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Review Article

Environmental studies for various simple and hybrid solar still configurations: A comprehensive review

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ABSTRACT

In this review article the results for the last three years are given with regard to the energy payback time, the embodied energy, the emissions of carbon dioxide (CO_2), conversion efficiency of life cycle, attenuation of the CO_2 and the carbon credit earned (CCE). The study parameters are relatively difficult to follow their evolution according to the experimental prototype studied and the materials used. All depend on the nature of the design and the economic part. The findings demonstrated that embodied energy ranges from 30 to 100 percent of the total life cycle consumed. EPT typically depends on the location and the equipment used, and it has the least negative environmental effects when used in products with an average shelf life of 10 years or less, regardless of the type of solar still. Desalination methods attain their optimum efficiency very quickly in terms of sustainability, according to LCCE. CO_2 mitigation is more likely to occur with active systems than with passive ones. The system (CSS + WM + PTC) with the highest embodied energy value among the systems under study has a value that is approximately 54% greater than that of CSS.

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INTRODUCTION

To protect our planet from the detrimental effects of climate change, it is imperative to reduce the release of carbon dioxide (CO_2) and added greenhouse gases. Life cycle analysis is a crucial tool for assessing and comparing solar desalination systems in terms of their overall environmental effect. Environmental analysis is quickly rising to the top of the list of crucial system design considerations. Various indicators, such as EE, EPBT, CO_2 emissions, and carbon credits earned, illustrate the environmental impact of the building system (CCE) [1-4]. To do this, the (CDM) idea gained popularity. A Kyoto Protocol agreement that allows for the reduction of emissions is known as the CDM. A developed nation would be granted carbon credits for achieving its emissions reduction goals. Kumar et al. [5] demonstrated that the embodied energy of a TSSS was measured at 2595.22 MJ, which is 9.28% lower than that of a double slope solar still. The construction cost for TSSS was Rs. 14,049, almost equivalent to the cost of a double SSS [6]. The EPBT for TSSS, excluding minor components, was calculated to be approximately 0.202 years. When factoring in all parts, the EPBT increased to 0.251 years. Importantly, TSSS showed a significantly smaller EPBT value compared to the double slope solar still, with a reduction of 153.7% [7]. In their study, Mousa et al. [8] conducted a comprehensive assessment of a linear Fresnel sensor designed for industrial roofs. Their analysis indicated that the embodied EPBT ranged from 1.2 to 15 years and Greenhouse gas Payback time (GHG PBT) ranged from 2 to 17 years, depending on the specific solar technologies considered. The findings indicated that solar thermal collector (ST) systems had a shorter EPBT in regions with high direct normal irradiation compared to single crystal PV systems. The Life-cycle Assessment (LCA) method suggested in their research provides valuable insights for manufacturers, policymakers, and upcoming sustainability reporting standards. It helps them pinpoint the solar technology that achieves the quickest EPBT and Greenhouse Gas Payback Time. Additionally, Dwivedi and Tiwari [9] conducted an analysis of carbon credits concerning passive solar stills, revealing the potential to earn 9.33 tons of CO_2 over a 20-year lifespan. Similarly, Sharon and Reddy [10] performed an Eco-Financial Evaluation on straight up solar distillation systems, indicating a potential mitigation of 69.85 tons of CO_2 over a 20-year period.

Capturing and storing carbon dioxide (CO_2) emissions from fossil fuel combustion for electricity generation or industrial activities like making steel and cement is known as carbon capture and storage (CSS). After being extracted from its source, the carbon is piped or shipped to geological formations for long-term storage. There are three main types of these systems: oxy-fuel combustion systems, post-combustion carbon capture (the main technique used in current power plants), and pre-combustion carbon capture (mostly utilized in industrial processes) [11].

In the absence of renewable energy sources, solar desalination (SD) might worsen climate change by increasing reliance on fossil fuels, increasing emissions of greenhouse gases, and the rate at which the planet warms [12].

Chemistry is clearly essential to the energy dilemma, as many power-to-chemicals (PTC) systems work with molecular or solid energy carriers. In order to conduct energy conversion reactions, chemistry supplies the necessary methods and ingredients. Both the energy conversion and its consumption may be controlled by chemical science in terms of their energetic "cost" [13].

There is a constant and strict requirement for energy in conventional chemical processes since they usually run constantly at a steady state. The generator side management's efforts to reduce renewable energy variability—through measures like renewable source diversification and surplus renewable energy provision—are ill-equipped to meet such a stringent requirement. So far, energy storage—specifically compressed hydrogen (H_2)—has been the mainstay in renewable chemical synthesis to level renewable power output; this has been shown in the manufacture of "green" ammonia and methanol. Despite hydrogen's importance in renewable energy storage, it isn't ideal for large-scale applications or long-term storage due to its high-pressure storage, possible safety concerns, and costly storage containers [14].

However, Khanmohammadi and Khanmohammadi [15] have concentrated on investigating exergoeconomics and CO_2 emissions/mitigations in solar stills, which is shown in their superior performance than conventional solar stills. Parsa et al. [16] conducted an experimental study between active and passive solar stills as the main objective of their research, which examines the exergoeconomic, environmental and energy parameters productivity were higher for active systems in the city of Tehran, while passive systems at the top of Touchal have the highest energy recovery times due to lower operating days and productivity. Since 2019, Bait [17]'s work has compared two solar systems: the traditional solar system and the tubular solar system. He discovered that the tubular system is more productive and thermally efficient than the standard one, although the modified system's energy payback period is significantly longer than the conventional system's, at roughly 13.3 years. According to Pal et al. [18], the day of the operation is a crucial variable that significantly affects energy matrices.

Rajaseenivasan and Srithar [19] investigated a finned passive solar system for various water depths in 2016 and found that when the depth drops, the reduction of CO_2 enhances the system's life as well. To dry banana and pineapple slices efficiently, Joshua et al. [20] designed a combine mode type drier and examined it with thermal energy storage and without. The inclusion of thermal energy storage systems was found to enhance drying efficiency by 75%. Over a 25-year period, the payback period for this system was reported to be 1.6 years. Furthermore, Singh and Gaur

[21] explored the carbon dioxide reduction potential of a hybrid greenhouse dryer with active features, examining scenarios with and without evacuated type collectors. They found that the lifetime carbon dioxide reduction potential ranged from 50.49 to 135.04 tons with the collectors and from 26.57 to 49.58 tons without them. Additionally, the drying duration for ginger, tomato, and bottle gourd decreased by 34.09%, 47.36%, and 61.9% correspondingly. The anticipated payback periods for these improvements were 1.79 years, 0.69 years, and 2.87 years, respectively. In their study, Rahman et al. [22] showed that the ZnO module outperforms the TiO_2 module in three vital damage categories: resources, human health, and ecosystem quality. Interestingly, the organic PV cell emerged as the top performer, exhibiting the least impact in these categories. Strikingly, when considering CO_2 emissions, perovskite modules were unexpectedly found to have higher emissions, whereas CdTe modules exhibited the lowest emissions in comparison to conventional modules [23]. The significantly shorter lifespan of perovskite modules compared to other solar technologies is the primary reason for their lower durability in comparison to conventional modules. According to Thakur et al. [24], traditional SS has an estimated 241.4 kWh of total embodied energy. Over the course of the SSs' entire 10-year lifespan, the mitigated CO_2 fluctuations and carbon credits produced were analysed. CSS, SS-Cu, SS-AL, and SS-Sn each had a net CO_2 mitigation of 9.96, 13.19, 12.08, and 11.01 tones, respectively. The reduction of CO_2 was significantly aided by the synthesis of microparticles, with traditional SS (without any modifications) showing the lowest value. The biggest amount of carbon credits, 144.86 US dollars, were produced for SS-Cu. For SS-Al and SS-Sn, its value dropped to 132.67 and 120.91 US dollars, respectively.

