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Research Article

Exergoeconomic, environmental, economic, and energy-matrices (4E) analysis of three solar distillation systems equipped with condenser and different heaters

Davoud JAVADI YANBOLAGH[1], Alireza SARAEI[3,*], Hossein MAZAHERI[2], Saeed Jafari MEHRABADI[1]

[1] *Department of Mechanical Engineering, Arak Branch, Islamic Azad University, Arak, Iran*
[2] *Department of Chemical Engineering, Arak Branch, Islamic Azad University, Arak, Iran*
[3] *Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran*

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ABSTRACT

The water scarcity in the world in the near future become to a global challenge.
The main aim of present study was to elucidate the performance of the three identical solar distillation units with different configurations under climatic conditions of the city of Tehran. All systems were equipped with different heating source that are thermoelectric heating modules (TEH), copper heater (CH), and solar water heater (SWH) while all system assisted with an active external condenser. Performance of all systems is scrutinized from different thermodynamic, thermoeconomic, environmental, and energy-matrices viewpoints. Findings revealed that the highest daily and annual productivity obtained by the system with CH. Economic analysis on the basis of uniform annual cost (UAC) revealed that the system with SWH has the lowest cost per liter (CPL) rather than other system while the highest CPL was for the case of TEH. Furthermore, it was concluded that the system with TEH obtain the most promising results in terms of exergoeconomic, enviroeconomic, and energy payback time (EPBT) because of the highest daily and annual energy and exergy output. Eventually, the environmental analysis indicated that the solar still with CH with 6342, 48.169, 18.46 kg emission of CO_2, SO_2. And NO have the best results rather than other systems.

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INTRODUCTION

The problem of providing safe drinking water in Iran and many Middle East and North Africa (MENA) regions become as one of the critical challenges that have many side effects in recent years. The social and health side effects of this challenge forced all countries to address solution in the context of Water-Energy-Environment-Nexus [1].

***Corresponding author.**
*E-mail address: a_saraei@azad.ac.ir

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In this regard, water desalination system in this context plays an important role for solving the water shortage. Mega-scale plants such as multi-effect desalination (MED) [2],[3], multi-effect desalination thermal-vapor compressio (MED-TVC) [4], multi-stage flash (MSF), reverse osmosis (RO) and electrodialysis (ED) that capable to produce several million liters of drinking water are proposed by researchers. Some of these technologies currently are operated in countries adjacent to the Persian Gulf. However, there are two problems in use of mega-scale plants. The first one is the high capital cost plants while the second parameter is their impracticality for off-grid regions. Therefore, small-scale water desalination systems such as humidification-dehumidification (HDH) and solar stills (SS) proposed as the suitable options. Nevertheless, SSs due to their unique characteristics such as simple constructing materials, simple structure, and operation at extremely remote regions [5],[6] have prominent advantages over HDH systems. The main problem of SSs is the low productivity and efficiency. To address this, researchers suggested different passive and active methods[7]. Among passive methods utilizing nanoparticles[8],[9], wick materials[10] internal/external reflectors[11],[12] condensers[13], sensible storage materials [14],[15], Phase change materials[16] are proposed while for active types of SSs integration by different flat plate collectors [17],[18], solar PV[19], evacuated tube collector [20],[21], parabolic trough[22], Fresnel lens [23], solar ponds [24], and thermoelectric modules[25] are suggested. All of these modifications performed to increase the performance of SSs that usually express different thermodynamic parameters including energy analysis, exergy analysis, and economic assessment. In the last decade, performance of the SSs is evaluated via new parameters which are exergoeconomic, enviroeconomic, energy-matrices, and CO_2 mitigation.

By taking the advantage of implementing these parameters, engineers, researchers, and decision-makers can be assisted to select the intended system based on the optimal conditions. Therefore, in recent years researchers (especially the energy experts) extensively concentrated to evaluate these parameters in different energy systems from mega-scale to small-scale application[26],[27].

