours before starting the reading, the water was supplied to the basin and its quantity and level checked carefully. Also, the saline water quantity, measuring instruments, insulations, glass cleaning, etc. were checked depending on each studied case.
(2) During each time measurement, we ensured that we took the measurements at the same time and were sure that the temperature logger registered the reading values, and pyranometer recorded solar energy, etc.
(3) The collected yield freshwater quantity was measured carefully and registered.
(4) The previous two procedures of (2) and (3) were repeated for each time step reading.
(5) At the end of all-day readings, the solar still system was prepared as the first reading day (ensuring that the glass cover was clean, all insulated system parts were well insulated to prevent leakage, etc.), and then the procedure (1) to do the next day readings were undertaken.

3. RESULTS AND DISCUSSION

3.1. Distillate output and temperature variation in FOSS and DOSS

After a continuous experiment for more than one month of winter, the research found that the distilled water yield of the new type solar still (FOSS) proposed in this paper was basically stable in one day; that is, the output at the same time on different days was similar. Therefore, the average temperature distribution and fresh water production of each solar still are drawn in this paper, as shown in Figures 5 and 6. The results show that the output efficiency of FOSS is higher than that of DOSS. The peak value of FOSS's water temperature is 37.4 °C, which is higher than 36.4 °C of DOSS. Similarly, the vapor temperature of 35.6 °C of FOSS is higher than that of 32.9 °C of DOSS. The peak temperatures of glass cover plates of two stills were almost the same, at 24.1 °C and 24.2 °C respectively. As shown in the figures, the cumulative yields of FOSS and DOSS are 245 and 205 ml respectively; and the daily productions considering the basin area are 0.98 l/m^2 and 0.82 l/m^2 respectively. That is, the water production performance of the solar still with fourfold slope is obviously better than that of double slope solar still, and the daily production of FOSS is 19.51% higher than that of DOSS. This is because the glass cover with fourfold slope has more surfaces than the double slope cover plate, so that when the solar height angle changes, more surfaces can receive

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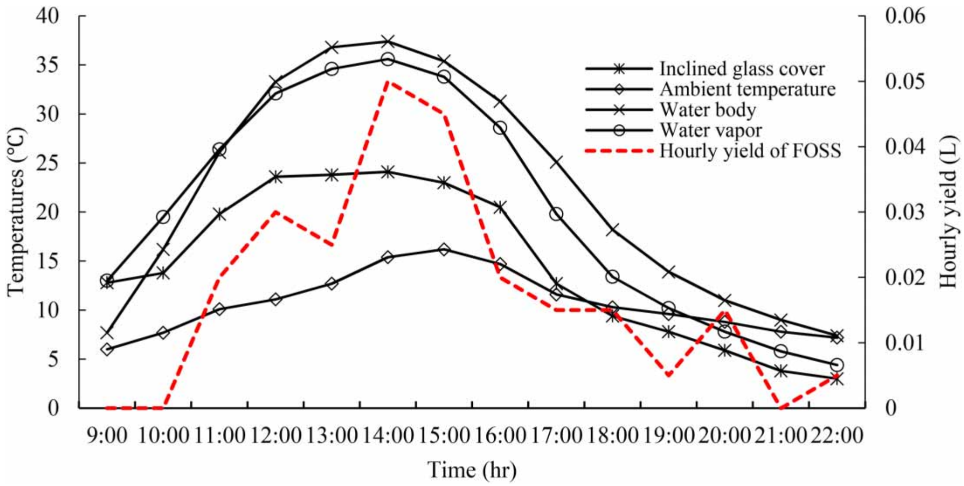

Figure 5 | Hourly yield and temperatures inside the FOSS.