Yousef et al. [25] conducted a comprehensive study involving energy and exergy efficiency, cost analysis, as well as environmental and economic assessments for a SS solar still. Their findings highlighted a remarkable energy efficiency of 52.5% with the utilization of steel wool fiber absorber plates, significantly outperforming the conventional solar still's efficiency of 42%. Additionally, the exergy efficiency reached 23%, relative to the conventional SS. The modified SS was estimated to reduce approximately 15.6 tons of CO_2 emissions compared to the traditional SS. This article presents various research works that focus on the environmental impact of simple and hybrid solar stills. These studies primarily revolve around parameters such as embodied energy (EE), which encompasses the energy required for all activities related to a production process, including activities upstream to resource acquisition. These assessments also take into account factors such as production factor, CO_2 emissions, EPBT, and life cycle conversion efficiency [26]. In other hand the emissions of CO_2, EPBT, production factor and LCCE. All these parameters are collected in this review work.

Despite this, the research has not yet conducted a comprehensive examination of environmental studies for a variety of solar still designs, including both basic and hybrid solar stills. This research, which takes into account technical, scientific, and development elements, focuses on the environmental studies for various solar still configurations. Both the technical and scientific aspects are taken into consideration. If a full understanding of the aforementioned characteristics is attained, the environmental studies have the potential to be developed in a variety of solar stills, including basic and hybrid solar stills. It is feasible that the findings of this study might be used as a reference for future research on environmental studies for the solar still, which has made some development but still needs to be improved. This is something that is achievable.

CONSTRUCTION PARTS OF SOLAR STILL

For many years, scientists have been trying to make solar stills more effective. Numerous solar still designs, simple and active configuration solar still have been developed during the past few years. Generally, cone-shaped, box-shaped, and frustum-shaped solar stills are the three standard configurations.

Solar Still's Workings

Across various solar water distillation methods, the fundamental concept for generating fresh water from salt water remains consistent. In these methods, saline water in the trough absorbs the majority of the sun's light as it passes through the cover. The cover and trough then absorb the remaining liquid, leading to the distillation process. As a consequence, the salty water is heated to cause it to evaporation. The water vapor density in the air rises as a result of evaporation from the liquid surface. Evaporation causes the water vapor that had accumulated on the cover's inner surface to lose its latent heat. After trickling down due to gravity, the condensed water is subsequently collected in a collector.

Embodied Studies in Simple and Active Configuration Solar Sill

The cumulative effect of all greenhouse gas emissions that can be traced to a substance during its entire life cycle is referred to as the material's "embodied energy" or "embodied carbon." Extraction, production, building, maintenance, and disposal are all considered to be components of this cycle.The physical environment is influenced by humans in a variety of ways, including but not limited to overcrowding, pollution, the burning of fossil fuels, and deforestation. Changes such as these have been responsible for climate change, soil erosion, poor air quality, and water that is unfit for human consumption. Embodied energy may be seen in the following examples: the energy that is required to extract raw resources, process materials, assemble product components, transport between each phase, create, maintain and repair, demolish, and dispose of structures [27].

Variability and Sensitivity Analysis

During the sensitivity analysis for solar technology-based active water purifiers, the relevance of parameters at the system's input is revealed in order to get a certain output. Consequently, the designer of the system will be aware in advance of the impact that the input parameters will have on the output that is chosen, and they will be able to easily monitor the input parameters in accordance with the requirements of the user or the client. The sensitivity investigation on active solar still can be carried out using the one at a time method, which consists of finding the output values that correspond to the dissimilarity in one input parameter while maintaining other input parameters as constant, followed by the repetition of this procedure until the estimation for all input parameters is finished. This method can be used to carry out the investigation. First, the sensitivity figure is determined by calculating the ratio of the percentage change in the output parameter to the percentage change in the input parameter, and then the findings are shown in two dimensions using the information gained [28].

Exergy Calculation and Significance

In order to establish whether or not the modified solar still is capable of performing more effectively than the standard solar still, it is essential to undertake a calculation that accounts for the energy and exergy efficiency of the system. Another way for determining the performance of the solar still in terms of the distillate yield CPL and its technological payback time is to conduct an economic study. This analysis is based on the selling price of water in a particular nation. More recently, there has been an increased focus on identifying the impact that the use of solar stills for the production of water has on the surrounding ecosystem [29]. Jijakli et al. [30] have expressed an increasing worry on the reduction and elimination of carbon footprints that are related with the life cycle of a technology. This coincides with that issue. On the basis of the five primary factors of productivity, energy, exergy, economics, and environment, a few studies on the performance of solar stills have been taken into consideration and analyzed. Nazari et al. [31] found that this combination was effective. Nazari and Daghigh [32] developed a non-cover solar still that used a thermoelectric cooling channel and a parabolic dish concentrator.

Validation and Reproducibility

According to what can be observed, SS are the focus of a great deal of research in the scientific community, both experimental and theoretical. On the other hand, when it comes to experimental investigations, the tests are often carried out over the course of many consecutive days. For instance, SS with a water depth of 1 cm is researched on the first day, and then an investigation with a water level of 2 cm is carried out on the second day, and so on. As a consequence of this, the weather conditions, which include solar irradiance, ambient air temperature, and wind speed, all have the potential to change throughout these days, which may have an impact on the outcomes of the tests [33]. Therefore, Kalbasi and Esfahani [34] and Kalbasi et al. [35] evaluated the performance of a solar collector (SS) under laboratory settings. In this study, the electric heater was employed as a heat source to replicate solar radiation. The first set of testing was conducted with a water depth of one centimeter and three constant input powers, namely 200 W/m^2, 500 W/m^2, and 800 W/m^2. The daily productivity for these three constant input powers was 4.25 L/m^2/day, 14.3 L/m^2/day, and 24.56 L/m^2/day, respectively. In the second set of trials, the input power was set at 200 W/m^2, and the water depth was set at 1 cm, 2 cm, and 3 cm. The productivity of SS was 4.25 L/m2/day, 3.96 L/m^2/day, and 3.63 L/m^2/day, respectively, for each of these water depths.

Solar Energy is used in solar stills to change saltwater seawater into distilled water using a condensation distillation process. Solar stills frequently lack moving components, thus their design and operation do not need specialized knowledge or incur significant maintenance expenses. In their theoretical study, Kumar and Kurmaji [36] investigated CO_2 emissions and carbon credits obtained from various models of solar stills in India. The carbon dioxide mitigation achieved by hybrid (PVT) active and weir-type solar stills with a range of 20-year lifespan amounted to approximately 26 tons per square meter. Additionally, they found that the hybrid active solar stills and weir-type solar stills yielded annual performances of 1,400 and 1,290 liters per square meter, respectively.

Sharon and Reddy [37] performed research on the performance and environmental impact of active vertically solar stills devices as shown. Cascaded vertical SS (CVSS) and then double slope (CDSS) still arrangements are two options for active mode performance. Figure 1 showed that the total distillate production of the distillation units studied. In comparison to a passive vertical still of identical size, the cascaded upright still yields additional distillate. They established that the CVDS unit with an energy payback period of around 2.2 years, could reduce CO_2 by about 69.85 tons over the duration of its 20-year life, and can produce distilled water at 34.3 USD/kL. The unit is more practicable and economical for rural and urban uses because to its high output, low cost for water production, and low surface area usage.

