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Techno-Economic and Enviroeconomic Analysis Review of Distinct Passive and Active Solar Distillation Still

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Abstract

Water scarcity is an issue that stems from the overconsumption and misuse of fresh water supplies, which leads to shortages and decreased quality of life. It most affects developing countries that do not have the infrastructure in place to mitigate these factors. Solar still become most suitable method for water purification in these types of places due to its cheapness and easily made from locally available materials. Current paper concentrate on a detailed techno-economic and enviroeconomic analysis of distinct configurations of active and passive solar distillation stills. Distilled water production, cost per litres, environmental cost comparison has been done between different types of passive and active solar still. Active solar still has a higher system cost compared to passive solar due to the addition of thermal energy by different components and mechanisms. Based on the results, minimum cost per litre is obtained for passive conventional solar still with the spherical ball as heat storage material and in case of active solar still, with PV module, reflectors, air-cooling technique are 0.0136 $/l and 0.0092 $/l, respectively. On the basis of energy, the highest environmental cost was found for AMSSFS air-cooled with evacuated mode (1456.38 $), while the lowest was found for active solar stills with N - Flat Plate Collectors (44 $).

Keywords: *Active solar still; passive solar still; economic and enviroeconomic analysis.*

1. Introduction

As the developing countries moving forward to becoming a developed country and wanted to decrease their dependency on the developed countries, lots of industrialization and urbanization needed and happing in the developing countries. Water act as a one of the main sources for any type of industry (for the production of product) and urban areas (for living and other daily use), due to which demand of clean water increases by 600% over the past 100 years [1]. At present, 47% of the world population living in those areas (among which 73% living in Asia), which suffer water scarcity for a month in a year and it will increase up to 57% by 2050 [2].

Improper irrigation system in agriculture act as a primary driver for the depletion of groundwater worldwide. Presently, more than 30% of world groundwater systems are in trouble [3]. In the last decades, water pollution become worse because of untreated water discharge from industries and lack of sanitation. Over 90% of sewage water discharged untreated in developing countries [4].

For treating or purify wastewater, lots of technologies classified as physical, chemical and energy-intensive methods used [5]. Over the last few decades, the cost of treatment goes significantly down due to improved membrane life (in case of membrane use), enhanced construction materials and low energy consumption [6]. Wastewater treatment is not only important for human health regulations but also for the environmental effects on plants and water bodies on earth.

As the water source and drinkable water availability are depleting in lots of areas of the world, the availability of seawater becomes hope due to which desalination technologies have an emerged market option for providing usable water. This technology continuously growing with a cumulative global capacity of 99.8 million m^3/d and register growth in productivity of almost 25 million m^3/d since 2010 IDA (International Desalination Association) and GWI (Global Water Intelligence). Cost of this technology was quoted around \$0.64 for 0.8/m^3 in mid of 1990 [7] and in the recent decade, it decreases to around \$0.50/m^3 for similar large-scale RO plants [8].

Solar still is an environment-friendly attractive option to obtain fresh water from saline/contaminated water and can be successfully used domestically. Solar still comprises of a water basin, a transparent glass roof and a collecting trough in which water evaporates from the basin due to absorption of sunlight and condenses on the glass cover wall and finally collected in the collecting trough which is discharged in a measuring flask. Further, it can be categorised as passive and active solar still. Passive solar still uses direct sunlight and further categorised as Single basin solar still (wick type, hemispherical, pyramid, triangular, spherical, stepped, tubular, inclined, plastic), multi basin solar still (double basin, pyramid, portable type [9]–[26]. Active solar uses direct and indirect sunlight by integrated it with different solar energy collectors like flat plate collector, evacuated tube collector, hybrid PV/T system, solar pond, Inverted absorber solar concentrators (parabolic trough collector and heat exchanger) and use for Waste heat recovery (Basin stills, Tubular stills) [27]–[43]. In India, for generating 1 kWh of electricity from a coal-based plant, it is expected that, amount of CO_2 rejected to the environment is approximately 1.58 kg [44]. Recently, some of the reviews were conducted on economic analysis of solar stills, including tubular-shaped solar stills [45], hybrid solar still economics analysis [46], as well as thermal analyses of various solar still filled with nanofluid [47], [48]. However, the recent reviews to the best of our knowledge. The current review of solar still systems deals with the techno-economic and enviro-economic analysis of several configurations of passive and active solar still systems chronologically and help in selecting suitable economic and sustainable designs of solar still systems.

2. Techno-Economic Analysis of the Different Types of Passive Solar Still

Now days, Techno-economic analysis (TEA) is one of the important factors for industries. Based on technological and monetary input variables, most industries perform these kinds of analyses to estimate the economic behaviour of their products and services. Comparative technical detail for different passive solar still provided in Table 1.

V.K. Dwivedi et al. [49] evaluated CO_2 emission, mitigation, and credits earned based on water depth (0.01 m, 0.02 m, and 0.03 m) and life of a double slope passive solar still (DSPSS), using energy and exergy analysis as shown in the Figure 1. In terms of energy, for 20 years of the lifetime of the solar still, the CO2 emission is 952.31 kg for all water depths. Carbon credit earned based on energy for a water depth of 0.01 m is Rs. 9,885.9 and Rs. 26,229.16 for a solar still that lasts for 20 years and 50 years, respectively.

Figure 1. Photograph of DSPSS [49].

Z.M. Omara et.al. [50] investigated finned and corrugated absorbers solar stills and compared them with conventional stills as shown in Figure 2. It is found that, at the same quantity of saline water (30 l) and water depth (50 mm), productivity increased by 40% for finned plate and 21% for corrugated plate compared to conventional ones. Although finned, corrugated and conventional solar stills have about 47.5%, 41%, and 35% daily efficiency respectively, when operated 340 days per year.

T. Arunkumar et.al. [51] done an experimental study on hemispherical solar still with and without the flowing water over the cover as shown in Fig. 3. The efficiency of this still is increased from 34% to 42%. With an output of 4.2 kg/m2/day, cost per litre (CPL) becomes approximately $0.017/kg water if we include its life of 15 years and an interest rate of 6%. T. Rajaseenivasan et. al. [52] investigates a double slope double basin solar still and also its effect on productivity by varying the water level in both lower and upper basin as shown in Figure 4. From theoretical and experimental results (deviation of 10%), not only the productivity increases by 85% but also fabrication cost of double basin solar still increases by 32% as compared to conventional double slope solar still the results were compared with the single basin still (with same basin area.

The performance of a “V” type solar still with a Cotton Gauze Top Cover Cooling (CGTCC) with and without air flow over the condensation surface (glass cover) are experimentally evaluated by P.U. Suneesh et. al. [53] as shown in Figure 5. The rate at which production increase is less as compared to the increase in cost of still with GCTCC and air flow.

Figure 2. Photograph of conventional, corrugated and finned solar still [50].

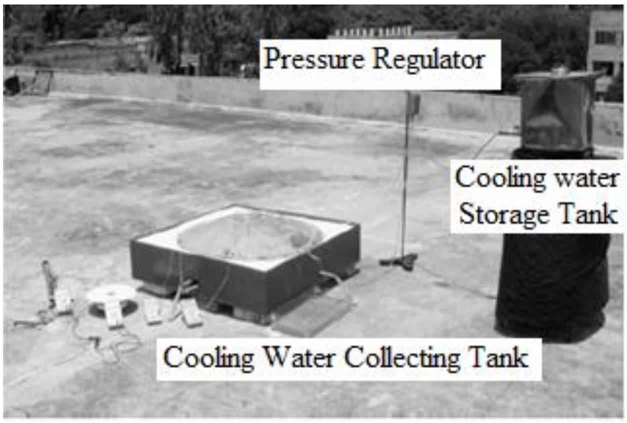


Figure 3. Hemispherical solar still with cooling system [10].

Z.M. Omara et. al. [54] investigate the performance parameters of a solar still with corrugated basin liner (CrSS), using internal reflectors and double wick layer by comparing it with conventional solar still (CSS) as shown in Figure 6. Results shows that, at 1 cm brine depth, productivities increase about 145.5% of CrSS with reflectors and wick as compare to CSS. Whereas, the daily efficiency of CrSS and CSS are 59% and 33% approximately, respectively.

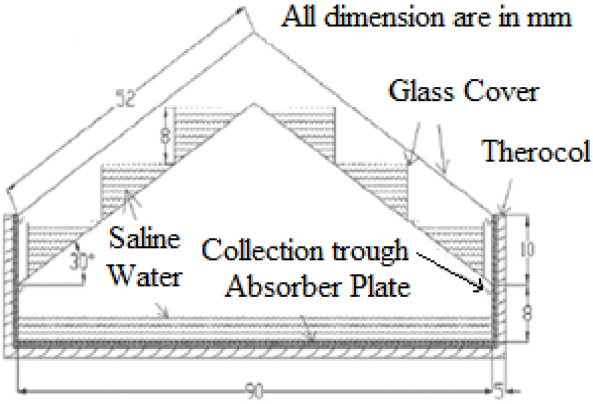


Figure 4. Schematic diagram of double slope double basin solar still [52].