Ibrahim et al.[28] theoretically evaluated the performance of a solar distiller unit by applying exergoeconomic optimization under climate condition of Egypt. The results revealed that the performance of system in summer and month of August is maximized. Furthermore, by applying exergoeconomic optimization, the exergy destruction and exergoeconomic cost diminished nearly 36% and 45% respectively. Efficacy of different solar stills incorporated with parabolic concentrator at different scenarios was examined by Hassan et al.[22]. By adding parabolic concentrator to the solar still the cost of system was increased but energy and exergy is also improved. Furthermore, the rate of CO_2 reduction, enviroeconomic, and exergoeconomic parameters are also higher than that of passive system. Hassan et al. [29] reported that among the six scenarios of solar stills which are conventional, with air-cooling, with water-cooling, with umbrella, with sand in basin, the system that utilized by force water cooling and sand in the basin mitigated the highest amount of CO_2 compare to other scenarios. Environmental analysis of three identical single-slope solar stills with sensible energy storage materials of pin fins and steel wool fiber was analyzed by Yousef et al. [30]. Findings showed that using hollow fins and steel fibers in solar stills lead to reduction of emitted CO_2 to the environment by around 14400 and 15600 kg respectively. Yousef et al. [31] calculated the exergoeconomic, enviroeconomic, exergoenvironmental, and exergoenviroeconomic of six solar stills with different hybrid modifications such as fins, steel wool fiber, and phase change materials. The results showed the system with steel wool fiber obtained the best results from exergoeconomic, enviroeconomic, exergoenvironmental, and exergoenviroeconomic points of view. Also, the amount CO_2 reduction for steel wool fiber rather than conventional system on the basis of energy and exergy was 41.6 ton and 1.56 ton respectively. Joshi and Tiwari.[32] evaluated the performance of solar still equipped with flat plate collector and photovoltaic thermal (PVT) collector on the basis of energy-matrices exergoeconomic and enviroeconomic. They concluded that the system used PVT has the highest exergoeconomic and enviroeconomic while it has lowest energy payback time. Khanmohammadi et al.[33] reported that multi objective optimization of solar stills with focus on exergoeconomic and CO_2 emission/mitigation results in higher performance compare to traditional solar still. Bait.[34] compared the performance of a tubular solar still with a conventional and reported that the productivity and thermal efficiency of the modified system is tremendously enhanced but the energy payback time for modified system is drastically higher than conventional system by around 13.3 years. Parsa et al.[35] performed series of experiments on two passive and active solar stills at different locations (top of the mountain Tochal and city of Tehran) to scrutinize the exergoeconomic, enviroeconomic, and energy-matrices parameters. The findings demonstrated that the parameters related to the productivity are higher for active systems at the city of Tehran while the passive systems at the peak of Touchal has the highest energy payback times due to lower days of operation and productivity. Also, Pal et al.[10] reported the day of operation as an important factor that have a huge effect on energy-matrices. Rajaseenivasan and Srither.[36] in series of experiments on passive fin-type solar still concluded that at different depth of water, the system with lowest depth of water has the highest rate of CO_2 reduction throughout the life of system. Sahota and Tiwari [37],[38] theoretically investigated the performance of three active and passive nanoparticle-based ($Al2O_3$, TiO_2, and CuO) double-slope solar stills from energetic, exergetic, exergoeconomic, enviroeconomic, and energy-matrices points of view. Their findings revealed that in all scenarios the active and passive systems utilized by CuO and Al_2O_3 nanoparticle have the most promising values compare to the other systems respectively. Nevertheless, several different parameters may affect the environmental benefits/hazards of the solar distillation units. Sharon and Reddy.[39] for the first time reported that increasing the salinity of the feed water results in higher rate of CO_2 emission compare to those systems fed by water with lower salinity. In another study, Sharon and Reddy.[40] mathematically simulated the performance of a multiple-effect solar still from environmental and EPBT viewpoints. The findings revealed that the proposed system at the optimum conditions mitigate 81.8 ton CO_2 whereas the EPBT stands on 1.3 years. Sharshir et al.[41] reported that among Cu and Fe_2O_3 nanoparticle in a wick-type solar still the system with Cu nanoparticle has better results from exergoeconomic, and environmental aspects compare to Fe_2O_3. Integration of solar stills by active methods not only increases the productivity and energy/exergy efficiency of the systems but it also improves the other important parameters such as exergoeconomic, enviroeconomic, CO_2 mitigation, and energy-matrices. It was reported that using different solar collector such as flat plate collectors, parabolic concentrator, photovoltaic/thermal collector [42],[43] and evacuated tube solar collectors [44] can increase these parameters in comparison with traditional solar stills.

From the aforementioned literature review it can be concluded that in recent years important parameters such as exergoeconomic, enviroeconomic, energy-matrices, CO_2 emission/mitigation are took researchers attention. In the present study, we examined these parameters for the first time for three solar still that each of them equipped with different source of heating to show that based on these parameters utilizing which of these methods is beneficial. Therefore, thermoelectric heating modules, flat plate collector, and copper heater are integrated with solar stills. Results of the all parameters evaluated for different interest rate and lifetimes. The pros and cons of each system from these viewpoints are examined and discussed.

THEORETICAL CONSIDERATION

In this section the theoretical formulation of the study is presented.

Annual energy and exergy output

The expression of annual energy and exergy is based on the daily energy and exergy output of the systems multiply by the day of operation throughout the year. It should be noted that the days of operation may be vary between 180-365 days based on the geographical location of experiments. In the current study the day of operation was taken about 250. Table 1 and 2 given the equation for annual energy and exergy output of the systems respectively.

In above equations $\dot{M}_{evap}$, LHV are represents as the rate of productivity, latent heat of vaporization of water which taken as 2300 kJ/kg, respectively.