Rajaseenivasan and Srithar [38] conducted both experimental and analytical studies to examine the efficiency of a solar still incorporating circular and square fins in the basin. They reported that the period of embodied energy payback is below one year in all situations, according to the carbon credit study, and it decreases as the number of operating days of the solar still increases. According to economic study, the cost of distilled water decreases as the number of operating days and the life of the solar still increases as shown in Figure 2.

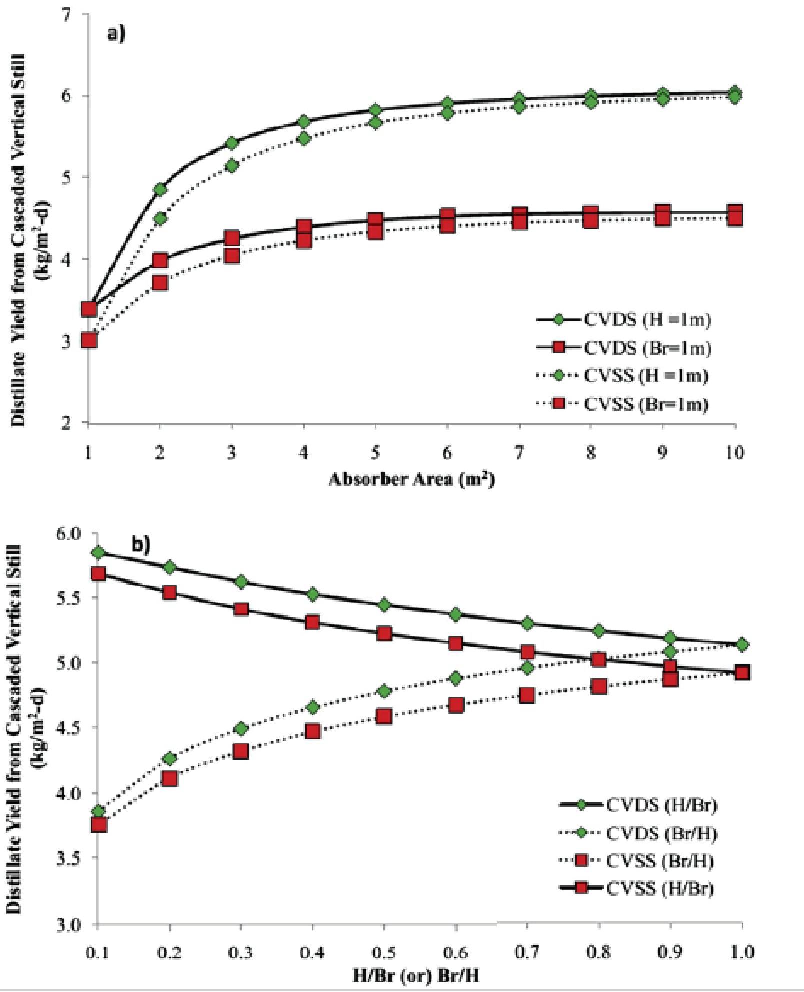

Figure 1. Impact of a) Area of absorber and b) Aspect ratio of cascaded vertical still on distillate yield [From Sharon and Reddy [37], with permission from Elsevier.]

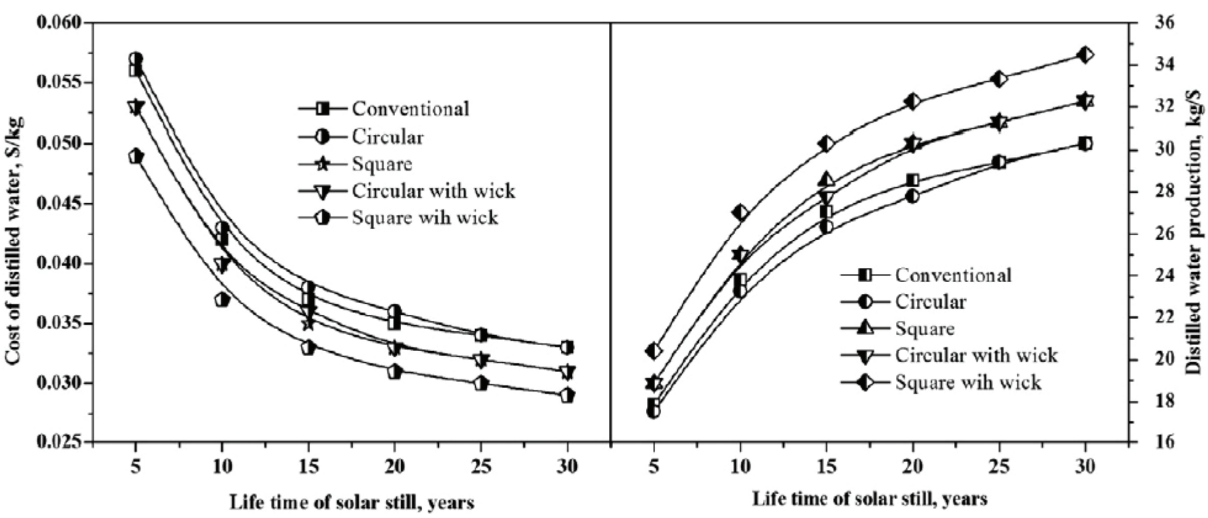

Figure 2. Analyzing the economics of solar stills with various modifications [From Rajaseenivasan and Srithar [38], with permission from Elsevier.]

Kumar et al. [39] employed a SSSDU in conjunction with N identically evacuated tube collectors (N-ETC) to investigate the impact of the number of collectors (N) on the environment. Utilizing analytical software integrated with MATLAB, the study was conducted for typical days in May and December, reflecting the environmental conditions in New Delhi. The researchers computed the average daily energy output for various values of N at selected fluid mass flow rates, followed by assessing the quantity of carbon reduced and the enviro-economic factor. Their findings revealed that as the value of N increased, there was a corresponding rise in average daily energy output, as depicted in Figure 3. Moreover, the increase in N led to higher values of carbon credits and the environmental cost-to-economic parameter.

For both the passive and active solar distiller units, the study was conducted by Dharamveer [40] using the identical basin area criterion. The average solar intensity per day for sunny days around 275 in a year was determined as 401.8 kW for New Delhi climatic conditions. As shown in Figure 4, the estimated asset cost to establishments for active and passive solar distillation systems is \$231.46 and \$1317.36, respectively. The major findings revealed that the active distillation device not only outperformed the passive distillation technique by 119 percent, but also had a significant increase in energy content and a 102% gain in carbon reduction during 30 years of operation for both systems. Furthermore, as compared to the passive setup, the active combination has better CO_2, SO_2, and NO pollution management. As a result, the associated programs are environmentally friendly and provide a significant quantity of earned carbon credit.