Figure 5. Photographic view of "V" type solar still with CGTCC [53].

Figure 6. Corrugated solar still [54].

Experimental and theoretical analysis are conducted by D.G. Harris Samuel et. al. [55] to find out the performance of CSS using different energy storage material (spherical salt ball and sponge) as shown in Figure 7. Results revealed, payback time of CSS is 4.3 months more as compare to present still. Hence, CSS with spherical ball as heat storage gives us lowest cost of water. Later, Experimental and theoretical performance of a solar still with square (hollow pipe 0.019 × 0.07) and circular fins (circular pipe 0.03 m dia × 0.07) integrated at the base of the conventional solar still (CSS) basin was investigated by T. Rajaseenivasan et. al. [56] with CO_2 mitigation and economic analysis. Daily productivity of the still increases by 26.3 and 36.7% for circular and square finned stills and it changes to 36 and 45.8% for fins covered with wick materials at 1cm water depth.

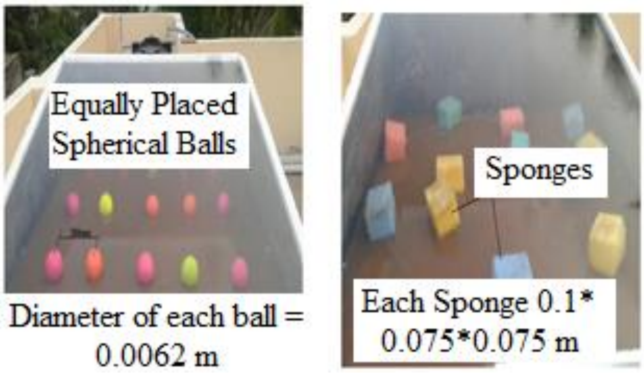


Figure 7. Photograph of CSS with spherical ball (left) salt heat storage and sponge (right)[55].

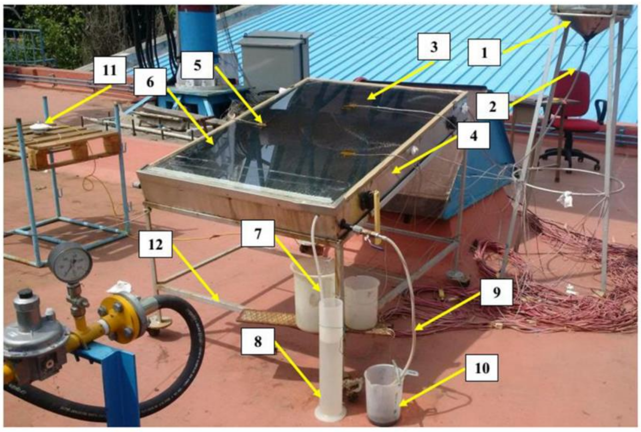
A modified double slope basin type multi–wick MBDSMWSS (black cotton and jute) solar still have been fabricated and designed to analyse its performance by Piyush Pal et. al. [57]. Maximum daily yield (at 2 cm water depth) and overall thermal efficiency of modified still is 9012 ml; 23.03% for black cotton wick and 7040 ml; 20.94% for the jute wick. In this study, exergy, economic and thermal performance investigated by Samir M. Elshamy et. al. [58] of a tubular solar still (TSS) with two different water basin shapes; semi-circular corrugated (TSS-SC) and flat plate (TSS-FP) as shown in Figure 8. The distilled production enhancement of TSS-SC was about 26.47 % rather than TSS-FP with increment in exergy and thermal efficiencies about 23.7% and 25.9 % respectively.

Figure 8. Photo of TSS with different water basin shapes (left) and different troughs in TSS (right) [58].

Piyush Pal et. al. [59] investigated both experimentally and theoretically a modified multi–wick basin type double slope solar still (MMWBDSSS) with jute and black cotton wicks as show in Figure 9. For jute cotton and black cotton wicks, the CO_2 mitigated per annum has been found to be 7.23 and 0.198 tons at 2cm water depth on the basis of energy; and 0.155 and 0.141 tons at 1 cm water depth, respectively on the basis of exergy; and 0.198 and 0.167 tons at 2cm water depth, respectively on the basis of exergy for year around operations. Tilted wick type and stepped solar stills are well known for increased distillate yield in the day and night conditions due to maximum exposure of solar radiation and sensible heat storage as in case of deep basin stills as compared to conventional solar still.

Figure 9. Photograph of MMWBDSSS [59].

K.S. Reddy et. al. [60] proposed a tilted solar distillation system with wick for treatment of RO reject and domestic sewage water as shown in Figure 10. Heavy metals removing efficiency for RO reject water and sewage water is in the range of 32.9–82.1% and 51.1–70.6%, respectively.



1 Wasterwater Tank	**2** Wastewater Supply Pipe
3 Wastewater Trough	**4** Distillation Chamber
5 Thermocouple	**6** Tempered Glass Cover
7 Treated Water Pipe	**8** Measuring Jar
9 Draining Reject Pipe	**10** Reject for Recirculation
11 Solar Pyrometer	**12** Mild Steel Stand

Figure 10. Schematic diagram of tilted solar still [60].

Kalpesh V. Modi et. al. [61] investigate the performance of two similar single-slope double-basin solar stills with the use of two different wick materials namely jute cloth and black cotton cloth in the form of small pile in the lower basin (Figure 11a). The distilled yield for small pile of jute cloth and black cotton was obtained 0.91 L/m^2 and 0.771 L/m^2 respectively at a water depth of 0.01 m, and 0.8287 L/m^2 and 0.6823 L/m^2 respectively for the 0.02 m water depth. Total capital cost per square meter was ₹ 5680 with payback time of 15 months for 250 sunny days in a year. Wen-Long Cheng et. al. [62] carried out experiment with a shape-stabilized phase change material (SSPCM) having solar absorption 0.94 and thermal conductivity 1.50 W/m K by, to replace the metal absorber plate used in CSS (Figure 11b). The experimental and simulation results revealed that, as the thermal conductivity of SSPCM increases from 0.2 to 4 W/mK, the daily productivity of CSS with SSPCM is 42% to 53% higher than that of CSS.

Mohamed S. Yousef et. al. [63] investigated single slope solar still using different absorbing material for analysing (4E) the energetic, exergetic, economic and enviroeconomic. The performance of the three cases, case 1) Traditional solar still (TRD), case 2) with hollow cylindrical pin fins, case 3) with steel wool fibers (Figure 12). In comparison with case 1, the daily cumulative yield of distillate water and average daily exergy efficiency in cases 2 and 3 enhanced by 16% and 25%; and 14% and 23%, respectively. The maximum energy efficiencies of all three cases 1-3 are 42%, 45.5%, and 52.5% respectively.

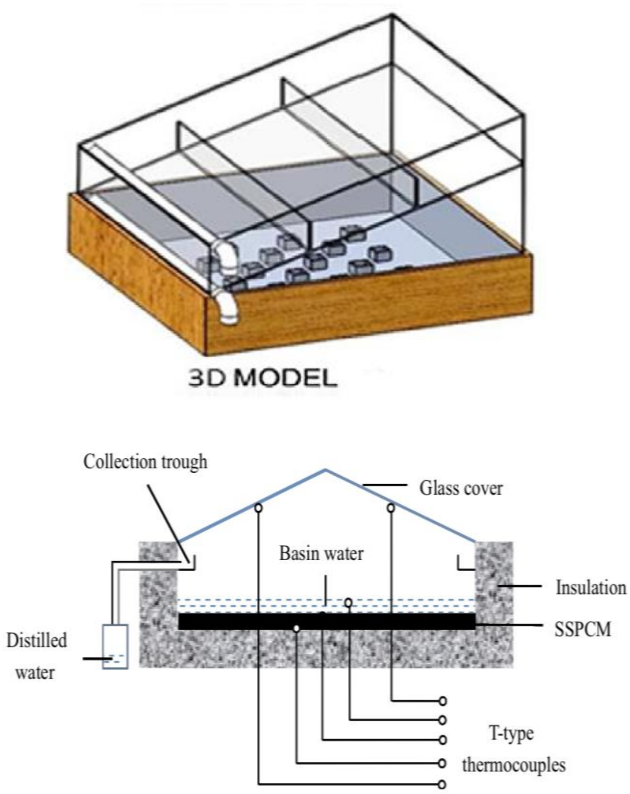


Figure 11. (a) 3D Model of single-slope double-basin solar stills (above) [61] (b) Schematic diagram of pyramid solar still with SSPCM (below) [62].