Energy-Matrices

For evaluating any energy systems energy-matrices can be used as a practical indicator to realize the pros and cons of the proposed system. Energy matrices consist of three indicators which are energy payback time (EPBT), energy production factor (EPF) and life cycle conversion efficiency (LCCE). The EPBT define as the period of the return of the prosed system regarding the materials used during manufacturer process. The EPF signifies the complete performance of active and passive solar stills. The EPF is the reciprocal of EPBT and it value yearly is equal to one. During the making

Table 1. Daily and annual energy output of systems

Equation	Description	Ref	No of Eq
$E_{out} = \frac{\dot{m}_{ev} \times LHV}{3600} + \frac{P_m - P_u}{0.38}$	The expression of overall annual energy output for active Solar still	[42]	(1)
$P_m = N \times I_s(t) \times Am \times \eta_{cN} \times \tau_g \times \alpha_c$	P_m represents annual power obtained from PV	[32]	(2)

Table 2. Daily and annual exergy output of systems

Equation	Description	Ref	No of Eq
$\sum EX_{output} = EX_{evaporation} = \frac{(\dot{m}_{ev} \times LHV)}{3600} \times \left(1 - \frac{T_a + 273}{T_w + 273}\right)$	Evaporation/output exergy of the solar still for active and passive solar still	[45]	(3)
$\sum EX_{output} = EX_{evaporation} = \frac{(\dot{m}_{ev} \times LHV)}{3600} \times \left(1 - \frac{T_a + 273}{T_w + 273}\right) + \frac{P_m - P_u}{0.38}$	Annual exergy output	[45]	(4)

Table 3. Energy matrices relations

Equation	Description	Ref	No of Eq
$(EPBT)_{energy} = \frac{(E_{in})ene}{(E_{out})ene} = \frac{\text{Embodied energy of the system based on energy analysis}}{\text{Annual output of energy from system based on energy analysis}}$	Energy payback time (EPBT) based on energy	[32]	(5)
$(EPBT)_{exergy} = \frac{(E_{in})exe}{(E_{out})exe} = \frac{\text{Embodied energy of the system based on exergy analysis}}{\text{Annual output of energy from system based on exergy analysis}}$	Energy payback time (EPBT) based on exergy	[32]	(6)
$(EPF)_{energy} = \frac{(E_{out})}{(E_{in})} = \frac{\text{Annual output of energy from system based on energy analysis}}{\text{Embodied energy of the system based on energy analysis}}$	Energy production factor (EPF) based on energy	[32]	(7)
$(EPF)_{exergy} = \frac{(EX_{out})}{(E_{in})} = \frac{\text{Annual output of energy from system based on exergy analysis}}{\text{Embodied energy of the system based on exergy analysis}}$	Energy production factor (EPF) based on exergy	[32]	(8)

of materials of any system in the company a certain amount of energy is consumed. The energy in in manufacturer is provided by conventional fuel resource that releases many pollutants. On the other hand, utilizing renewable energy systems lead to decrease the amount of pollutant to the environment due to eliminating the conventional energy resource. Thus, trade-offs between the amount of pollutant emitted during the manufacturing process and mitigating due to use of clean energy should be clarified. In the present study, the EPBT and EPF parameters based on energy and exergy approach is evaluated for all systems. Table 3 given the equation of the energy-matrices.

Exergoeconomic analysis

The exergoeconomic parameter originated by combining the energy/exergy analysis and the UAC approach and it developed to assist the engineers/designers/decision-makers to design/choose systems in a cost-effective prospect while considering the optimal design parameters. In the present study, the exergoeconomic parameter is evaluated based on the energy and exergy approach. Briefly, the exergoeconomic parameter defines as the amount of total energy and exergy output of system divided by the total cost of the unit (i.e. UAC). The exergoeconomic relations based on the energy and exergy are given in Table 4.

Economic analysis

The economic analysis is one of the most vital parameters that should be evaluated for any energy system. In the present, study uniform annual cost (UAC) method was done to scrutinize the performance of system from economic standpoint. Table 5 given the relations of the UAC.

Environmental analysis

Evaluating any energy system from environmental analysis is an important factor to realize that whether the propose system is environmentally beneficial or not. Environmental analysis comes in to the spotlight to show how much pollutant can be decrease due to the full use of renewable energy. Since, the systems are fully powered by solar of energy, a certain amount of pollutant annually and throughout the lifetime is mitigated. On the other hand, as it mentioned in the section of energy-matrices a certain amount of the pollutants are emitted through the fabrication of systems component. Thus, the amount of CO_2 mitigation and emission through the lifetime of solar stills can elucidate the environmental impact of systems. The amount of CO_2 emission by coal plants for producing 1kWh electricity considering the loss of transmission/distribution estimated by about 2 kg. Table 6 given the annual and lifetime CO_2 emission and mitigation of solar stills. Furthermore, enviroeconomic parameter is indicated that how much credit would be earned if the emitted carbon can be sold in the market. It should be noted that, in the present study besides of CO_2, the amount SO_2 and NOx emission is also calculated. Table 7 show the relation of the environmental analysis and enviroeconomic of solar stills.