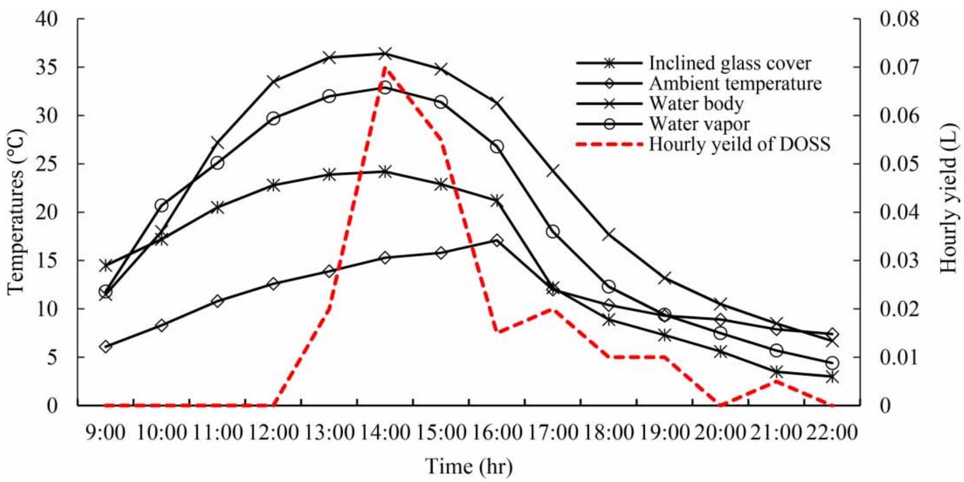

Figure 6 | Hourly yield and temperatures inside the DOSS.

sunrays in the FOSS. As such, it is ensured that the FOSS can absorb and store more solar radiation energy, and provide more driving energy for distillation.

According to the research results of Fang *et al.* (2018), it is possible to predict the water yields of the solar stills of FOSS and DOSS in Hangzhou (only considering sunny days), as shown in Figure 7. The results show that the solar still's water productivity is higher during May to August, and the productivity is lower during winter. Although the lower temperature in winter will lead to greater external heat transfer and condensation, the average sunshine hours in winter are much less than those in summer. As a result, the total solar radiation accepted by the solar still in winter is low, which leads to the slow heating rate and the low water yield. The average daily outputs of FOSS and DOSS are 1.87 kg/m^2 and 1.62 kg/m^2 respectively according to the annual average. These solar stills are expected to operate about 330 days a year. Therefore, the annual output of FOSS is 616.55 kg and DOSS's yield is 533.78 kg.

3.2. Energy and exergy efficiencies

Figure 8 shows the hourly energy efficiency changes of FOSS and DOSS. The results show that the energy efficiency of FOSS increases with time, and reaches the maximum at about 21:00 p.m. The average instantaneous energy efficiencies of FOSS and DOSS are 14.42% and 11.00% respectively. It can be seen that the average instantaneous energy efficiency of FOSS is 31.11% higher than that of DOSS.

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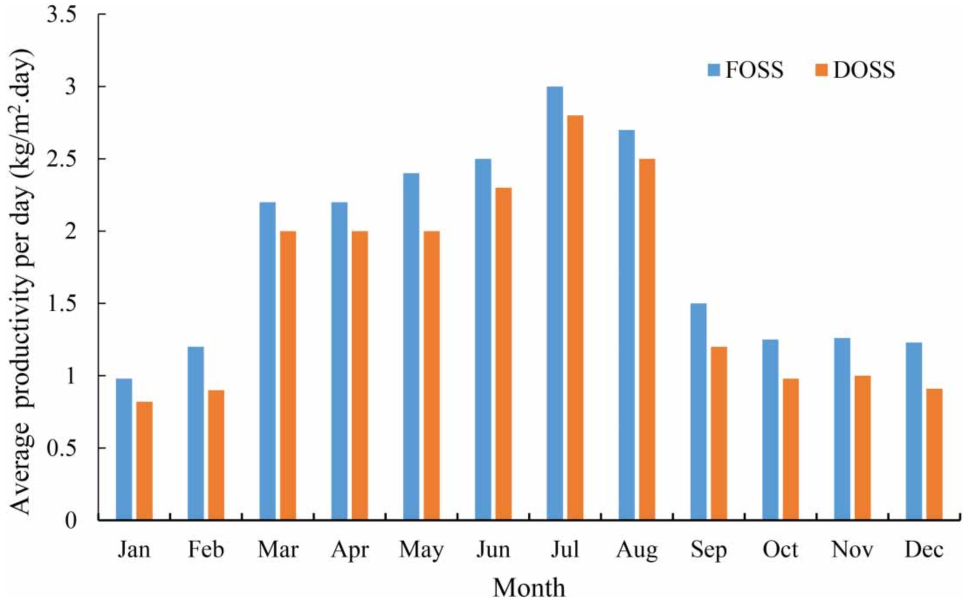

Figure 7 | Seasonal variation of portable water of FOSS and DOSS.