Figure 12. Photographic view of steel wool fibers and hollow cylindrical pin fins [63].

Table 1. Comparative detail for different passive solar still.

Paper	Type of still	system cost ($)	Daily yield (l/m^2)	Basin area (m^2)	Solar radiation W/m2	place
[50] Z.M. Omara et. al. (2011)	CSS CSS with finned CSS with corrugated	412 490 480	2.5 3.5 3	1	1100	Kafrelsheikh University (31.07°N, 30.57°E), Egypt
[10] T. Arunkumar et. al. (2012)	Hemispherical without cooling with cooling	165 165	3.66 4.2	0.71	732	Coimbatore (11° North, 77° East), India
[52] T. Rajaseenivasan et. al. (2013)	Double slope with Single basin with double basin	93.63 137.27	2.56 4.75	0.63	750	Kovilpatti (9° 11′N, 77° 52′E) Tamil Nadu, India
[53] P.U. Suneesh et. al. (2014)	V type solar still with CGTCC with CGTCC and air flow	200 220 520	3.3 4.3 4.6	1.5	732	Coimbatore (11° North, 77° East), India
[54] Z.M. Omara (2016)	CrSS with wick CrSS with wick and reflecting mirrors	488 520	5 6	1	1100	Kafrelsheikh University (31.07°N, 30.57°E), Egypt
[55] D.G. Harris Samuel et. al. (2016)	CSS CSS with spherical ball heat storage CSS with sponge	68.18 68.18 68.18	2.4 3.7 2.6	1	627	(IITD), New Delhi, India (28°350 N, 77°120 E,
[57] Piyush Pal et. al. (2017)	Double slope with jute wick with black cotton wick	201.08 203.4	4.5 3.52	2	935	Allahabad (U.P.) (25°27′ N)
[58] Samir M. Elshamy et. al.(2018)	Tubulor solar still with SC with FP	100 100	4.3 3.4	0.4	1040	Giza, Egypt (29.9381° N, 30.9140° E)
[61] Kalpesh V. Modi (2019)	Single-slope double-basin solar still with jute cloth with black cotton cloth	81.14 81.14	0.91 0.771	0.25	870	Valsad, Gujarat, India (20.61°N, 72.91°E)
[49] V.K.Dwivedi et. al. (2010)	Double solar still with water depth 0.01 0.02 0.03	- - -	1.66 1.57 1.45	1	627	Greater Noida 28.4572° N, 77.4984° E, India
[56] T. Rajaseenivasan et. al. (2016)	CSS CSS with Square finned still CSS with Circular finned still	121.66 156.67 154.17	3.11 4.25 3.99	1	850	Madurai, Tamil Nadu, India

[59] Piyush Pal et.al. (2018)	Double slope with jute wick with black cotton wick	215.82 218.32	3.52 3.53	-	935	Allahabad (U.P.) (25°27′ N)
[60] K.S. Reddy et. al. (2018)	Tilted solar distillation with RO reject with sewage water	277 277	4.79 4.48	-	867	Chennai (30.08 N 80.27 E) Tamil Nadu, India.
[63] Mohamed S. Yousef et. al. (2019)	TRD TRD with pin fins TRD with steel fibers	190 220 192	3.96 4.65 4.98	1	932	New Borg El-Arab City, Egypt
[64] Pankaj Dumka et. al. (2020)	CSS CSS with ultrasonic fogger & cotton cloth	75.16 83.37	2.7 4.3	1	1050	Guna, Madhya Pradesh, India
[65] H.Sharon (2021)	novel hybrid solar still	520.02	4.59	1 & vertical basin area 3 m^2	860	Chennai, India
[66] Belkheir Benoudina et. al. (2021)	CSS CSS with micro-particle of Al2O3 CSS with Nano-particle of Al2O3	105.87 107.84 109.82	3.02 4.96 6.12	0.25	1010	El Oued, Algeria

The performance of conventional solar still with and without using an ultrasonic atomiser and a cotton cloth was studied and compared experimentally and theoretically by Pankaj Dumka et. al. [64]. Modified solar still (CSS with ultrasonic atomiser and cotton cloth) introduced with the aim of decreasing the excessive fogging issue at low radiation hours, enhance evaporation area and reduce distinctive length of solar still. H.Sharon [65] introduced a novel hybrid solar still (as shown in Figure 13) by combining the effects of conventional solar still with vertical diffusion under reduced ground area under the climatic conditions of Chennai, India. The model is thermodynamically investigated for basin to vertical diffusion area ratio, water depth in basin, shade, vertical still diffusion gap and inlet water flow rate. Belkheir Benoudina et. al. [66] utilizes various concentration of micro-particle and Nano-particle of aluminium oxide in the production of condensate for three types of solar still. In comparison, the first solar still is conventional (CSS), the second one contains micro-particles of aluminium oxide with a concentration ranges of 0.1-0.3%, while the third solar still contains Nano-particles of aluminium oxide with a concentration range of 0.1-0.3%.

3. Techno-Economic Analysis of Different Type of Active Solar Still

A small size portable thermoelectric solar still is proposed by J. A. Esfahani et. al. [67] as shown in Figure 14. All four walls are made up of Plexiglas to make it durable. To evaluate the average daily yield output, experiments were conducted for nine winter days under climate condition of Semnan, Iran. Results show that average annual productivity of fresh water was 620 L/m^2 which is less when compared to portable still and CPL of portable still is calculated on 12% interest rate for 10 year of life.

An evacuated tubular collector integrated solar still (EISS) introduced, not only for getting hot water but also distilled water. Rahul Dev [68] evaluated its performance annually in 2008 as shown in Figure 15.

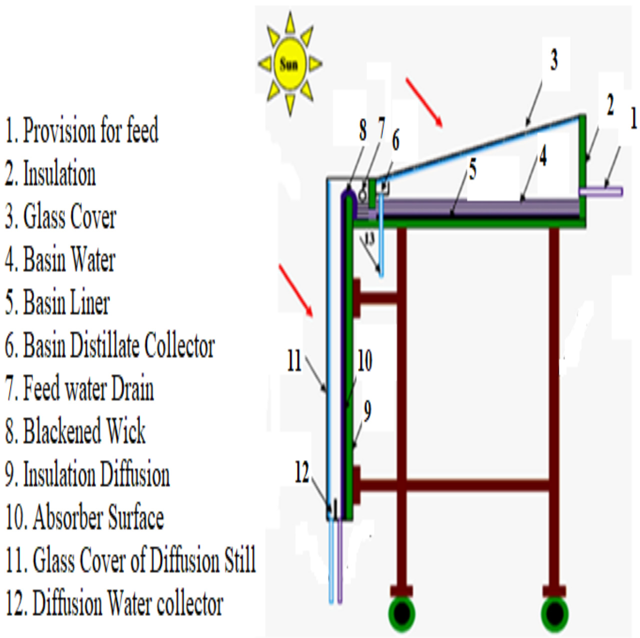


Figure 13. Schematic diagram of hybrid solar still [65.]

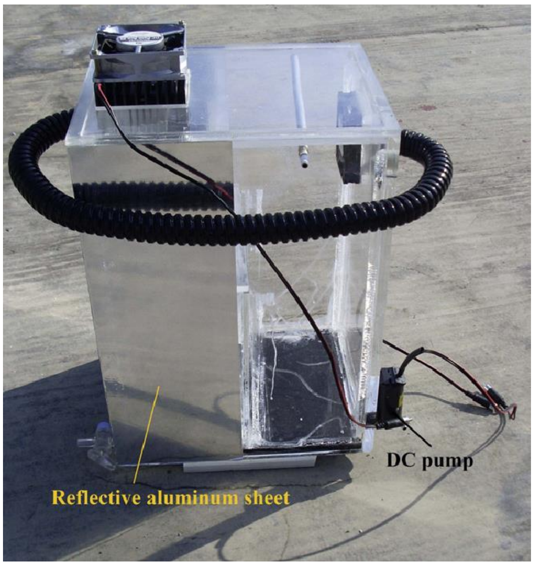


Figure 14. Photograph of portable thermoelectric solar still [67].

Here, heat loss from ETC's (evacuated tubular collector) hot water is used by solar still during the off-sunshine hours and also develop a thermal model to compare it with experimental results. Yearly yield output of EISS and SS system is 630 and 327 kg/m^2, respectively.

Figure 15. Schematic diagram of EISS [68].

Z.M. Omara et. al. [69] presented a hybrid solar desalination system using wicks/solar still and evacuated tubular collector. Various case is studied (Figure16): Single layer plane wick (SLPW), Single- and double-layer lined wick (SLLW/DLLW), Single- and double-layer square wick (SLSW/DLSW) layers; hot water feeding during night and two wick base slope angles of still (20 and 30°). Also verified theoretical analysis through experiments. Yield output for DLSW is increased by 114% as compared to CSS (conventional solar still).