Table 4. Exergoeconomic parameters on the basis of energy and exergy

Equation	Description	Ref	No of Eq
$J_{exgo,en} = \frac{E_{out}}{UAC}$	Exergoeconomic parameter based on the energy	[42]	(9)
$J_{exgo,ex} = \frac{EX_{out}}{UAC}$	Exergoeconomic parameter based on the exergy	[42]	(10)

EXPERIMENTAL SETUPS AND PROCEDURES

A detailed description of the experimental apparatus and procedures can be found in our previous study [13]. Herein, a brief description about the setups and procedures are presented. Three identical single-slope solar stills with different heating sources and external condenser are constructed with galvanized sheet and glass. The external condenser is equipped with two thermoelectric modules to provide a cool environment to further the rate of

Table 5. Economic analysis relations

Relation	Definition	Ref	No of Eq
$PC_{TOT} = PR_{Still} + PR_{PV} + PR_{Thermoelectric} + \frac{PR_{Thermoelectric}}{(1+i)^{10}}$	Total cost of the experimental setup	[35]	(11)
$CR = \frac{i(1+i)^n}{(1+i)^n - 1}$	The factor for Capital Recovery of experimental setup	[9]	(12)
$FAC = PC_{TOT} \times (CR)$	First annual cost of the experimental setup	[9]	(13)
$YMC = 0.15 \times (FAC)$	Yearly maintenance cost experimental setup	[46],[9]	(14)
$SV = 0.1 \times PC_{TOT}$	Salvage Value of experimental setup	[9]	(15)
$SFF = \frac{i}{(1+i)^n - 1}$	Sink Fund Factor	[9]	(16)
$YSV = SV \times (SFF)$	Yearly Salvage Value of experimental setup	[9]	(17)
$UAC = FAC + YMC - YSV$	Uniform end of year annual cost of experimental setup	[9]	(18)

Table 6. Annual and lifetime emission/mitigation of CO_2

Equation	Description	Ref	No of Eq
$CO_{2emission} = E_{in} \times 1.58$	CO_2 emission during the lifetime of the solar still (kg)	[30]	(19)
$CO_{2\ emission} = \frac{E_{in} \times 1.58}{n}$	Annual CO_2 emission by the solar still unit (kg/y)	[30]	(20)
$CO_{2mitigation} = E_{out} \times 1.58$	CO_2 mitigation during the lifetime of the solar still (kg)	[30]	(21)
$CO_2 mitigation = \frac{E_{out} \times 1.58}{n}$	Annual CO_2 mitigation during the lifetime of the solar still (kg)	[30]	(22)

Table 7. Net CO_2, SO_2, and NO alleviated by the systems

Equation	Ref	No of Eq
$\text{Net } CO_2 \text{ emission alleviated (tons)} = \frac{((E_{output} \times n) - E_{in}) \times 1.58}{1000}$	[47]	(23)
$Z'CO_2 = zCO_2 \times \text{Net } CO_2 \text{ emission}$	[30]	(24)
$zCO_2 = 14.5$		
Net SO_2 emission alleviated (tons)$=((E_{output} \times n) - E_{in}) \times 0.012$	[47]	(25)
Net NO emission alleviated (tons)$= ((E_{output} \times n) - E_{in}) \times 0.046$	[47]	(26)

evaporation. Each solar still equipped with heating resource which are thermoelectric heating modules (TEH), copper heater (CH), and flat plate solar water heater (SWH). It should be noted that the power consumption by thermoelectric modules and cooper heater is almost equal (CH consumed slightly higher power than TEH) and only a small part of electricity used to derive the pump in SWH. Series of experiments are conducted in one month under climatic conditions at the city of Tehran. All experiments performed in ten hours between 9:00 to 18:00. All environmental conditions were recorded at each hour. After each experiment all setups are washed and cleaned to prevent the effect of previous experiment results on next experiments. Figure 1 and 2 shows the experimental setup and schematic of the proposed systems respectively.

RESULTS AND DISCUSSION

In this section, all calculated results are presented. Figure 3 shows the variation of solar radiation with water and ambient temperature in a selected typical day of experiment. As it can be seen, temperature of water at the beginning of the experiment has sharp trend and it reach to highest amount when the solar intensity and ambient temperature are maximum at 14:00. The water temperature from highest to lowest was obtained by solar still with CH

Figure 1. Experimental setup during experiments.