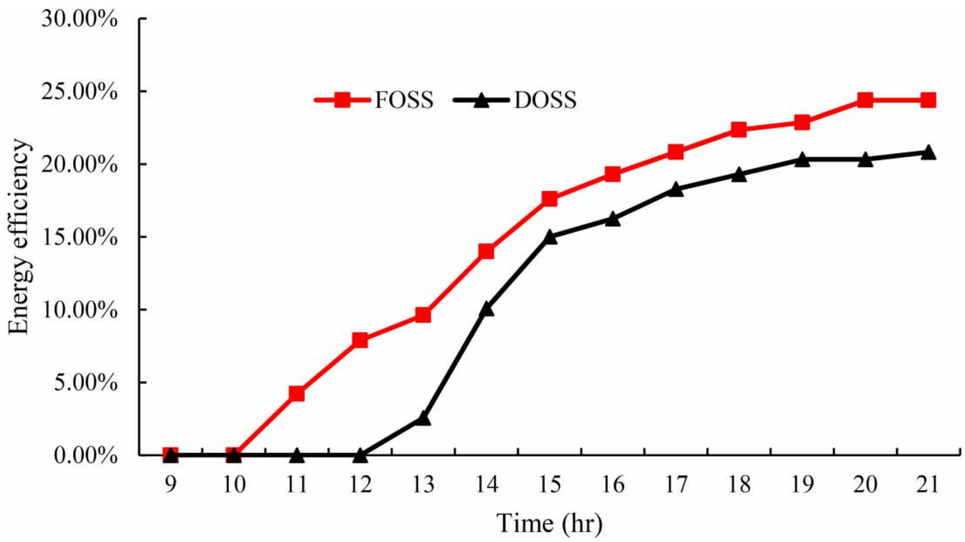

Figure 8 | Variation of the hourly energy efficiency of FOSS and DOSS.

Figure 9 illustrates the hourly variation of exergy output of FOSS and DOSS. The exergy outputs of the solar stills reach their maximum at 14:00 p.m., and then they drop to near zero at the end of the daytime. The results show that the maximum exergy outputs of DOSS and FOSS are 3.22 W and 2.40 W respectively. In addition, the total exergy outputs of DOSS and FOSS are 7.89 W and 9.73 W, respectively, and the total exergy output of the fourfold slope solar still is 23.24% higher than that of DOSS. This finding can be explained by the higher temperature of brackish water in FOSS. Exergy efficiency is directly related to water temperature. The higher the water temperature, the higher the enthalpy of evaporation. With the increase in water temperature, evaporation rate and exergy also increase.

Figure 10 shows the hourly exergy efficiency changes of FOSS and DOSS. As shown in the figure, the trends of hourly exergy efficiency are basically the same. The maximum exergy efficiencies of FOSS and DOSS are about 1.59% and 0.82% respectively. By comparing the exergy efficiency value in the figure with the energy efficiency value in Figure 8, it can be seen that the energy efficiency value is significantly greater than the corresponding exergy efficiency value. The

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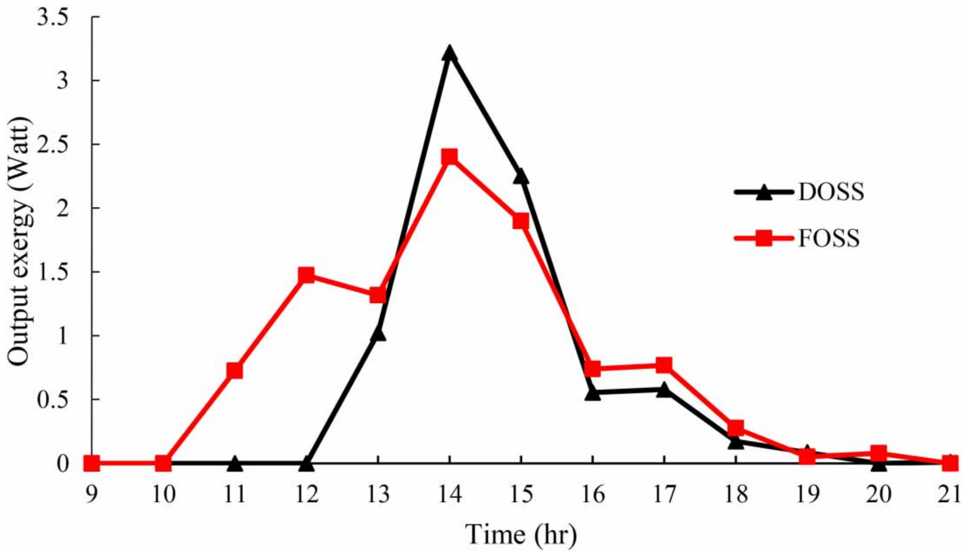

Figure 9 | Hourly output of exergy for FOSS and DOSS.