The study realized at Al-Kufa about environmental impacts of inexpensive square pyramid solar were experimentally and numerically examined by Al-Madhhachi and Smaisim [41] during the 4 seasons of Al Kufa weather

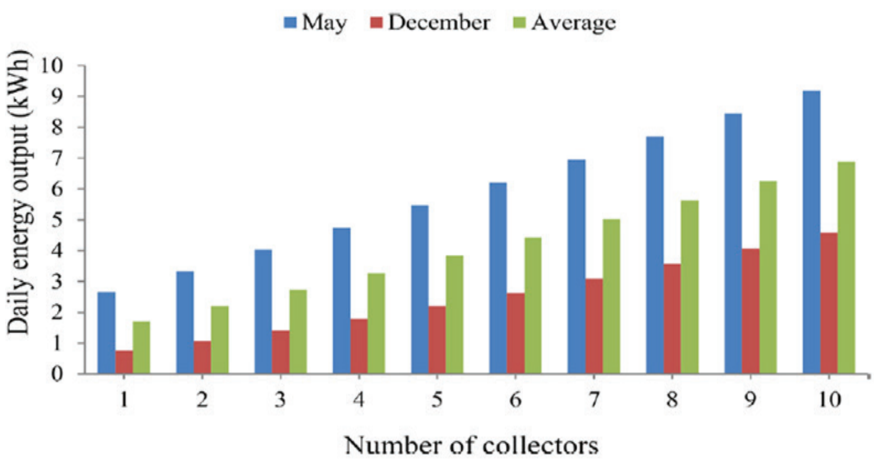

Figure 3. Variation of daily yield with flow of fluid mass per unit time at environmentally friendly and provide a significant quantity of earned carbon credit [From Kumar et al. [39], with permission from Elsevier.]

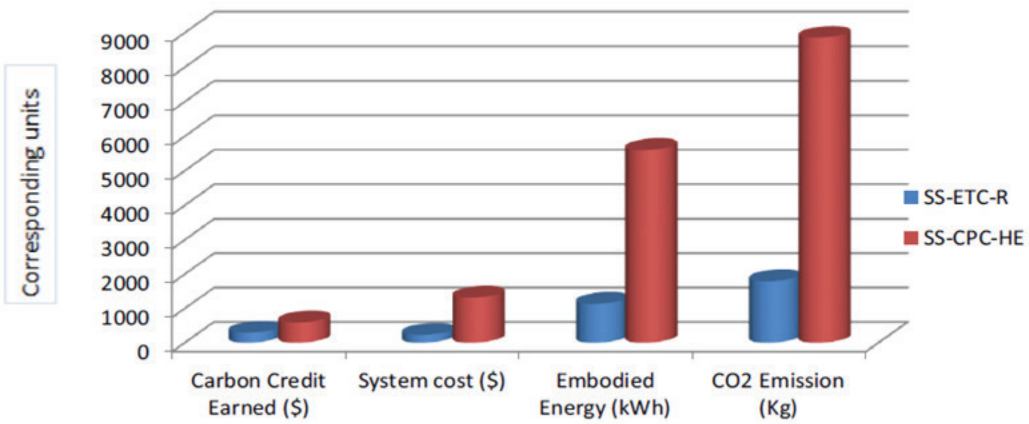

Figure 4. Energy matrices observations for the proposed systems [From Dharamveer [40], with permission from Elsevier.]

conditions. They determined that the portable solar still generates 2.2 L/m^2 of water in any village in Iraq's south where there is no power and high sun intensity. Furthermore, the cost of their work is cheap, since the square solar still's entire manufacturing cost was approximately $15, while the triangle and pentagon solar stills' fabrication prices were around $10 and $20, respectively.

In Jaipur, India, Thakur et al. [24] investigated the efficacy of a modified solar still that was constructed and tested with three major microparticles mixed in a black paint-coated absorber. Copper, aluminum, and tin microparticles with particle sizes of 50 to 80 m and weight concentrations of 10% were added to black paint before being put on the solar still's absorber. According to the findings, copper, aluminum, and tin coating on the absorber increased the full-day water output by 33.13, 22.18, and 11.53 percent in comparison to traditional solar still without coating, as shown in Figure 2. Due to copper's better thermal conductivity and superior solar-thermal conversion characteristics, the full-day energy and exergy efficiency of solar stills with copper-coated absorbers also shown maximum values when compared to all other solar stills.

In their study, Sun et al. [42] introduced a single basin fourfold SSS equipped with a fourfold slope glass cover plate. Relative experiments were performed in winter whether in Hangzhou to assess the operational efficiency of a DOSS in comparison to the fourfold. The aim was to analyze and demonstrate the effectiveness of the fourfold SSS design. The results showed that the fourfold SSS increased the average hourly energy efficiency by 31.11%. Additionally, it was found to be 19.51% more efficient than the double slope solar still.

Kumar et al. [43] conducted an examination of the embodied energy, pay-back period, and cost analysis of the triple SSS(TSSS) in comparison to the double slope sun still (DSSS). The selection of the optimal material for a solar still relies on local material availability and production methods, with a crucial focus on embodied energy. Their study revealed that the TSSS has a total embodied energy of 3297.35 MJ. The energy pay-back time (EPBT) for TSSS construction was calculated to be 0.251 years, and the overall cost was Rs. 14049. Importantly, the embodied energy of TSSS was found to be 9.28% lower than that of the double slope solar still. Furthermore, the EPBT of TSSS

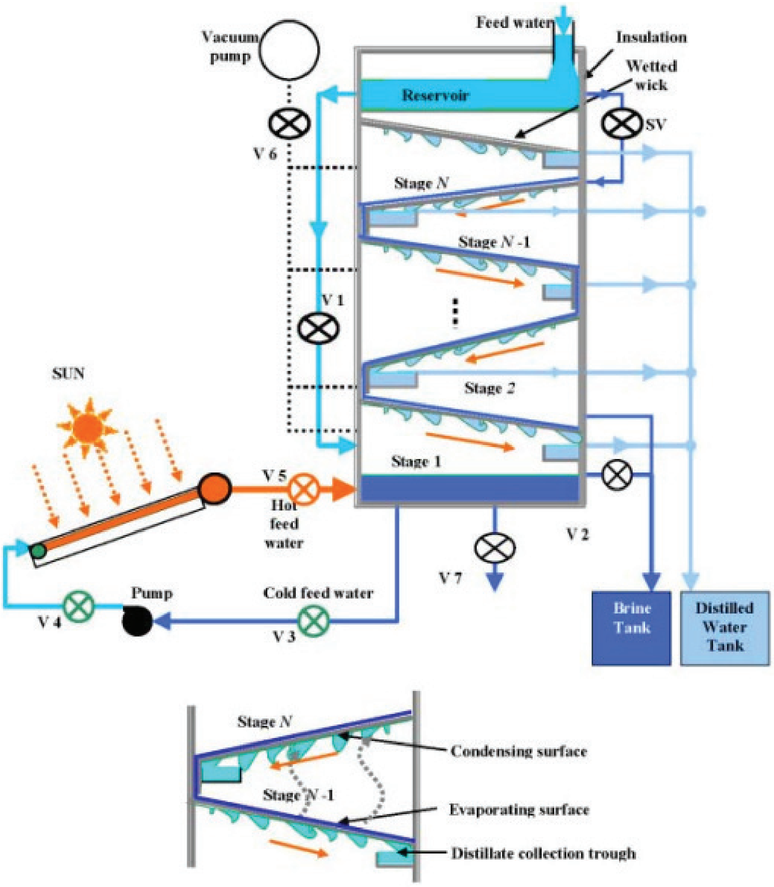

Figure 5. Flow inside solar distillation unit for active multistage series [From Reddy and Sharon [45], with permission from Elsevier.]

was 153.7% smaller than that of DSSS, indicating its higher efficiency and reduced environmental impact.