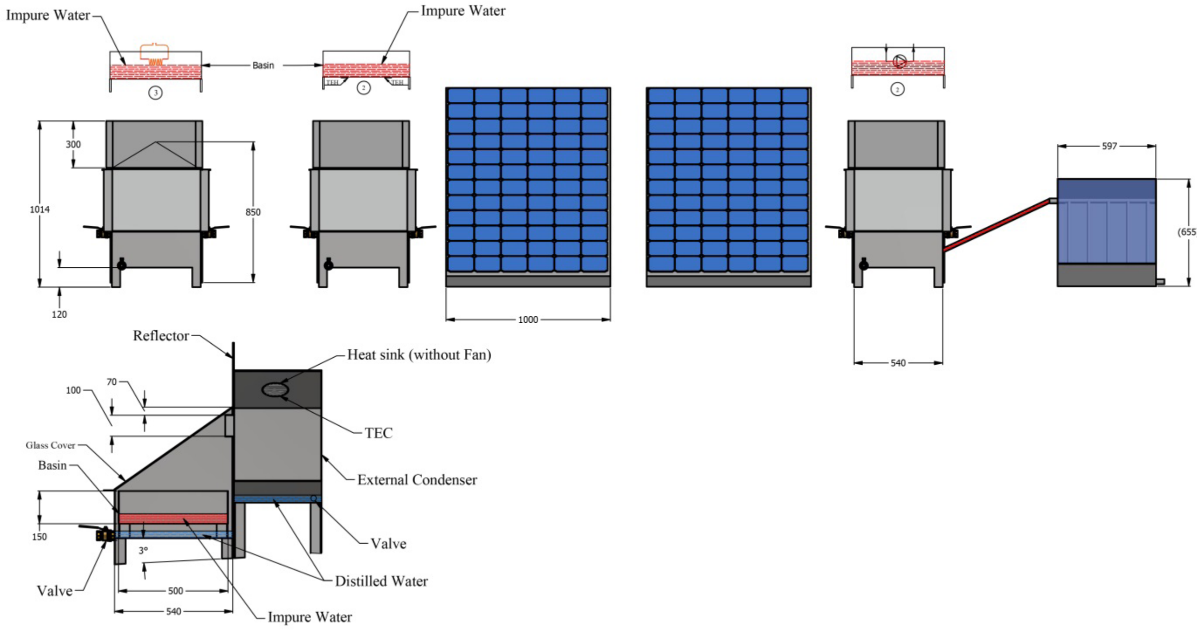

Figure 2. Schematic of the experimental setups with different configurations.

and it followed by TEH and SWH 77, 75, and 71°C respectively. It should be noted that the temperature difference of the solar still with CH and TEH is marginal due to the use of external heating source while their difference is obvious with SWH-based solar still because the system with SWH uses solar energy to increase the temperature while in the systems with CH and TEH, electrical energy utilize to generate heat alongside direct solar radiation.

Figure 4 shows the instantaneous and overall productivity of solar stills during ten hours in a typical day of experiments. The highest instantaneous yield for all systems was obtained at 14:00. Also, the system with CH has higher productivity than solar stills with TEH and SWH by about 6.26% and 23.92% respectively.

Figure 5 shows the daily energy and exergy output of the systems. As it can be seen the system with TEH has higher energy and exergy output than the system with CH and SWH by around 5.6% and 30.5% respectively. Regarding Fig 4 the system with CH has higher productivity than the system with TEH; subsequently it seems that the CH should have higher energy and exergy output but in equation 1 the productivity is not the only parameter that have effect on

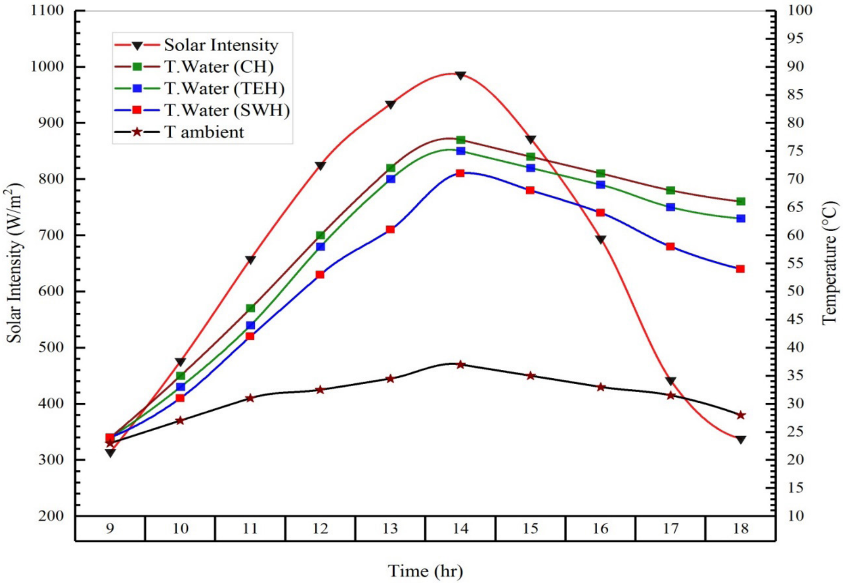

Figure 3. Variation of water temperature with solar intensity and ambient temperature.