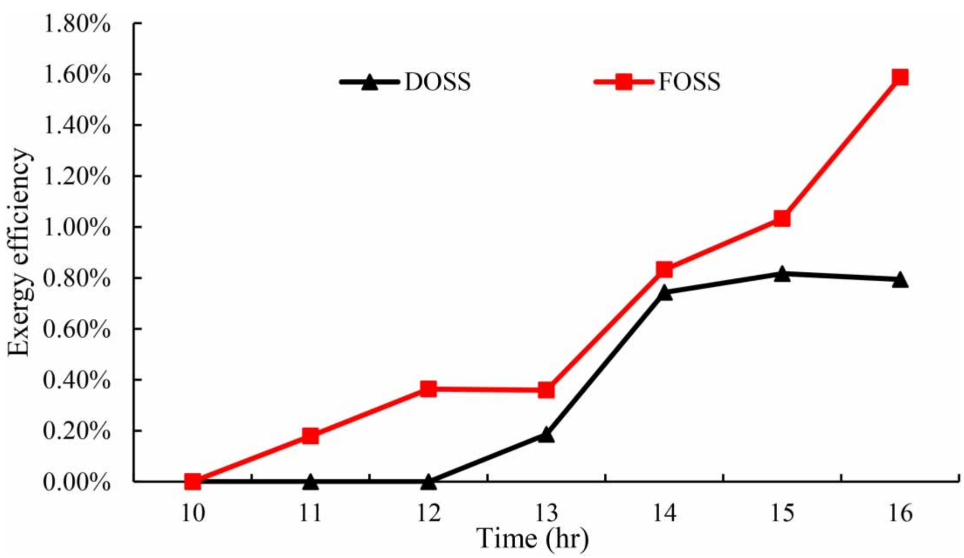

Figure 10 | Variation of the hourly exergy efficiency of FOSS and DOSS.

reason is that exergy analysis means the decrease of energy quality and considers the irreversibility of the system process rather than the concept of energy conservation. That is to say, the solar radiation with high exergy content from the sun (high temperature of 5,600 K) is converted into low energy exergy of evaporated brackish water. Then the difference between sun and water temperatures is too large, which leads to the small ratio of evaporation exergy and solar radiation exergy, and this ratio is the embodiment of exergy efficiency.

3.3. Energy payback time evaluation

3.3.1. Embodied energy

In order to ensure that the new solar still device proposed in this study is economically feasible, we have carried out the quantitative and comparative study on the embodied energy of FOSS and DOSS. Table 2 describes the specific energy values of the materials and components of the solar stills in the experiment. The total energy contents of FOSS and DOSS are 323.25 kWh and 314.36 kWh, respectively. The embodied energy of FOSS is a little higher than that of DOSS.

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Table 2 | Embodied energy calculations for FOSS and DOSS

Components	Embodied energy MJ	kWh	FOSS	DOSS
Basin	216	60	60	60
Fourfold slope cover	432	120	120	
Double slope cover	400	111.11		111.11
Solar still walls of FOSS	407.7	113.25	113.25	
Solar still walls of DOSS	407.7	113.25		113.25
Basin coating	108	30	30	30
Total embodied energy (kWh)			323.25	314.36

3.3.2. Energy payback time

Assessing the energy recovery period (EPBT) of an energy system is a necessary condition to verify its sustainability. The energy recovery times (EPBT) of the solar stills in this experiment are shown in Table 3. Based on the energy method, the EPBT values of FOSS and DOSS are 64.88 months and 75.42 months, respectively. The corresponding values based on exergy method are 1,143.48 months and 1,327.28 months, respectively. The results show that the EPBT of FOSS is lower than that of DOSS based on the energy method and exergy method.