Mohamed A. Eltawil et. al. [70] enhanced the productivity of conventional single slope solar still (CSS) by equipping it with a flat plate solar collector, spraying unit, perforated tubes, external condenser and solar air collector (Figure 17).

Figure 16. Schematic diagram of a) Conventional still b) Double layers wick still c) Single layer wick still [69].

The water either sprayed into developed solar still (DSS) or making upwards fountain by pumping from bottom and a hot air also forced at the bottom of DSS. Results shows that the productivity of DSS (depending upon the type of modification) was 51–148% more in comparison to CSS.

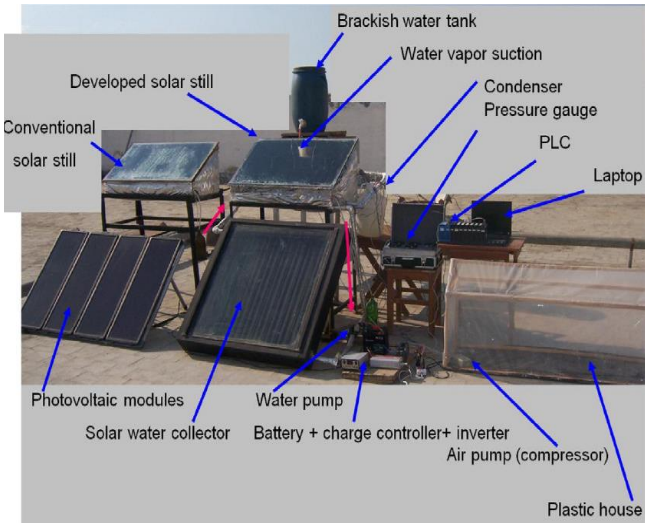


Figure 17. Photograph of Developed solar still [70].

For the first time M.R. Karimi Estahbanati et. al. [71] conducted indoor experiment on 4 similar solar stills with different stages (1–4 stages) effect on the productivity of a multi-effect active solar still (Figure 18). Moreover, compared all four system performances for continuous and non-continuous modes. The experimental result revealed that as the number stage increases, water production also increases in continuous mode compared to non-continuous mode. PPT (payback time) of a four-stage still are 237 and 199 days in non-continuous and continuous modes.

A hybrid (partially covered) photovoltaic thermal (PV/T) flat plat collector (FPC) active solar still has been experimentally studied by D.B. Singh et. al. as shown in Figure 19 [72]. Along with the design and fabrication of the system, a thermal model also developed. Annual water productivity and water production cost of the system have been varying between 120.29% and 883.55%; Rs. 0.19 per kg to Rs. 4.08 per kg, respectively with varying rate of interest between 2% to 10% and life between 30yr. to 50yr. Later B. Praveen kumar et. al. [73] fabricated and experimental studied PV/T solar still with NiCr heater at different water depths of 0.05 m, 0.10 m, and 0.15 m for three consecutive days (Figure 20). Proposed solar still uses saline water for cooling purpose of PV module also which increases its thermal efficiency by 25 % and daily yield by 6 times more as compared to conventional passive still.

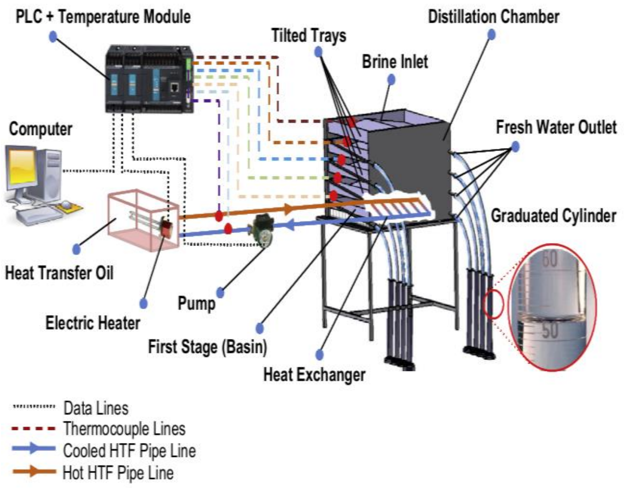


Figure 18. Schema of the 4-stage experimental set-up [71].

Figure 19. Sectional top view of PV/T-FPC active solar still [72].

Omar Bait et. al. [74] developed a numerical simulation and an economic analysis of a multi-stage desalination system and are seeking to promote it as a startup for Batna city. Initially, a general model is involved in the study just to know the global thermal and mass quantities. Investigate the effect of radiation term on temperature as well as yield production in the next step. As a consequence of the variations in the trays, the distillate output for each stage was determined to be: 5.02 kg/day for the first stage, 8.29 kg/day for the three stages, and 8.88 kg/day for all stages.

Multi effect and multistage solar distillation system are widely known for their high rate of distilled water productivity and also capable to fulfil the water requirements in remote and rural areas. In the same scenario, K.S. Reddy et. al. [75] studied the role of number of effects, gap between condensing and evaporating surface, feed water mass flow rate, feed water salinity (0, 5 & 10%), operating pressure of system (normal and evacuated mode) and climatic conditions on distilled water increment of AMEVSS (active multi-effect vertical solar still) by developing mathematical model. Results shows that interest rate (5% to 12%) and salinity of feed water play an important. Later on, Reddy et. al. [76] worked upon AMSSFS (active multiple stage series flow solar distillation unit), which is an improved version of tray type distillation unit with series flow.

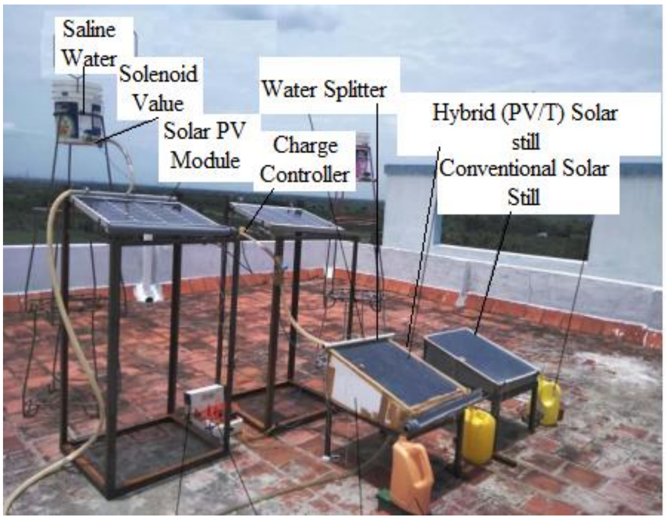


Figure 20. Photograph of proposed hybrid (PV/T) active solar still [73].

Anil Kr. Tiwari et. al. [77] presented an economic analysis of two small single slope solar still plant (FRP single slope solar still and FRP multiple wick solar still) coupled with fountain reservoir to meet 300l/day requirements. The performance of both the plants was analysed theoretically, with the flow of cooled water stored in fountain reservoir over glass cover and compared with CSS plant (without flow). CPL of distilled water for proposed plant-1and plant-2 is 29.2% to 32.5% less than the CSS plant. Annual yield increases for proposed plant-1and plant-2 is 56.4% to 61.4% for, with flow of cooled water over the glass cover.

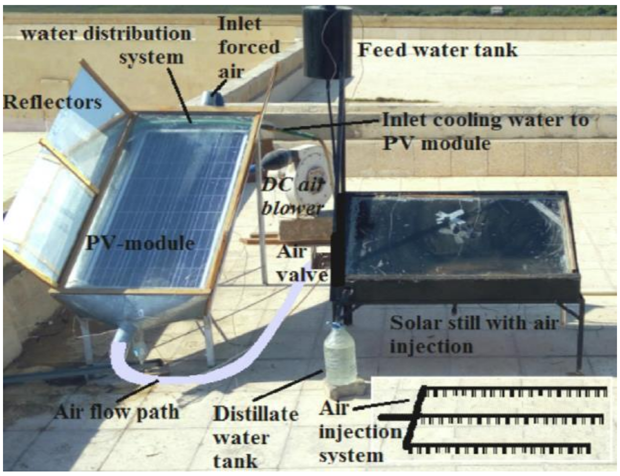


Figure 21. Photographic view of hybrid solar still [78].

Present studies more focused on hybrid use of solar still with PV panel which not only overcome the cleaning problem of PV panel (increases electricity production) but also increase the output of solar still. In the same scenario A.E. Kabeel et. al. [78], proposed a hybrid system (PV panel using reflectors, cooling and air injection) with five operating cases (Figure 21). Only two cases C and E uses cooling air out from PV module into the developed solar still for improving the fresh water productivity (increasing evaporation rate inside the still) by 40.98% and 21.96%, respectively compared to the cases without air injection.