Reddy and Sharon [44] developed an evacuated desalination unit, which demonstrated a maximum annual average daily distillate yield of 29.43 kg/m^2.d on the west coast of India and 27.22 kg/m^2-d on the east coast of India.

In their research, Reddy and Sharon [45] introduced various concepts, types, and methods of solar energy-driven desalination processes aimed at enhancing the productivity of solar desalting units. Their focus was on fundamental principles, thermodynamic analysis. They establish the superiority and viability of multi-stage solar desalination units, as depicted in Figure 5.

Sahota and Tiwari [46] discovered that the embodied energy for a single-SSS is higher than that of a double-slope PVT-CPC active solar still with the same basin area. This difference is attributed to the greater amount of material needed for assembling a single-slope PVT-CPC active solar still due to its system geometry. In terms of energy, EPBT for an active double-SSS is lower (by 7.5%) than that of a single-slope PVT-CPC active solar still. This difference arises from the lower value (2.83%) of embodied energy and the higher value (4.2%) of annual energy for the double-slope active solar still.

Yousef and Hassan [47] used energy and exergy approaches to assess the performance of a solar still that included a (TES) unit of PCM. In accordance with the weather in Alexandria, Egypt, experiments on solar stills with and without PCM are carried out in the summer and winter. The results revealed that adding a PCM storage unit to a solar still system boosted yearly energy savings by 10%and exergy savings by 3%. In order to better understand the performance of the three identical solar distillation units with various configurations in the Tehranian climate, Javadi Yanbolagh et al. [48] published a research. Thermoelectric heating modules (TEH), copper heaters (CH), and solar water heaters (SWH) were the different types of heating sources that were included in each system, and each system also included an active external condenser. Results showed that the system with CH achieved the maximum daily and yearly production. The system with SWH had the lowest cost per liter (CPL) compared to other systems, according to economic study based on uniform annual cost (UAC), whereas the case of TEH had the highest CPL.

Comparative analyses were carried out for the pyramid-shaped solar stills' CO_2 role and life cycle conversion efficiency by Kumar et al. [49, 50]. The authors employed SPS (shaded pyramid still) and CPS (out shaded pyramid still), two different types of solar stills (shaped pyramid shaped) Figure 6. The findings revealed that the carbon footprint of the SPS model is more notable than that of the CPS model [51, 52], and that the CPS model has higher life cycle conversion efficiency (LCCE), CO_2 mitigation, and carbon credit (CC) than the SPS model. The LCCE values for CPS were 30.39 percent and for SPS were in the range of 19.98 percent at 30 years of age (Table 1). The CO_2 mitigation for the SPS was 13.19 tones, where as it was 20.07 tons for the CPS. Distilled water may be purchased at Rs. 23.28 per kg for CPS and Rs. 22.67 per kg for SPS. The payback years for both stills were 0.52 and 0.82 years, respectively, when considering the carbon credit for the still anticipated 30-year life (Table 2, A and B).

The effectiveness of the PTC connected to a single SSS was investigated by Hassan et al. [53]. Based on productivity, energy, exergy, exergoeconomics, and environmental techniques are assessed, as well as energy payback time. The goal of this work was to develop six different solar still systems: conventional solar still (CSS), conventional solar with wire mesh (CSS+WM), CSS contains and (SD) in the basin (CSS +SD), CSS coupled with PTC (CSS +PTC), basin CSS contains wire mesh (WM) and coupled with PTC (CSS + WM + PTC), and basin CSS contains and integrated with PTC (CSS + SD + PTC) (Table 3).

The studies are conducted in the hot and cold weather of the Egyptian city of Sohag. The findings indicated that (CSS + SD + PTC) achieves the greatest fresh water output in the summer with an increase of 1.21 percent compared to CSS and 102.1 percent compared to (CSS +SD + PTC) in

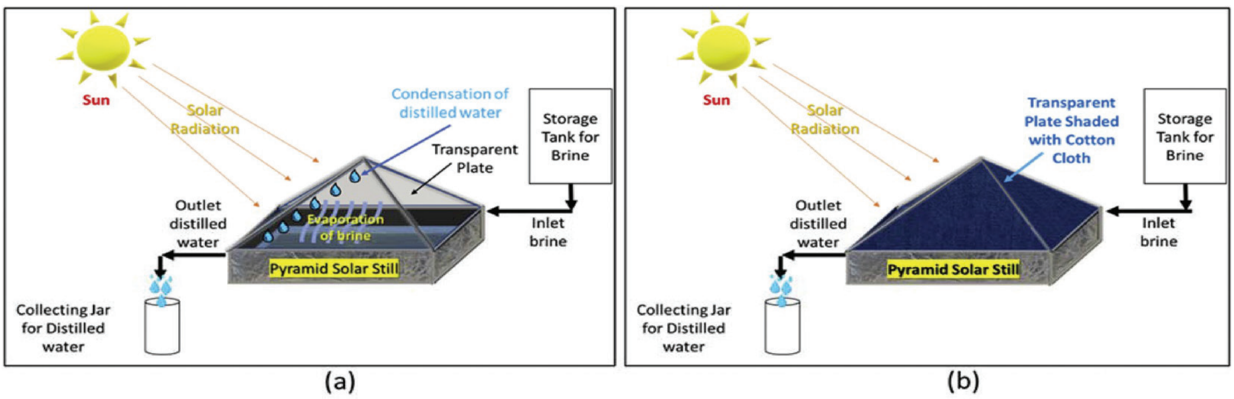

Figure 6. Schematic diagram of pyramid solar still CPS (a) without shading, (b) with shading SPS [From Kumar et al. [50], with permission from Elsevier.]

Table 1. Summary of previous studies about the solar still systems

Author [reference]	Type of study	Year	Type of solar still	Results/findings
Kumar and Kurmaji [36]	Numerical	2013	23° cover tilt - SS passive solar still 30° cover tilt -SS passive solar still Hybrid active solar still - SS and Pyramid type passive solar still (area 1.5m$^{2)}$ Pyramid type active solar still (area 1m$^{2)}$ Basin type passive solar still with ribs (1m^2) Hemisphere type passive solar still Weir-type passive solar still (area 1 m^2)	The hybrid active type and weir-type solar stills produce 1,400 and 1,290 l/m^2 of yearly performance, respectively
Sharon and Reddy [37]	Numerical	2015	Vertical solar still	In comparison to a passive vertical still of identical size, the cascaded vertical still yields more distillate
Rajaseenivasan and Srithar [38]	Experimental and Numerical	2016	The basin of solar still is attached with different shape fins	According to economic study, the cost of distilled water decreases as the number of operating days and the life of the solar still increases
Kumar et al. [39]	Numerical	2020	SS solar stile with N similar evacuated collectors of tubular shape	They discovered that when the value of N increased, the average daily energy output increased
Dharamveer [40]	Comparative analysis	2021	Double slope with helically coiled	A significant increase in energy content and a 102 percent gain in carbon reduction during 30 years of operation for both systems
Al-Madhhachi and Smaisim [41]	Experimental and Numerical	2021	Solar still with shape of square pyramid	the cost of their work is cheap, since the square solar still's entire manufacturing cost was approximately $15, while the triangle and pentagon solar stills' fabrication prices were around $10 and $20, respectively