3.4. Economic analysis evaluation

This research estimates the cost of each solar still. P is the present capital cost of a fourfold slope solar still or double slope solar still, i is the annual interest (assumed to be 12%), and n is the service life (assumed to be 20 years). All materials are priced according to the local market. According to the previous research results, the annual yield of FOSS is 616.55 kg, and that of DOSS is 533.78 kg. The total cost of FOSS is 1200 RMB (1$ = 7.08 RMB) and that of DOSS is 1100 RMB. The calculation results are shown in Table 4. The cost values of FOSS and DOSS are 0.28 RMB/kg and 0.30 RMB/kg respectively. This analysis clearly shows that the cost of FOSS is lower than that of DOSS. In other words, FOSS can collect more solar heat at the cover plate through the fourfold slope structure. This new type of solar still not only has low manufacturing cost, but also has much higher evaporation efficiency than the traditional solar still.

Table 3 | Energy payback time (EPBT) for solar stills

Parameters	FOSS	DOSS
Yield per month (kg)	7.35	6.15
Embodied energy (kWh)	323.25	314.36
Enout per month (kWh)	4.98	4.17
Exout per month (kWh)	0.28	0.24
EPBTen (months)	64.88	75.42
EPBTex (months)	1,143.48	1,327.28

Table 4 | Cost comparison between FOSS and DOSS

	P (RMB)	SFF	CRF	FAC (RMB)	S (RMB)	ASV (RMB)	AMC (RMB)	AC (RMB)	M (kg)	CPL (RMB/kg)
FOSS	1,200	0.014	0.134	160.8	240	3.36	16.08	173.52	616.55	0.28
DOSS	1,100	0.014	0.134	147.4	220	3.08	14.74	159.06	533.78	0.30

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3.5. Exergoeconomic evaluation

In order to ensure the effectiveness of the evaluation, the exergoeconomic method is used to analyze the two solar stills. The actual economic evaluation results of FOSS and DOSS are shown in Table 5. It can be inferred that FOSS's economic parameter value is greater than the corresponding DOSS value. From the actual economic situation, the fourfold slope solar still has greater economic potential. In sum, exergoeconomic analysis considers the economic aspects on the evaluation of these two solar stills, so as to ensure the effectiveness of assessment.

In this paper, we also evaluate the environmental benefits of FOSS and DOSS in terms of carbon footprint. The environmental and enviroeconomic assessments based on energy and exergy methods are shown in Table 6. The results show that FOSS and DOSS reduce 5.47 tons and 4.58 tons of CO_2 respectively based on the energy method. Then, the corresponding values based on the exergy method are 0.21 tons and 0.18 tons of CO_2, respectively. Therefore, FOSS proposed in this study can reduce more CO_2 emissions, and its performance is better than that of DOSS. The reason for this is that FOSS has higher energy and exergy outputs in its whole life cycle. Therefore, it can be concluded that the solar distillation system with fourfold slope cover is feasible in the environmental aspect. Table 6 shows that the environmental economic parameters of FOSS and DOSS are 79.29 $ and 66.35 $ respectively. The corresponding values based on exergy environment parameters are 3.05 $ and 2.56 $, respectively.

This part displays the calculation of the exergoeconomic parameter for both systems at different interests and lifetimes of the still. It can be observed from the table that FOSS has higher exergy output (Exout) at any lifetime of the still compared to conventional still, also it has a higher exergoeconomic parameter. It can be concluded from Table 6 that the inclusion of fourfold slope in solar still is attractive from the exergoeconomic evaluation. This can be explained by the low added cost of the glass material and the increase of exergy output of solar still. Therefore, it can be inferred from such analysis that one dimensional assessment of solar stills considering exergy methodology is not adequate where the economic features in line with the exergy approach should be considered.

3.6. Application prospect of fourfold slope solar still

According to the above results, the main motivation of the present study is to maximize the solar energy storage by installing fourfold slope cover. Such still can concentrate a large amount of sunray at the still's bottom basin. Then, in view of the

Table 5 | Exergoeconomic parameters for FOSS and DOSS

	Years	*i* (%)	AC (RMB)	Annual Enout (kWh)	Annual Exout (kWh)	$R_{g,en}$ (kWh/RMB)	$R_{g,ex}$ (kWh/RMB)
FOSS	20	12	173.52	136.71	5.26	0.79	0.03
DOSS	20	12	159.06	114.39	4.41	0.72	0.03