Poonam Joshi et. al. [79] presents an analysis of enviro-economic, energy matrices and exergo-economic of three cases of single slope solar still (same basin area of 2 m^2) integrated with helical coiled copper heat exchanger (Figure 22): (i) and (ii) having N – partially and fully covered Photovoltaic Thermal (PV/T) Flat Plate Collectors, and (iii) N – Flat Plate Collector. Results report that the cost of water is lowest for case (i) followed by case (iii) and then case (ii) at the interest rate of 2% and 5%.

Figure 22. Photographic view of PV/T flat plate collector [79].

Theoretical analysis of double slope solar still (DSSS) integrated with N number of series of identical evacuated tubular collectors (N-ETCs) has been presented by D.B.Singh [80] as shown in Figure 23. Also, the proposed system (N-ETC-DSSS case (i)) has been compared with the different DSSS systems incorporated with case (ii) N identical PV/T flat plate collectors (FPCs), (iii) N identical PVT compound parabolic concentrator collectors (CPCs) and (iv) conventional DSSS on the basis of productivity and enviro- economics parameters. Later on, Omar Bait [81], presented a comprehensive mathematical model of DSSS integrated with a tubular solar collector (TSC) (Figure 24) and also compared it with Conventional DSSS on the basis of economic and enviro-economic parameters. It was revealed from the results that payback time of passive and active solar still was around 7.7 yrs and 21 yrs, respectively.

Emad M.S. El-Said et. al. [82] presented a novel work for increasing the performance and productivity (by heat absorbing capacity) of tubular solar still (Figure 25) by utilizing steel wire mesh porous packing with vibratory excitation system (for transvers harmonic forced vibration to destroy the surface tension and boundary layer of salty water). Yield increment of tubular modified solar still (TMSS) is 34% as compare to tubular conventional solar still (TCSS). CPL of TMSS reduced by 14.39% as compare to TCSS.

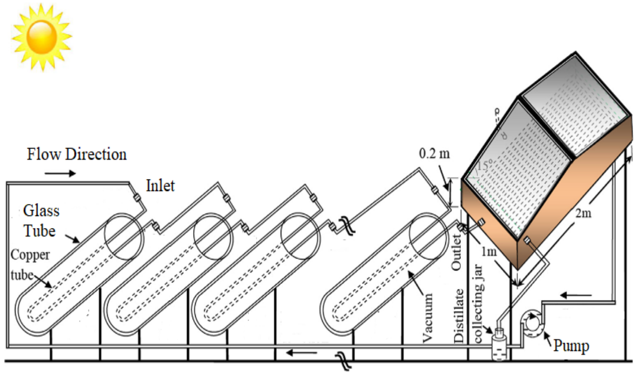


Figure 23. Schematic representation of N-ETC-DS [80].

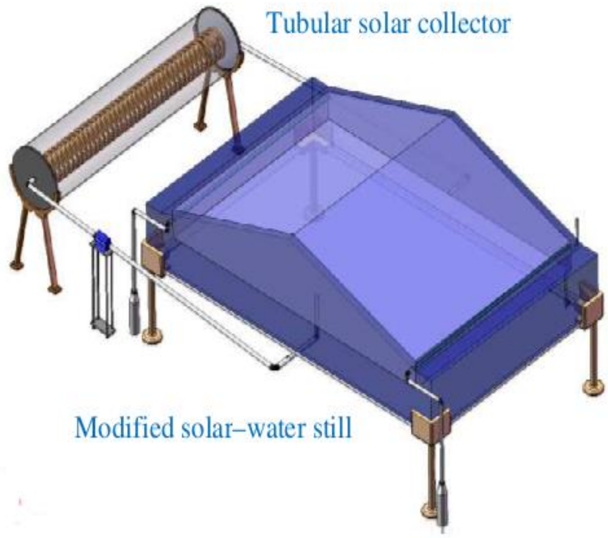


Figure 24. Schematic view of DSSS-TSC [81].

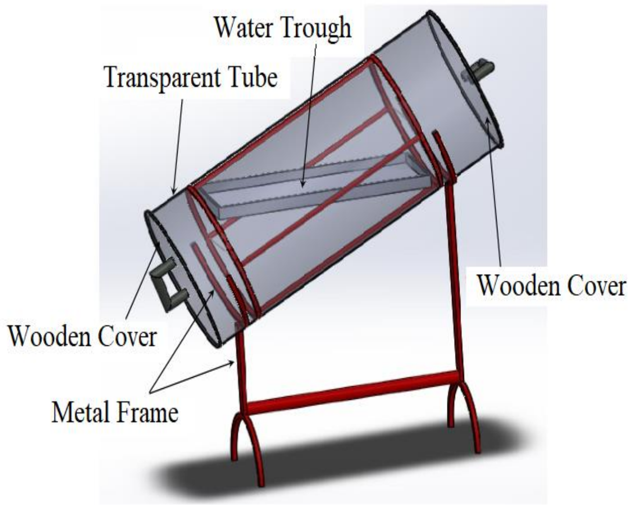


Figure 25. Schematic sketch of TMSS [82].

Hamdy Hassan et. al. [83] investigated single solar slope still in six different ways using parabolic through collectors (PTC), wire mesh (WM) and sand (SD) in the basin (as show in Figure 26). Results revealed that CSS+ SD + PTC in the summer has a higher maximum yield production compared with CSS and CSS+ SD + PTC in the winter by 1.21% and 102.1%, respectively. The maximum increase in energy and exergy in CSS+ SD + PTC as compared to CSS is found to be 216.6% and 325%, respectively.

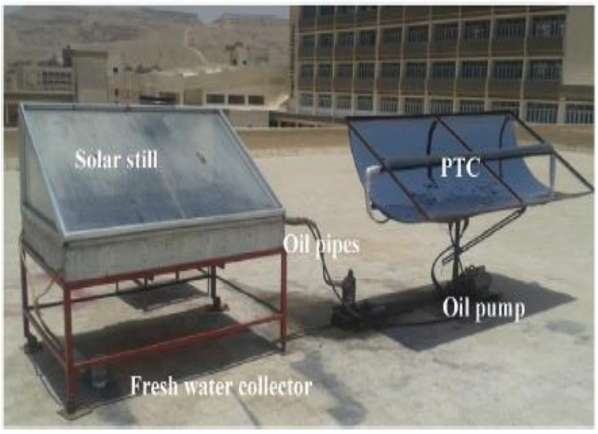


Figure 26. photograph of Solar still with PTC, WM and SD [83].

Rasoul Fallahzadeh et. al. [84] modified a conventional pyramid solar still (MPSS) by incorporating an evacuated tube collector (ETC) containing heat pipes, utilizing two types of fluids, ethanol and water, in three different combinations (as show in Figure 27). When using water as the working fluid at a filling ratio (FR) of 40%, MPSS produces the maximum yield of 6.97 l/m2. Shahin Shoeibi et. al. [85] investigates a double slope still with thermoelectric cooling of the glass cover and heating of basin water simultaneously in order to improve condensation and heating in the climatic conditions of Tehran, Iran.

Figure 27. photograph of modified pyramid solar still (bottom) [84].

Water from the cold side of thermoelectric system flows over the glass, while the hot side passes through a heat exchanger within the basin water of the solar still and on the other hand utilizes wind velocity for cooling of glass cover. Denise Mevada et. al. [86] compares the performance of CSS and modified solar stills (MSS) with fins, evacuated tube collectors (ETC), and a novel air-cooled condenser in the climatic conditions of Gandhinagar, India. The results revealed a 73.45% increase in yield productivity in MSS compared to CSS. Comparative technical detail for different active solar still provided in Table 2.

Table 2. Comparative detail of different active solar still.