Table 2A. The exteriorized energy of CPS and SPS

Component	Materiel	Mass (kg)	exteriorized energy (MJ/kg)	exteriorized energy			
				CPS		SPS	
				KWh	MJ	kWh	MJ
Basin	Stainless steel	16.6	56.7	941.22	216.45	941.22	216.45
Transparent plate	Glass	4.2	15	63	17.5	63	17.5
Insulation	Expanded Polystyrene	1.36	88.6	120.49	33.47	120.49	33.47
Basin coating	Paint	0.25	97	24.25	6.74	24.25	6.74
Shading	cotton	0.4	44	---	----	17.6	4.89
				1148.97	319.16	1166.57	324.05

Table 2B. The EPF and LCCE of the CPS and SPS

	CPS		SPS	
	EPF	LCCE (%)	EPF	LCCE (%)
Annual	1.36		0.9	
5	6.82	26.59	4.51	16.15
10	13.65	28.87	9.03	18.45
15	20.47	29.63	13.54	19.21
20	27.30	30.01	18.05	19.6
25	34.12	30.25	22.57	19.83
30	40.94	30.39	27.08	19.98

Table 3. Solar still conventional systems

Sl No	Specification
1	Conventional solar still (CSS)
2	CSS coupled with PTC (CSS+PTS)
3	CSS contains wire mesh in the basin (CSS+WM)
4	CSS +WM and coupled with PTC (CSS+WM+PTC)
5	CSS sand in the basin (CSS+SD)
6	CSS+SD coupled with PTC (CSS+SD+PTC)

winter. The combined implementation of Carbon Capture and Storage (CSS), Solar Desalination (SD), and Power-to-Chemicals (PTC) technologies leads to a substantial annual increase in energy and exergy output compared to CSS alone, ranging from 216.6 percent to 325 percent. For all six case studies, adding PTC to the still is proven to be better. When compared to passive systems, active systems are proven to have more effective exergoeconomic and environmental factors. The assessment of the EPBT is important for any renewable and sustainable system, including solar energy systems, in order to determine the system's long-term viability. The EPBT Eq. (1) is defined as the amount of time required for an item to accumulate the energy required for its creation. Any item can only be produced by putting forward some kind of energy [54]. The amount of energy used to prepare and produce system components is indicated by the energy return equation (EPBT) (Figure 7).

$$(EPBT) = e_i/e_{en,\,out} = e_i/e_{ex,out} \qquad (1)$$

The term "ei" refers to embodied energy, representing the total energy consumed during the fabrication of an object. In the context of the proposed experimental setups, the embodied energy values are provided in Table 4. This table illustrates how the build system affects the

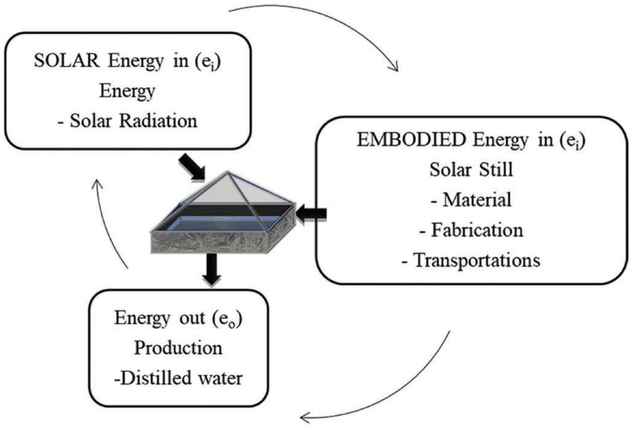

Figure 7. Simple cyclic flow chart of energy analysis for Pyramid shape still. *S.* [From Kumar et al. [50], with permission from Elsevier.]

environment, measured through various indicators including embodied energy (ei). "een, out" and "eex, out" denote the energy and exergy outputs over the solar still's lifetime, respectively. Table 5 gives the results of all EPBT considered system. From Table 4, it is evident that incorporating PTC into CSS leads to a 45% increase in embodied energy compared to CSS without PTC. Notably, the addition of sand to CSS or CSS+PTC does not raise embodied energy since sand is naturally occurring and does not undergo manufacturing processes. Among all the studied systems, the (CSS + WM + PTC) setup exhibits the highest embodied energy, approximately 54% higher than CSS alone.

Table 5 findings reveal that active systems, especially (CSS + SD + PTC), are more efficient in terms of EPBT compared to passive ones. This efficiency can be attributed to the substantial increase in annual energy and exergy production in (CSS + SD + PTC).

Table 4. Embodied energy calculation for solar still systems

component	Embodied energy MJ kWh	CSS	CSS+PTC	CSS+SD	CSS+PTC+WM	CSS+WD	CSS+SD+PTC
Water basin	600 166.7	166.7	166.7	166.7	166.7	166.7	166.7
Frame	300 83.3	83.3	83.3	83.3	83.3	83.3	83.3
Solar still walls	942 216.3	261.3	261.3	261.3	216.7	216.7	261.7
Insulation	139 38.6	38.6	38.6	38.6	38.6	36.6	38.6
Basin coating	181 50	50	50	50	50	50	50
Silicone rubber	11.8 3.2	3.2	3.2	3.2	3.2	3.2	3.2
PTC	626 174	--	174	--	174	174	174
Heat exchanger	250 69.4	--	69.4	--	69.4	..	69.4
sand	0 0	--	--	0	0	--	--
Wire mesh	200 55.5	--	--	--	--	55.5	55.5
Total embodied energy(kWh)		603.8	875	603.8	875	659.3	930.6

Table 5. EPBT calculation for all the systems under consideration

parameter	CSS	CSS+PTC	CSS+SD	CSS+SD+PTC	CSS+WM	CSS+WM+PTC
Annual yield (kg)	1140	2182	1330	2469.7	1230	2289
Embodied energy (kWh)	603.8	875	603.8	875	659.3	930.6
Een, out(kWh) per year	798	1527.4	931	1728.79	861	1602.3
Eex, out(kWh) per year	90.945	233.94	111.105	295.79	102	264.57
EPBT en	0.756	0.573	0.65	0.506	0.765	0.58
EPBT ex	6.64	3.74	5.43	2.96	6.46	3.52

A study of different environmental parameters such as EPF, EPT, LCCE was the work objective of Singh et al. [55]. The authors studied four different types of solar stills and proved that the solar still system having a square fin structure showed the best results compared with the other three (fins with circular and square structures, a cotton wick and a jute wick) as it has much less EPT with a noticeable amount of LCCE compared to other systems. The results of their work are attentive to the environment because there is no CO_2 emission but on the contrary, there is a considerable attenuation of CO_2 and SO_2. The comparative study in the present work shows that the square fin structured still system is more economical and efficient than other systems. This system produces a yield of 4.55 l for the effective pond surface of 1 m^2 per day and an equivalent saving of 36600 kg of CO_2 for its entire working life, i.e. 30 years system life. The embodied energy for the different systems and better for that of square fins (397.62kWh), the return energy with a higher efficiency of 20.88%) at 1.9 times the energy return value, The SSDS with square fin has the greatest value of EPT 48% as compared with other studied systems (Figure 8). The LCCE its equal to 0.44 for SSDS with square fin and 0.28 for double sloped black cotton wick system. The solar still system associated with fins exhibits a 36% reduction in carbon dioxide emissions. Conversely, this system generates 22.13% more monetary value in earned carbon credits compared to the double sloped cotton wick associated still system (Figure 9).