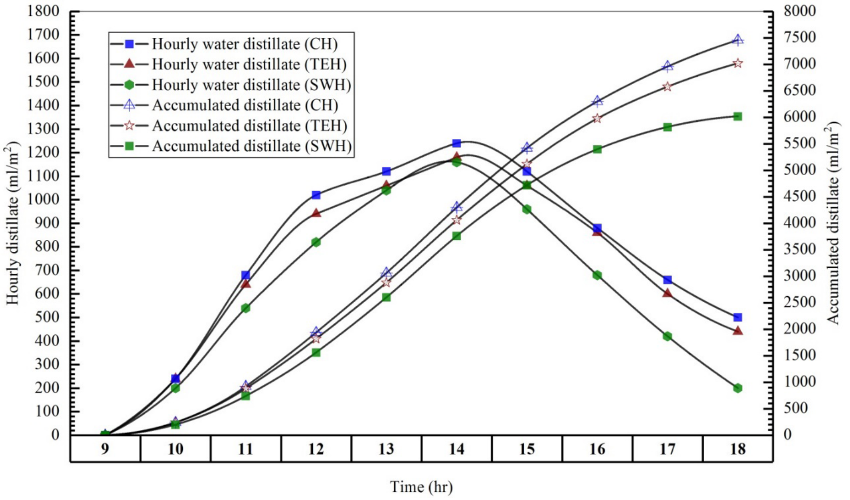

Figure 4. Hourly and total productivity of solar stills.

annual energy and exergy output but the term of "P_u" which represented as the electrical consumed by the system is also have effected in the energy output. Since the consumed power by the CH is slightly higher than TEH and the productivity of CH is marginally higher than TEH the annual energy and exergy output for the system with TEH is higher than other systems.

Table 8 exhibited the embodied energy of all solar stills with respect to the materials used in their structure. It is obvious that the embodied energy of the system with SWH is virtually one fourth of solar stills with CH and TEH. The reason of this difference is that the system with SWH has not used PV panel for heating and only small part of electricity (the power of pump in collector) is used. It should be reminded that a huge part of the embodied energy belongs to PV panels. In this regard, the embodied energy of the solar stills with SWH, TEH, and CH calculated by around 635, 2384, and 2390 kWh respectively.

The costs of materials for each solar still are presented in Table 9. The capital cost of the systems with SWH, TEH, and CH evaluated by around 199, 269, and 274$ respectively. The high cost of solar stills with TEH and CH is associated with solar PV panels.

Table 10 shows the results of economic analysis for all systems based on the concept of UAC for 20 years lifetime and interest rate of 10% and 20% and compare the results

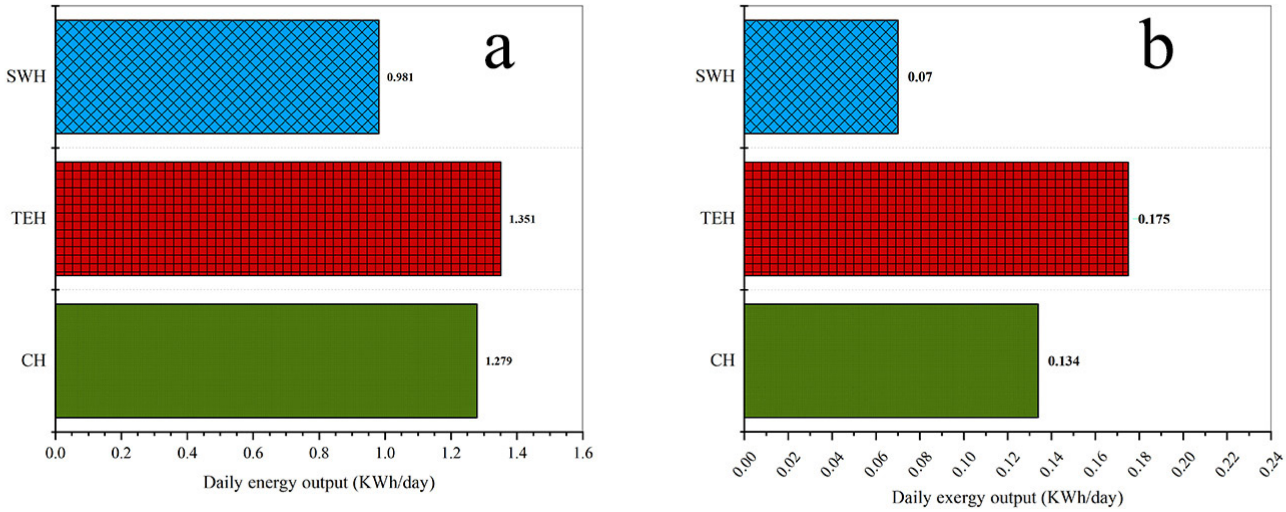

Figure 5. daily energy and exergy out by solar stills.

with previous studies. It should be noted the salvage value for systems taken by 10% of the whole structure. The UAC for solar stills with CH and TEH is higher by about 28% and 26% rather than the SWH due to the use of PV. The findings indicated that the maximum and minimum cost of produced water obtained for 20 years and 20% and 10% interest rate by around 0.0365 and 0.0184 $\$/L.m^2$ for solar still with CH and SWH respectively. The cost of produced water for solar stills with SWH is lower by about 10.2% and 13.6% compared to solar stills with CH and TEH respectively. Also the cost of produced water (i.e. CPL) in the case of that the interest rate consider 10% is lower than those results of Rahbar et al. [48] and Abd Elbar et al. [49].