Paper	Type of still	Component Incorporated and cost ($)		system cost ($)	Daily yield (l/m^2)	place
[67] Javad Abolfazli Esfahani (2011)	Thermoelectric solar stills	Thermoelectric cooler DC fan DC pump	12.5 8 4	290.5	1.2 winter	Semnan (35° 33′ N, 53° 23′ E), Iran
[68] Rahul Dev (2012)	Single slope	ETC Water pump (AC)	436.8 24.96	694.53	2.5	(IITD), New Delhi, India (28°350 N, 77°120 E
[69] Z.M. Omara (2013)	CSS, DLSW, DLSW with feeding hot brackish water during night	Evacuated solar water heater	450	412 520 1070	2.87 6.29 13.40	Kafrelsheikh University (31.07°N, 30.57°E), Egypt
[70] Mohamed A. Eltawil (2014)	CSS, DSS with condenser, DSS with water solar collector and condenser	Condenser and fan Photovoltaic system Pump Spraying unit Water solar collector Compressor Air solar collector	57 180 10 5 70 7 5	412 760 1348	2.5 4 6	Kafrelsheikh University (31.07°N, 30.57°E), Egypt
[71] M.R. Karimi Estahbanati (2015)	Multi-effect active solar still with 4 stages with non-continuous and continuous modes	Solar collector Circulating pump Heat exchanger	500 50 40	1030	5.95, 8.5, 10.3, 11.45 and 6.2, 8.85, 11.35, 13.55	Sharif University of Technology,Tehran, Iran

[72] D.B. Singh (2016)	Single slope	2PV module Flat Plate collector Motor and pump	253.24 395.69 15.82	807.21	4.25	(IITD), New Delhi, India (28°350 N, 77°120 E,
[74] Omar Bait et. al. (2016)	multi-stage distillation system	solar panel Steel and aluminum metallic structures	30.767 44.637	867.33	5.02	Batna city (35330 N, 6110 E), Algeria
[73] B. Praveen kumar (2017)	CSS CSS with PV/T	nickel-chromium (NiCr) heater powered by solar photovoltaic (PV)	126.62	90.54 145.02	2.9 7.2	KCET, Virudhunagar, Tamilnadu, India (9.5680°N, 77.9624°E)
[77] Anil Kr. Tiwari (2018)	CSS (177 m2) plant-1 (110 m^2) plant-2 (107 m^2)	fountain reservoir Plant installation cost 1089.23 676.92 658.56		11637 8086.1 7888.8	2.98 4.66 4.82	Jodhpur (India)
[78] A.E. Kabeel (2019)	CSS with Case C CSS with Case E	photovoltaic (PV) panel with reflectors and cooling system -		75.42 75.42	6.034 5.22	Tanta, Egypt
[82] Emad M.S. El-Said (2020)	TCSS TMSS	vibratory excitations Wire mesh with aluminium frame	38 17	- 295	3.25 4.2	Fayoum University, Fayoum, Egypt
[75] K.S. Reddy (2016)	AMEVSS with normal with evacuated mode	Flat plate collector DC pump (50 W)	138 58.11	748.27 870.16	9.75 27.80	Chennai (30.08 N 80.27 E) Tamil Nadu, India.
[76] K.S. Reddy (2017)	AMSSFS with Air cooled with Non-evacuated and evacuated AMSSFS with Wetted wick cooled with Non-evacuated and evacuated	Flat plate collector Capillary wick Vacuum pump pump	307.03 15.13 110.53 97.48	1638 1799 1666 1828	10.95 21.13 12.63 44.07	Chennai (30.08 N 80.27 E) Tamil Nadu, India.
[79] Poonam Joshi (2018)	Active single slope solar still with cases (i) case (ii) case (iii)	heat exchanger Photovoltaic Thermal FPC each Motor	28.57 78.57 14.28	2192.8 2192.8 1214.2	5.52 3.68 6	(IITD), New Delhi, India (28°350 N, 77°120 E,
[80] D. B. Singh (2019)	Double slope solar still (DSSS)	ETC Motor and pump	161.53 15.38	295.12	16.71	Greater Noida 28.4572° N, 77.4984° E, India
[81] Omar Bait (2019)	DSSS Modified solar still	tubular solar–water heating system (TSC)	-	63.831 175.62	1.31 1.82	Batna city (35330 N, 6110 E), Algeria

[83] Hamdy Hassan et. al. (2020)	CSS CSS + SD + PTC CSS + WM + PTC	parabolic trough collector steel wire mesh	103.255 14.473	143.79 248.97 261.52	3.96 8.77 8.15	Alexandria, Egypt
[84] Rasoul Fallahzadeh et. al. (2020)	CSS MPSS	heat pipe solar collector	65	82.5 169	3.3 6.97	Mashhad, Iran
[85] Shahin Shoeibi et. al. (2021)	DSSS with air cooled water cooled Modified water-cooled	5 thermoelectric modules PV module 2 DC Pumps	25 75 30	267 300 425	1.41 2.57 3.12	Tehran, Iran
[86] Denise Mevada et. al. (2021)	CSS MSS	Evacuated tubes (6 nos.) Condenser Fins	55 3 3	75 136	2.26 3.92	Gujarat, India

4. Comparison of all Active Solar Still on the Basis of Different Components Incorporated

Till before this sections, different types of active and passive solar still are compared on the basis of their system cost, daily yield and incorporated component cost (in case of active solar still). By the help of tables, it is easier to calculate most yield productive solar still with lowest cost. Further, economic analysis and enviroeconomic is going to be present in next sections for more details. In addition to this, how solar still have been improved with the addition of different organs like reflectors, PV modules, etc in some performance indexes such as water productivity and efficiency as show in the below Figure 28 & 29.

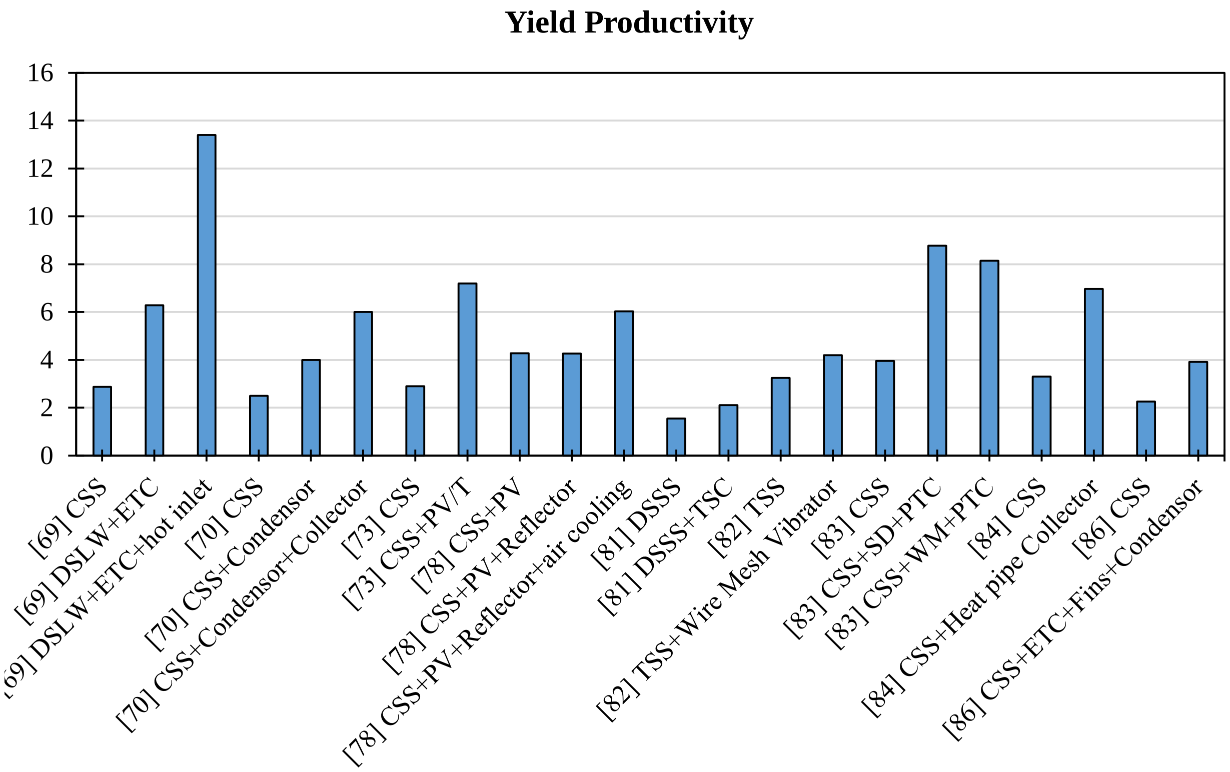


Figure 28. Comparative analysis of active solar still on the basis of yield productivity.

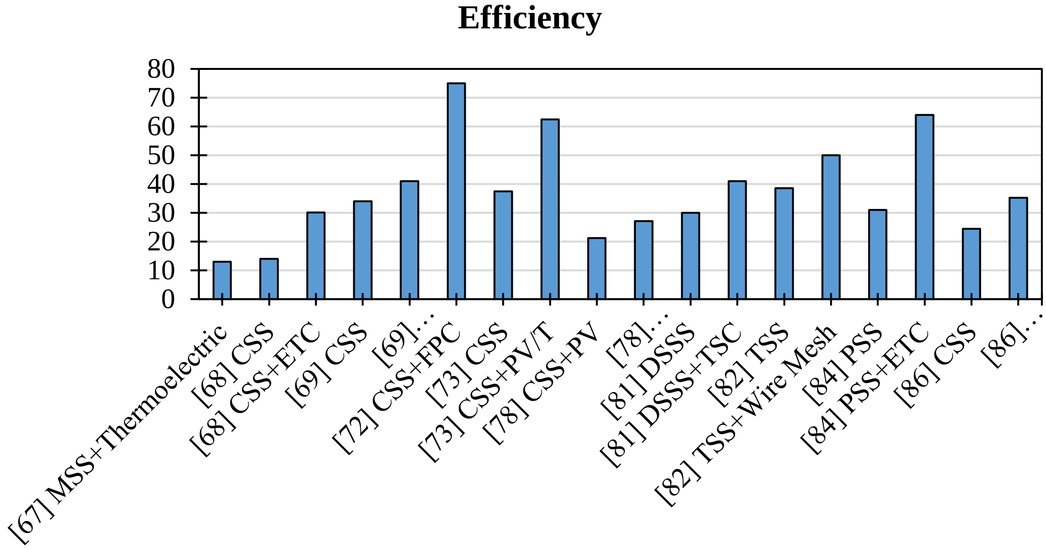


Figure 29. Comparative analysis of active solar still on the basis of efficiency.