Table 6 | Environmental and enviroeconomic parameters for FOSS and DOSS

Parameters	FOSS	DOSS
Lifetime (years)	20	20
Embodied energy (kWh)	323.25	314.36
Annual Enout (kWh)	136.71	114.39
Annual Exout (kWh)	5.26	4.41
Enout (kWh) for lifetime	2,734.2	2,287.8
Exout (kWh) for lifetime	105.16	88.11
Environmental parameter (tons CO_2)	5.47	4.58
Enviroeconomic parameter ($)	79.29	66.35
Exergoenvironmental parameter (tons CO_2)	0.21	0.18
Exergoenviroeconomic parameter ($)	3.05	2.56

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shortage of water resources and the serious problem of soil salinization in South Xinjiang, this research group adopts the whole physical method to study the water salt separation technology of condensation water formed by solar photothermal evaporation and extraction of crystal salt from saturated salt water. A new method of extracting distilled water and sodium chloride crystal salt by concentrating solar energy is proposed. This project provides new ideas and scientific basis for the economic and effective utilization of salt water and condensate water resources and the improvement of saline alkali land in southern Xinjiang, and realizes harmless discharge with the utilization of water resources and the improvement of saline alkali land. This paper is one of the important supporting achievements of this project, aiming to study the mechanism of gas-liquid separation.

3.6.1. A circulation system containing three loops for avoiding the deposited sediments

First loop is the brackish water (low salinity) loop: the original brackish water solution enters the novel solar still. The salinity of the original brackish water solution in Xinjiang is 5‰. Under the influence of solar radiation in southern Xinjiang, the saline water rapidly heats up in the still to reach the evaporation condition, and a part of the original brackish water evaporates into water vapor. Then the gas rises to the inclined glass, and the water vapor is condensed, and the high-salinity water solution will be discharged once the salinity reaches 25%.

The second loop is the water vapor loop: through vacuum pumping action, the whole loop of water vapor is under negative pressure. The evaporator is affected by the negative pressure, the boiling point of salty water decreases and the evaporation is enhanced. The upper water vapor enters the condenser under the guidance of negative pressure, producing potable water.

The third loop is the concentrated salty water solution loop: after the continuous evaporation and continuous condensation, the potable water is constantly collected and the salty water solution at the bottom of still finally reaches the critical salinity of 25%. At this time, we will close the water intake and open the discharge valve at the bottom of the still.

To sum up, deposits will not occur in Xinjiang. We have installed an outlet in the novel solar still device for regularly cleaning the deposits. Then, the concentration of brackish water in Xinjiang is low (5‰), which is far lower than the salinity of sea water (25%).

3.6.2. The prospect of this proposed solar still in Xinjiang

Abundant solar energy resources: Xinjiang is located in the west of China, with abundant solar energy resources. Total solar radiation in Xinjiang is 5,000–6,400 MJ/m^2 a year, ranking first in China. Southeast of Xinjiang is blessed with more than 6,000 MJ/m^2/year radiation, higher than that in the northwest (below 5,800 MJ/m^2). Tarim River Basin, with an area of 1.02×10^6 km^2, is the largest continental river basin in Southern Xinjiang, China. It has an extreme desert climate with an average annual temperature of 10–11.5 °C. There is a great unevenness of precipitation distribution within a year.

Enough space for solar energy equipment location: Xinjiang is the largest region in China, covering an area of 1.66 million square kilometers. It is the provincial administrative region with the largest land area in China, accounting for one sixth of China's total land area.

Commercialization prospect: Due to the higher energy and exergy outputs of the novel still throughout its lifetime, the novel solar still proposed in this study mitigated more CO_2 compared to the conventional still. Compared with the double slope single basin solar still, the average energy efficiency per hour of the fourfold slope single basin solar still is improved by 31.11%. According to the energy method, the EPBT values of the fourfold slope solar still and double slope solar still are 64.88 months and 75.42 months respectively. According to the environmental parameter method, FOSS and DOSS reduce 5.47 tons and 4.58 tons of CO_2 respectively. The corresponding values based on the exergy environment parameters are 0.21 and 0.18 tons of CO_2, respectively. The fourfold slope solar still has more obvious emission reduction function than the double slope solar still. By comparing the cost of the fourfold slope solar still and double slope solar still, the cost of distilled water for the fourfold slope solar still is 0.28 RMB/kg, and the cost of the double slope solar still is 0.30 RMB/kg. The results show that the cost of distilled water from the fourfold slope solar still is lower than that of the double slope solar still. In addition, the environmental and economic parameters of the fourfold slope still and double slope still are 79.29$ (561.37RMB) and 66.35$ (469.76RMB), respectively, while the corresponding values based on the exergoenvironmental parameter are 3.05$ (21.59RMB) and 2.56$ (18.12RMB), respectively.