Table 11 presented the results of exergoeconomic analysis based on the energy and exergy approach. As it can be observed, the exergoeconomic parameters directly affected by the UAC and energy and exergy output of the system. The highest and lowest values for exergoeconomic parameter based on the energy and exergy were obtained by solar still with TEH and SWH respectively.

Table 12 presents the results of environmental and envinroeconomic analysis for all systems. The rate of CO_2 reduction for solar stills at different years of operation of 20 and 30 years from highest to lowest were evaluated by around 6.89, 6.75, 6.34 ton.CO_2/year and 12.23, 10.63, 11.39 ton.CO_2/year for solar stills with TEH, CH, and SWH respectively which shows that solar still with TEH has higher rate of CO_2 reduction by around 6.8% and 13.3% in comparison with CH and SWH. Furthermore, the enviroeconomic parameter for 20 and 30 years of operation calculated by about 100.038, 91.95, 97.91 and 177.443$, 165.25, 154.14 for solar stills with TEH, CH, and SWH respectively which shows from environmental viewpoints the system with SWH is more beneficial than other systems.

Table 13 represented the EPBT and EPF on the basis of energy and exergy viewpoints. From energetic point of view the EPBT for solar stills with SWH, CH, TEH examined by around 2.59, 7.07, 7.45 while from exergetic viewpoint these values stand on 36.01, 54.52, 70.89 years respectively. Furthermore, the EPF based on the basis energy and exergy approach evaluated 0.386, 0.141, 0.134 and 0.027, 0.018, 0.014 for solar stills with SWH, TEH, and CH respectively. As it can be observed the EPBT based on energy for solar still with SWH is around half of the systems with TEH and CH which can be justified due to the high embodied energy of those systems. Thus, from energetic viewpoint the project is rational since the lifetime of the system is 20 years. However, the EPBT based on exergy is higher than 30 years. This means that from exeregtic point of view the project is not feasible. Regarding the above discussions it can be concluded that to attain the most promising results in energy-matrices the daily yield of the system should be maximized while the embodied energy should reduce as much as it possible.

Figure 6 illustrated the net NO, SO_2, CO_2 of all solar stills for different lifetime of 20 and 30 years. The Overall CO_2, SO_2 and NO emission in lifetime of 20 years for solar stills with CH, TEH, and SWH are 6342, 48.169, 18.46 kg and 6890, 52.39, 20.086 kg, and 6752, 51.28, 19.65 kg respectively. Furthermore, for lifetime of 30 years the CO_2, SO_2, and NO for solar stills with CH, TEH, and SWH are 11390, 86.55, 33.18 kg and 12237, 92.94, 35.62 kg and 10630, 80.74, 30.95 kg respectively. It is obvious that the emission of pollutions by solar stills is drastically depended on the overall productivity of the systems as well as the lifetime. In this regard, to decrease the amount of emitted pollution, solar stills should have a design to obtain higher productivity while constructed with materials that have long-lasting

Table 8. Embodied energy values for all considered solar stills systems

No	Component MJ	Materials (kW h / kg)	Energy	density	Mass of (CH) component (kg)	Mass of (TEH) component (kg)	Mass of (SWH) component (kg)	(CH)embodied energy in (kW h)	(TEH) embodied energy in (kW h)	(SWH)embodied energy in (kW h)
1	Body	Galvanized iron	50	13.88	21.1	21.1	30.12	292.8	292.8	418.06
2	Basin	Galvanized iron	50	13.88	4.4	4.4	4.4	61.07	61.07	61.07
3	Basin coating	Black paint	90	25	0.5	0.5	0.8	12.55	12.55	20.08
4	Cover	Glass	15	4.16	5.1	5.1	15.6	21.21	21.21	64.9
5	Copper wire	Copper & plastic	70.6	19.61	0.4	0.4	0.4	7.84	7.84	7.84
6	Nut and bolt	Iron	25	6.94	0.5	0.5	0.5	3.47	3.47	3.47
7	SWH Pipe	Iron	25	6.94	—	—	5.08	—	—	35.25
8	heat-sinks	Aluminum	199	55.28	0.420	0.420	0.420	23.21	23.21	23.21
9	Rubber gasket		11.83	3.28	0.6	0.6	0.6	1.96	1.96	1.96
10	Copper heater	Copper	100	27.78	0.240	—	--	6.66	—	—
11	PV module		980 kW h/m^2		2 m^2	2 m^2	--	1960	1960	—
	Total embodied energy in (kW h)							2390.77	2384.11	635.84