5. Economic Analysis of Different Passive and Active Solar Still

In Solar desalination still, the Cost per litre (CPL) of distilled water is calculated in economic analysis. Economic analysis of Solar still initially carried out by Govind and Tiwari [87]. Later Kabeel et al. [88] presented the economic analysis of different configuration passive and active solar still. In this analysis, values of n (number of life years), i (interest per year), sunny days per year and x is assumed as 10, 12%, 260 and 20% respectively and an excel programme was prepared for the calculation. Economic analysis parameters are represented in Table 3 [89]:

Table 3. Economic analysis formulas applied for most of the still system.

Economic Method	Formulas
Present capital Investment (P)	CRF = $i(1+i)^n/[(1+i)^{n-1}]$
Capital recovery factor (CRF)	AFC = P(CRF)
Annual first cost (AFC)	SFF = $(i)/[(1+i)^{n-1}]$
The sinking fund factor (SFF)	ASV = (SFF) ×S (Salvage value)
The annual salvage value (ASV)	AC = AFC + AMC –ASV
Annual maintenance cost (AMC) = 15% of AFC	AC/L = AC/M (Annual Yield)
Annual cost (AC)/m^2	AUE = M × 0.65
The annual cost per liter (AC/L)	AC/kWh=(AC/m^2)×AUE
Annual useful energy (AUE)	S = (x × P)
Annual Cost/kWh	
Percentage of degradation rate (x)	
Cost per litres (CPL)	

Table 4. Economic analysis for passive solar still.

Sr. No.	M (L/m2)	CRF	FAC	SSF	S	ASV	AMC	AC	CPL
[50]	650	0.177	72.917	0.057	82.4	4.6955	10.938	79.16	0.1217
[50]	910	0.177	86.722	0.057	98	5.5844	13.008	94.146	0.1034
[50]	780	0.177	84.952	0.057	96	5.4705	12.743	92.225	0.1182
[10]	951.6	0.177	29.202	0.057	33	1.8805	4.3804	31.702	0.0333
[10]	1092	0.177	29.202	0.057	33	1.8805	4.3804	31.702	0.0290
[52]	665.6	0.177	16.571	0.057	18.726	1.0671	2.4857	17.99	0.0270
[52]	1235	0.177	24.295	0.057	27.454	1.5644	3.6442	26.374	0.0213
[53]	858	0.177	35.397	0.057	40	2.2794	5.3095	38.427	0.0447
[53]	1118	0.177	38.937	0.057	44	2.5073	5.8405	42.27	0.0378
[53]	1196	0.177	92.032	0.057	104	5.9264	13.805	99.91	0.0835
[54]	1300	0.177	86.368	0.057	97.6	5.5617	12.955	93.762	0.0721
[54]	1560	0.177	92.032	0.057	104	5.9264	13.805	99.91	0.0640
[55]	624	0.177	12.035	0.057	900	0.775	1.8052	13.065	0.0209
[55]	962	0.177	12.035	0.057	900	0.775	1.8052	13.065	0.0136
[55]	676	0.177	12.035	0.057	900	0.775	1.8052	13.065	0.0193

[57]	1170	0.177	35.591	0.057	40.216	2.292	5.3386	38.637	0.0330
[57]	915.2	0.177	36.00	0.057	40.68	2.318	5.4002	39.083	0.0427
[58]	1118	0.177	17.698	0.057	20	1.1397	2.6548	19.213	0.0171
[58]	884	0.177	17.698	0.057	20	1.1397	2.6548	19.213	0.0217
[61]	236.6	0.177	14.36	0.057	16.228	0.9247	2.1541	15.59	0.0658
[61]	200.46	0.177	14.36	0.057	16.228	0.9247	2.1541	15.59	0.0777
[64]	702	0.177	13.30332	0.057	15.032	0.856824	1.995498	14.44199	0.020573
[64]	1118	0.177	14.75649	0.057	16.674	0.950418	2.213474	16.01955	0.014329
[65]	1193.4	0.177	92.04354	0.057	104.004	5.928228	13.80653	99.92184	0.083729
[66]	785.2	0.177	18.73899	0.057	21.174	1.206918	2.810849	20.34292	0.025908
[66]	1289.6	0.177	19.08768	0.057	21.568	1.229376	2.863152	20.72146	0.016068
[66]	1591.2	0.177	19.43814	0.057	21.964	1.251948	2.915721	21.10191	0.013262

Table 4 presenting the comparative analysis of distinct passive type solar still on the basis of cost of a liter. This study found that the highest cost per liter (CPL) of distilled water production is 0.1217 \$/L in traditional solar stills at Kafrelsheikh University, Egypt, and the lowest production cost of distilled water is 0.0132 \$/L in CSS with Nano-particles of Al_2O_3 at El Oued, Algeria. Additionally, it is observed that the production price of distilled water is directly proportional to the total price of the still and indirectly proportional to the distilled water produced rate. Furthermore, the choice of material utilized during the construction of the solar still system, while considering overall cost reduction and increased longevity, will result in lower water costs.

Table 5. Economic analysis for active solar still.

Sr. No.	M (L/m2)	CRF	FAC	SSF	S	ASV	AMC	AC	CPL
[67]	312	0.17698	51.4139	0.057	58.1	3.3108	7.712085	55.815	0.1789
[68]	650	0.17698	122.921	0.057	138.906	7.9154	18.43812	133.44	0.2053
[69]	746.2	0.17698	72.9175	0.057	82.4	4.6955	10.93762	79.16	0.1061
[69]	1635.4	0.17698	92.0318	0.057	104	5.9264	13.80476	99.91	0.0611
[69]	3484	0.17698	189.373	0.057	214	12.195	28.40596	205.58	0.059
[70]	650	0.17698	72.9175	0.057	82.4	4.6955	10.93762	79.16	0.1218
[70]	1040	0.17698	134.508	0.057	152	8.6616	20.17619	146.02	0.1404
[70]	1560	0.17698	238.575	0.057	269.6	15.363	35.7862	259	0.166
[71]	5954	0.17698	182.294	0.057	206	11.739	27.34405	197.9	0.0332
[72]	1105	0.17698	142.863	0.057	161.442	9.1996	21.42951	155.09	0.1404
[73]	754	0.17698	16.0241	0.057	18.108	1.0319	2.403622	17.396	0.0231
[73]	1872	0.17698	25.6662	0.057	29.004	1.6528	3.849937	27.863	0.0149
[77]	774.8	0.17698	2059.62	0.057	2327.466	132.63	205.9623	2133	2.7529
[77]	1211.6	0.17698	1431.11	0.057	1617.22	92.156	143.1112	1482.1	1.2232
[77]	1253.2	0.17698	1396.2	0.057	1577.768	89.908	209.43	1515.7	1.2095
[78]	1568.8	0.17698	13.3481	0.057	15.084	0.8595	2.002222	14.491	0.0092
[82]	1092	0.17698	52.2103	0.057	59	3.3621	7.831549	56.68	0.0519
[83]	1029.6	0.17698	25.45083	0.057	28.758	1.639206	3.817625	27.62925	0.026835
[83]	2280.2	0.17698	44.06769	0.057	49.794	2.838258	6.610154	47.83959	0.02098
[83]	2119	0.17698	46.28904	0.057	52.304	2.981328	6.943356	50.25107	0.023715
[84]	858	0.17698	14.6025	0.057	16.5	0.9405	2.190375	15.85238	0.018476
[84]	1812.2	0.17698	29.913	0.057	33.8	1.9266	4.48695	32.47335	0.017919
[85]	366.6	0.17698	47.259	0.057	53.4	3.0438	7.08885	51.30405	0.139946
[85]	668.2	0.17698	53.1	0.057	60	3.42	7.965	57.645	0.086269
[85]	811.2	0.17698	75.225	0.057	85	4.845	11.28375	81.66375	0.10067
[86]	587.6	0.17698	13.275	0.057	15	0.855	1.99125	14.41125	0.024526
[86]	1019.2	0.17698	24.072	0.057	27.2	1.5504	3.6108	26.1324	0.02564

Table 5 shows comparative economic analysis of distinct active type solar stills. In the study, the highest cost for a litre of water was 2.75 $/l when using a solar still with a fountain reservoir plant, while the lowest cost per liter was 0.0092 $/l when using a hybrid solar system with photovoltaics, reflectors and air-cooling systems. Moreover, it is important to use different ways to reduce the cost of construction, to enhance the lifespan of the system and the productivity of the water, with a low-interest rate to lower the price of water production. In addition, solar stills comprising photovoltaic/thermal panels, solar collectors and condenser have a substantial impact on both distillation production and system construction prices.