Cleaning and maintenance for the solar still: the salinity of the original brackish water solution in Xinjiang is 5‰, which is far lower than the salinity of sea water (25%). So deposit sediment is uncommon in Xinjiang, which will reduce the cleaning and maintenance costs. For the solar still device, we have installed an outlet in the novel solar still device for regularly

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cleaning the deposits. The water vapor rises to the inclined glass, and it is condensed, then the high-salinity water solution will be discharged once the salinity reaches 25%. In addition, the cost of cleaning and maintenance for lenses and reflectors is low because their manufacturing technology and after-sale service are all very mature.

3.6.3. Other prospective regions in China that could benefit from this research

(1) Eastern coastal saline soil

It is estimated that there is 14 million ha coastal saline soil land in shallow seas and beaches at the 15 m depth line. The coastal saline soil areas of Jiangsu, Shandong, Hebei, Tianjin and Liaoning north of the Yangtze River Estuary reaches 1.0 million ha. Coastal saline soil is characterized by high salinity in the whole soil, and the main composition of salt is chloride.

(2) Salted soil in North China Plain

According to the satellite data, there is about 1.33 million ha salted soil land in the North China Plain. After a long period of treatment and improvement, the salted soil area has been greatly reduced. A 1–2 cm thick salt crust is formed in the surface of the soil, with salt content over 1%, and the salt content in the soil layer below the crust has been decreased to about 0.1%.

(3) Salted soil in Northeast Plain

There is 3.20 million ha of saline soil and alkaline soil, among which the developed and utilized land area is 1.4 million ha. The saline soil in Northeast Plain contains sodium carbonate and sodium bicarbonate, and its pH value is very high. But the saline soil and alkaline soil are rich in organic matter, and the fertilizer conservation performance is good. Once this area is developed and utilized, the crop yield will be very high.

(4) Extreme arid saline soil

Tarim Basin, Turpan basin and Qaidam Basin contain tens of millions of acres of saline alkali soil. The soil has high salt content, and the surface forms thick and hard salt crusts. Salinity of the whole soil profile is very high.

4. CONCLUSIONS

The energy, exergy, exergoeconomic, and enviroeconomic evaluation was carried out to make a comparison between the double slope solar still and fourfold slope solar still. It is observed that the use of fourfold slope cover enhances the performance of the solar still compared to the conventional still. The conclusions of this study are:

1. In winter, the total cumulative freshwater yield of the fourfold slope single basin solar still is close to 0.98 kg/m^2, which is 19.51% higher than that of the double slope single basin solar still. Their water production rates reach the peak between 14:00 and 15:00 p.m.
2. Compared with the double slope single basin solar still, the average energy efficiency per hour of the fourfold slope single basin solar still is improved by 31.11%. According to the energy method, the EPBT values of the fourfold slope solar still and double slope solar still are 64.88 months and 75.42 months respectively. According to the environmental parameter method, FOSS and DOSS reduce 5.47 tons and 4.58 tons of CO_2 respectively. The corresponding values based on the exergy environment parameters are 0.21 and 0.18 tons of CO_2, respectively. The fourfold slope solar still has a more obvious emission reduction function than the double slope solar still.
3. By comparing the cost of the fourfold slope solar still and double slope solar still, the cost of distilled water for the fourfold slope solar still is 0.28 RMB/kg, and the cost of the double slope solar still is 0.30 RMB/kg. The results show that the cost of distilled water for the fourfold slope solar still is lower than that of the double slope solar still. In addition, the environmental and economic parameters of the fourfold slope still and double slope still are 79.29$ (561.37RMB) and 66.35$ (469.76RMB), respectively. While, the corresponding values based on the exergoenvironmental parameter are 3.05$ (21.59RMB) and 2.56$ (18.12RMB), respectively. From the analysis of exergoeconomic and exergoenvironmental parameters, the fourfold slope single basin solar still appears to be more effective.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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