In their research, Singh and Samsher [56] conducted an analysis of passive solar still performance incorporating (ETC). This system utilized the simple thermo-siphon principle, where improved heat transfer was achieved through ETC application. The variation of density between hot and cold water facilitated the natural flow of water within both the ETC and the basin, as illustrated in Figure 10.

The equations used to make the environmental part calculations are as follows (Eq. (2)) to (Eq. (9))

Energy payback time [55]

$$EPT = \frac{EE}{Annuele_{out}} \tag{2}$$

Energy production factor

$$EPF = \frac{Overall\,e_{out}}{EE} \tag{3}$$

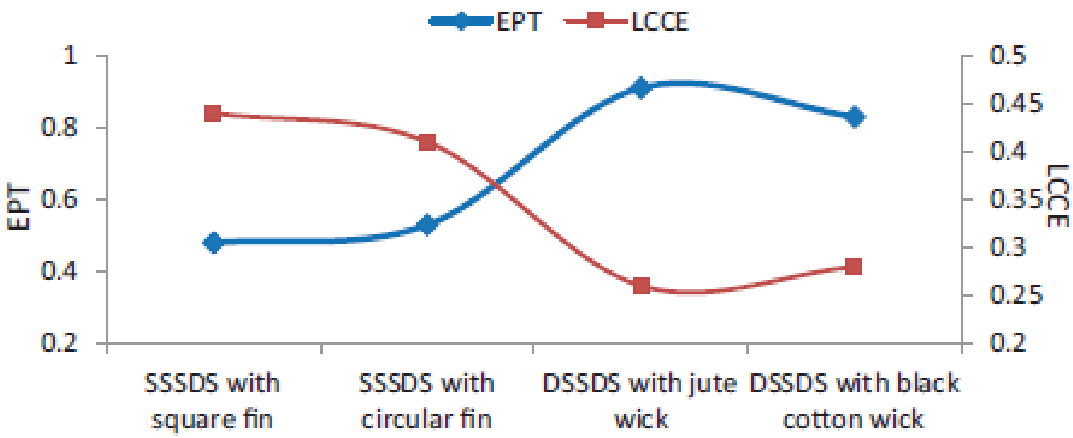

Figure 8. Investigation in terms of the variations in EPT and LCCE for the suggested combinations of the systems [From Singh et al. [55], with permission from Elsevier.]

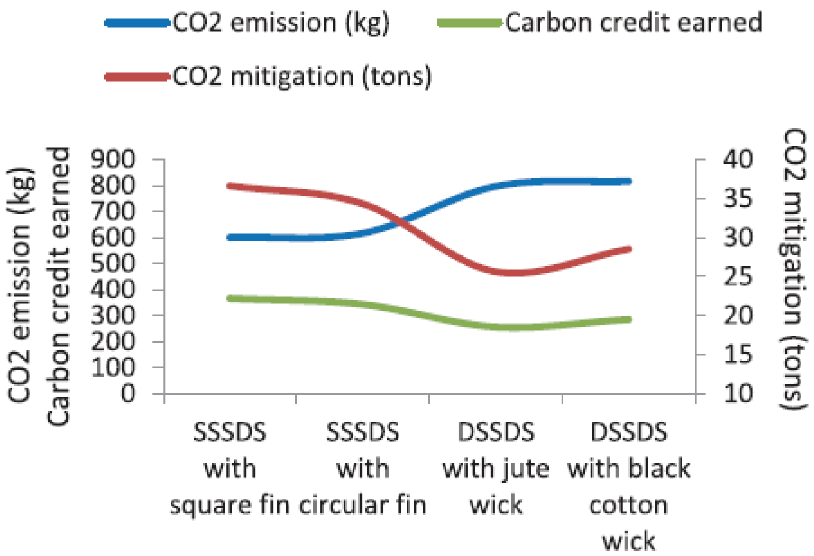

Figure 9. Investigation in terms of the variations in environ-economy for the suggested combinations of the systems [From Singh et al. [55], with permission from Elsevier.]

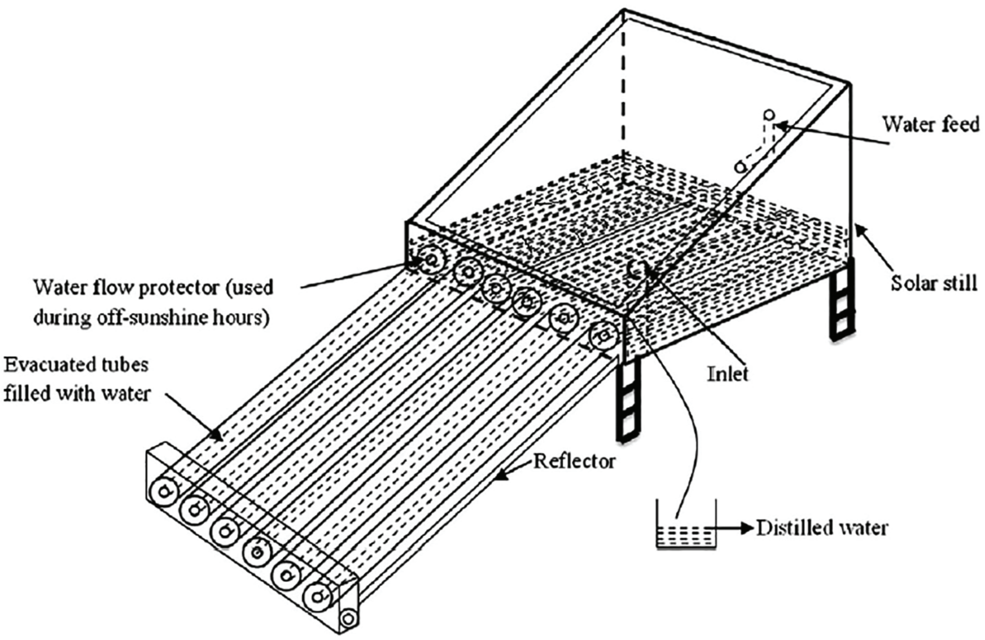

Figure10. Schematic diagram for passive ETC solar still [From Singh et al. [57], with permission from Elsevier.]

Life cycle conversation efficiency (LCCE)

$$LCCE = \frac{e_{out} \times n - EE}{e_{sol} \times n} \tag{4}$$

Annual energy output can be evaluated as ($Annuale_{out}$):

$$Annuale_{out} = \text{Daily thermal output} \times n \tag{5}$$

Where, n = 250 sunny days/year, [57]

$$\text{Daily thermal output} = \frac{m_{ev} \times \lambda}{3.6 \times 10^{6}} \tag{6}$$

Emission of carbon dioxide

The average value of CO_2 emissions reported for the production of electricity with the help of coal is 0.98 kg of CO_2/kWh. Total CO_2 emission/year can be evaluated as [58]:

$$CO_2 \text{ emission per year} = \frac{e_i \times 0.98}{\text{Lifetime}} \quad (7)$$

CO_2 mitigation

The total CO_2 mitigation for the entire operational lifespan of the experimental setups can be assessed as [58]:

$$\text{Net } CO_2 \text{ mitigation} = (\text{Annual } e_{out} \times \text{Lifetime} - e_i) \times 2.042 \text{ kg} \quad (8)$$

Carbon Credit Earned (CCE)