6. Enviro-Economic Analysis of Different Passive and Active Solar Still

It is a way of providing economic incentives against the reduction amount of emission pollutants and also controlling the quantity of harmful pollutants in the environment. It promotes in developing renewable technologies for better future. It is analysed on the basis of enviro-economic parameter which included the price of CO_2 (Carbon Dioxide) emission and quantity of emitted carbon. From a coal plant, generation of 1 KWh of electricity emitted 980 g CO_2 as per B.K. Sovacool [90]. Therefore, Value of CO_2 mitigates/ annum for solar distillation still on the energy and exergy bases as follow:

$$\Phi_{CO_2 \text{energy}} = \frac{\Psi_{\text{energy}} \times E_{\text{out}}}{1000}; \ \Phi_{CO_2 \text{exergy}} = \frac{\Psi_{\text{exergy}} \times G_{\text{ex}}}{1000} \quad (1)$$

Where, Φ_{CO2} is CO_2 mitigated/ annum (tones CO_2/annum), Ψ_{CO2} is average CO_2 emitted from coal power generation plant (2.08 kg CO_2/kWh), E_{out} and G_{ex} is the annual energy and overall thermal exergy obtained from the solar distillation unit.

In international market, price range of CO_2 mitigated [91] is varies from 3 to 16 $/ton of CO_2. Thus, CO_2 average value taken for the calculation is $14.5/ton CO_2 [92]. So, the environmental cost Z_{CO2} ($/annum) on the bases of energy and exergy expressed as:

$$Z_{CO_2 \text{energy}} = P_{CO_2} \times \Phi_{CO_2 \text{energy}} ; \quad Z_{CO_2 \text{exergy}} = P_{CO_2} \times \Phi_{CO_2 \text{exergy}} \quad (2)$$

Where, P_{CO2} is carbon dioxide price/ton CO_2. The enviro-economic cost for different passive and active solar still have been shown in Table 6.

Table 6. Enviro-economic analysis of passive and active solar still.

Paper	Type of still	Embodied energy (kWh)	Environmental cost ($) energy and exergy		CO_2 mitigates energy (Tones)	Energy payback time
Passive solar still						
[49] V.K.Dwivedi (2010)	Double solar still with water depth 0.01 0.02 0.03	602.73 602.73 602.73	219.68 206.39 188.66	- - -	9.33 8.76 8.01	1.85
[59] Piyush Pal (2018)	Double slope with jute wick with black cotton wick	1009.99 1032.91	106.86 118.78	2.12 2.71	7.82 8.69	0.692 0.637
[56] T. Rajaseenivasan (2016)	CSS CSS with Square finned still CSS with Circular finned still	320.59 379.62 390.03	280.81 359.42 384.58	- - -	16.13 20.62 22.06	0.65 0.62 0.57
[60] K.S. Reddy (2018)	Tilted solar distillation with RO reject with sewage water	1397.13 1397.13	344.08 319.72	- -	23.73 22.05	1.70 1.82
[63] Mohamed S. Yousef (2019)	TRD TRD with pin fins TRD with steel fibers	235 318 250	179.5 208.9 226.6	- - -	12.38 14.4 15.63	- - -

[65] H.Sharon (2021)	novel hybrid solar still	1915.67	-	-	49.83	1.17
Active solar still						
[75] K.S. Reddy (2016)	AMEVSS with normal with evacuated mode	1228.5 1228.5	344.23 1186.24	- -	23.74 81.81	4.00 1.37
[76] K.S. Reddy (2017)	AMSSFS with Air cooled with Non-evacuated and evacuated AMSSFS with Wetted wick cooled with Non-evacuated and evacuated	6785.12 6698.02 6824.94 6737.84	682.95 1456.38 813.59 3229	- - - -	47.1 100.44 56.11 222.69	3.66 1.92 3.19 0.93
[79] Poonam Joshi (2018)	Active single slope solar still with cases (i) case (ii) case (iii)	14154 14154 7824	103 249 44	26.82 86.56 3.33	7.14 17.20 3.08	4 2 5
[80] D. B. Singh (2019)	double slope solar still (DSSS)	2824.34	5814.35	561.73	400.99	-
[81] Omar Bait (2019)	DSSS modified solar still	1152.605 1584.9 out	33.42556 45.96206	2.552197 4.41875	2.305211 3.169797	7.7 21
[83] Hamdy Hassan et. al. (2020)	CSS CSS + SD + PTC CSS + WM + PTC	603.8 875 930.6	231.42 501.35 464.67	26.37 85.67 76.72	15.96 34.57 32.05	0.756 0.506 0.58
[85] Shahin Shoeibi et. al. (2021)	DSSS with air cooled & water cooled	202.8 843.5	189.79 235.92	1.03 6.51	13.09 16.27	1.49 3.42

Table 6 provides the Embodied energy (kWh), CO_2 mitigated energy (Tones/year) and environmental benefits of various types of solar stills. On the basis of this table, the AMSSFS with wetted wick cooled with evacuated tube collector mitigated the most CO_2 by around 222.69 tons per year. While the DSSS attained the lowest mitigation of CO_2 per year, which was approximately 2.30 tons/year. The lifetime of solar still seems to have a significant impact on environmental cost (enviroeconomic parameters). From the results, the highest environmental cost ($) incurred by double slope solar still with N-identical evacuated tubular collectors during a lifetime of 50 years equalled 5814.35, while the lowest environmental cost ($) incurred by passive double slope solar stills during 30 years was 33.42. Additionally, the embodied energy of the solar still has been inversely impacted on CO_2 mitigates value during stills life time. According to the results, the N-type photovoltaic thermal flat plate collectors' single slope solar stills had the highest embodied energy value in comparison to the other solar stills.

7. Conclusion

The current work effort seeks to analyse the passive and active solar distillation unit on a techno-economic and enviro-economic analysis basis. These analyses play an important role in selecting the suitable solar still based on capital cost, construction material and CPL, environmental cost, and CO_2 mitigates. Based on finding in this work, the following conclusion is as follow:

- Active solar still has a higher system cost compared to passive solar due to the addition of thermal energy by different components and mechanisms.
- CSS with spherical balls of heat storage shows a minimum CPL of 0.0136 $/l due to the lower initial investment cost of 68.18 $.
- On the basis of energy, value of environmental cost of CSS with circular finned still is found to be highest (384.58 $) whereas passive double slope with jute wick solar still having the lowest (106.86 $) among analysed passive solar stills.
- Active solar still with PV modules, reflectors, and forced air cooling has the lowest CPL of 0.0092 $/l, but the active solar still using a fountain reservoir plant has the highest CPL of 2.7529 $/l.
- On the basis of energy, the highest environmental cost was found for AMSSFS air-cooled with evacuated mode (1456.38 $), while the lowest was found for active solar stills with N - Flat Plate Collectors (44 $).
- The study found that CPL increases by decreasing lifetimes and increasing interest rates, and vice versa.
- There are no studies and analyses of cleaning and conservation mechanisms for the particular solar stills as it lacks numerous performing hurdles and automatic maintenances options for whole life functions in the previous literature.
- Several studies have used nanofluids in solar stills in order to increase the temperature of basin water and the evaporation rate of distilled water. Nanofluids could serve as cooling fluids for glass, which would significantly impact distillate production as well as CO_2 mitigates.
- All previous studies considered nominal interest rate in the calculation of cost per liters (CPL). It is necessary to take into account compounded interest rate, effective interest rate, and inflation rate to make the CPL close to reality.

Nomenclature

n	Number of life years
i	Interest per year
x	Percentage of degradation rate
S	Salvage Value
E	Annual energy
G	Overall thermal exergy
Z	Environmental cost
CO_2	Carbon Dioxide
CSS	Conventional solar still
DSSS	Double slope solar still
PV/T	Photovoltaic thermal
ETC	Evacuated tube collector
FPC	Flat plate collector
CPCS	Compound parabolic concentrator collectors
CPL	Cost per liter
Nu	
CGTCC	Cotton Gauze Top Cover Cooling
TSS	Tubular solar still
TISS	Evacuated tubular collector Solar still
Subscript	
ex	Exergy
en	Energy

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