Carbon credits are licenses that enable the owner to release a particular quantity of carbon dioxide or other greenhouse gases. Similar to carbon offsets, carbon credits are sometimes known as carbon credits. A single credit allows for the release of one ton of carbon dioxide or the equivalent amount of other greenhouse gases. Companies are able to establish an internal price on carbon via the financing of climate action, which provides them with an incentive to decarbonize their operations more quickly. Additionally, a recent research that was carried out by Trove indicated that businesses that make use of considerable quantities of carbon credits are decarbonizing at a pace that is twice as fast as those that do not make use of carbon credits. An individual may earn one carbon credit by reducing one ton of carbon emissions, and the computation for this credit is based on [59]:

$$\text{Carbon credit earned (CCE)} = CO_2 \text{ mitigation in lifetime} \times \text{Cost of carbon credit} \quad (9)$$

The specific solar decontamination system earns a carbon credit equivalent to €11.09 per ton of CO_2 or $9.99 per ton of CO_2, which represents the international carbon price. According to Table 6, the system demonstrates promising performance metrics, with an energy payback time of 0.683 years, an energy payback factor of 1.46, and a life cycle conversion efficiency of 0.34. These values are detailed in Table 6. The system effectively mitigates 77.2 tons of carbon, resulting in a total earned carbon credit of $771.23 over its lifetime, as indicated in Table 7. Combinations like these are crucial for fostering a cleaner atmosphere due to their enhanced carbon mitigation capabilities and correspondingly higher earned carbon credits.

Table 6. EPBT, EPF and LCCE with related parameters

Annual yield (l)	1045
Daily yield (l/day)	3.8
Yield for life (l)	31.350
System life (yrs)	30
Total energy output over life time (kWh)	50006.65
Embodied energy (kWh)	1138.52
Average daily solar intensity (8 AM-6PM)	401.8 kW
Solar energy for life (kWh)	144.648
Annual solar energy (kWh)	4821.6
Annual energy output from solar still(kwh)	1666.9
Energy payback time (EPT)	0.683 yrs
Energy production factor (EPF)	1.46
Life cycle conversion efficiency (LCCE)	0.34

Table 7. Environment analytical results of system

PCC ($)	231.46
CO_2 emission (kg)	1798.86
CO_2 mitigation (tons)	77.2
Carbon credit eamed ($)	771.23

A cascade SSDS in the presence of different types of insulation and PCM was the objective of the study made by Khanmohammadi and Khanmohammadi [60]. Environmental analyzes were also carried out on the desalination system of the solar still with different types of insulation and PCM (Table 8). Embodied energy is the total energy needed to generate any equipment or service. The analysis of embodied energy can assist in determining the EPBT for the system. Table 8 provides the specifications and corresponding embodied energy values for different insulations.

The analysis of embodied energy for the suggested SSDSs reveals that epoxy and glass covers have the highest values, with 38 and 24 kWh/kg, respectively, owing to the energy-intensive nature of their manufacturing processes [61]. Table 9 displays findings related to carbon credits and reduced CO_2 emissions derived from energy and exergy

Table 8. Characteristics of different insulating materials used in solar still desalination systems

Insulation type	Embodied energy (kWh/kg)	Thermal conductivity (W/m°C)	Density (kg/m³)	Specific heat (J/kg)C)	Price ($/m²)
Glass wool	3.61	0.0033	35	1054	0.63
Fiber glass	5.55	0.03	19	843	0.91
Cellular glass	5.55	0.044	160	843	1.06
Phenolic foam	6.94	0.025	35	525	3.01

Table 9. The values of carbon credits and mitigated CO_2 for different insulation types

Insulation type	Energy -base	Exergy –base
	mitigation de CO_2 (tones) carbon credits ($)	mitigation CO_2 (tones) carbon credits ($)
Glass wool	4.441422 64.400	0.101538 1.47230
Fiber glass	4.443011 64.424	0.10160 1.47325
Cellular glass	4.409218 63.934	0.100791 1.46146
Phenolic foam	4.444600 64.447	0.101673 1.47426

analyses. The data indicates that cellular glass shows the lowest mitigated CO_2 and carbon credit values in both energy and exergy-based assessments. Among the insulating materials under consideration, phenolic foam exhibits the most advantageous results.

To assess the environmental impact of the studied SSDS, [62] calculated and presented exergy-based mitigated CO_2 for various PCM (PCMs) and insulation types. The change in insulation type has a minimal impact on mitigated CO_2, especially when Stearic acid is considered as the PCM.

CONCLUSION

Although calculating embodied energy is challenging, accurate estimations of life cycle energy and CO_2 emissions are achievable through robust modeling principles. These tools enable effective comparison of design options, serving as invaluable decision-making aids for developers, builders, and consumers. Given the significance of Embodied Energy (EE), EPT, LCCE, and CO_2 emissions, these methods offer essential insights for stakeholders. The combined results showed that embodied energy is between 30 to 100% of the total life cycle consumed, EPT in most cases depends on the location and the equipment used it has the least impact on the environment with products of organic origin of the order of 10 years whatever the nature of the solar still. LCCE in relation to sustainability, desalination technologies reach the maximum very quickly CO_2 mitigation is highly potential for active systems than passive ones. Among the systems under consideration, the system (CSS + WM + PTC) with the greatest embodied energy value has a value that is almost 54% higher than that of CSS. The results show that compared to the SPS model, the CPS model has a higher LCCE, CO_2 mitigation, and CC, and its carbon footprint is more obvious. SPS had LCCE values around 19.98% and CPS had LCCE values around 30.39% at that age.

The examination of the embodied energy for the recommended SSDSs indicates that epoxy and glass covers have the highest values, with 38 and 24 kWh/kg, respectively. This is due to the fact that the production procedures for these SSDSs need a significant amount of energy. A change in the kind of insulation has a negligible effect on the amount of carbon dioxide that is mitigated, particularly when stearic acid is assumed to be the PCM. The SPS was responsible for 13.19 tons of CO_2 mitigation, while the CPS was responsible for 20.07 tons of CO_2 mitigation. It is possible to acquire distilled water for a price of Rs. 23.28 per kilogram for CPS and Rs. 22.67 per kilogram for SPS. When the carbon credit for the still's estimated 30-year life was taken into consideration, the payback years for both stills were 0.52 and 0.82 years, respectively.

In terms of carbon dioxide emissions, the solar still system that is coupled with fins demonstrates a decrease of 360 percent. On the other hand, as compared to the double sloping cotton wick related still system, this system creates a considerable amount of additional monetary value in the form of earned carbon credits. Because sand is a naturally occurring substance that does not go through any production processes, the incorporation of sand into CSS or CSS+PTC does not result in an increase in the amount of embodied energy. Among all of the systems that were investigated, the configuration that consists of CSS, WM, and PTC had the most embodied energy, which is roughly 54% greater than CSS by itself.

NOMENCLATURE

EE	Embodied energy
$e_{en,out}$	Energy output
$e_{ex,out}$	Exergy output
EPBT	Energy payback time
ETC	Passive solar still with Evacuated Tube Collectors
CC	Carbon Credit
CCE	Carbon Credit Earned
CDM	Clean Development Mechanism
CPS	Conventional Pyramid Still
CVSS	Cascaded vertical SS
CVDS	Cascaded Vertical Double Single
SSS	Slope solar still
SPS	Shaped Pyramid Shaped
SSSDU	Specific Slope Solar Desalination Unit
LCCE	life cycle conversion efficiency
PTC	Parabolic trough solar collector
CSS	Conventional Solar Still
LCA	Life-Cycle Assessment
SSDS	A cascade solar still desalination system
PCM	Phase Change Material
SS	Single slope

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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