Table 9. Cost of fabricating solar stills

No.	Parameter	Cost per unit ($)		
		(TEH)	(SWH)	(CH)
1	Solar still body	10	10	10
2	Basin	4	4	4
3	External condenser	6	6	6
4	Photovoltaic panel	220	110	220
5	Thermoelectric	20	10	10
6	Copper heater	—	—	15
7	Solar collector	—	40	—
8	Valve	3	3	3
9	DC pump	—	10	—
10	mirror	1	1	1
11	Glue	2	2	2
12	Glass cover	2	2	2
13	Paint	1	1	1
	Total	269	199	274

endurance against adverse environmental conditions. As it can be observed, from environmental viewpoint the solar still with CH has the highest rate of CO_2, SO_2, and No reduction in all scenarios and it is followed by solar stills with SWH and TEH.

CONCLUSION

In the present study performance of three identical solar stills with external active condenser and different heating sources are examined from different thermodynamic, environment and economic point of views. The finding showed that the system with CH has the highest results in parameters that only related to the productivity of system such as the amount of CO_2, SO_2 and NO emission. Furthermore, the system with TEH has the best results in parameters that related to the energy and exergy output of the system such as exrgoeconomic, enviroeconomic, and energy-matrices. It was revealed that a huge amount of embodied energy related to the PV module which has negative effect on environmental and economic parameters. Thus using affordable materials with low embodied energy is one of the key roles to decrease the cost of produce water while maintaining the environmental benefits of the systems.

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

Table 10. Results of the cost analysis of the studied solar stills

N (yr)	i (%)	CR	PC (capital cost $)	SV ($)	FAC ($)	SSF	YSV ($)	YMC ($)	UAC ($)	Annual Yield (L/m^2)	(CPL) \$/liter/m^2
(CH)											
20	10	0.117	274	28.36	33.31	0.0175	0.4952	4.997	37.818	1865	0.0205
20	20	0.205	274	27.80	57.096	0.0053	0.1489	8.564	65.512	1865	0.0351
(TEH)											
20	10	0.117	269	27.67	32.502	0.0175	0.4831	4.875	36.894	1755	0.0213
20	20	0.205	269	27.22	55.904	0.0053	0.1458	8.385	64.144	1755	0.0365
(SWH)											
20	10	0.117	199	20.28	23.827	0.0175	0.3541	3.574	27.047	1505	0.0184
20	20	0.205	199	20.06	41.197	0.0053	0.1074	6.179	47.269	1505	0.0314
Rahbar.[48]											
10	12	0.177	181	76	32	0.0557	4.332	4.8	32.5	180	0.18
CSS with PV , Abd Elbar.[49]											
20	10	0.117	202	40.4	23.726	0.0175	0.7054	3.559	26.58	770.44	0.0345

Table 11. Exergoeconomic parameter based on energy and exergy

n (Yr)	i (%)	UAC ($)	En_{out} (KW h)	EX_{out} (KW h)	$J_{exgo,en}$ (KW h/$)	$J_{exgo,ex}$ (KW h/$)
(CH)						
20	10	37.818	319.91	33.62	8.45	0.88
20	20	65.512	319.91	33.62	4.88	0.51
(TEH)						
20	10	36.894	337.86	43.85	9.15	1.18
20	20	64.144	337.86	43.85	5.26	0.68
(SWH)						
20	10	27.047	245.47	17.65	9.07	0.65
20	20	47.269	245.47	17.65	5.19	0.37
A.R Abd Elbar.[49]						
CSS with PV						
20	4	15.736	622.88	42.964	39.194	2.703
20	8	23.002	622.88	42.964	27.078	1.868
20	10	26.843	622.88	42.964	23.204	1.6
M. S. Yousef .[31]						
With Paraffin						
30	4	12.660	79.38	5.049	6.270	0.398
30	8	20.228	79.38	5.049	3.924	0.249
30	10	24.346	79.38	5.049	3.260	0.207

Table 12. Environmental and environeconomic parameters values for both cases at n = 20 – 30 years

parameter	(CH)		(TEH)		(SWH)		M. S. Yousef.[31]		Parsa.[35]
Lifetime (years)	20	30	20	30	20	30	30	30	20
Embodied energy (kWh)	2390.77	2390.77	2384.11	2384.11	635.84	635.84	615	667.6	2244.34
Enout annual (kWh)	319.91	319.91	337.86	337.86	245.47	245.47	570.85	661.5	588.66
EXout annual (kWh)	33.62	33.62	43.85	43.85	17.65	17.65	36.52	42.075	81.60
Enout for lifetime (kWh)	6398.2	9597.3	6757.2	10135.8	4909.4	73641	17125.5	19,845	11773
EXout for lifetime (kWh)	672.4	1008.6	977	1465.5	353	529.5	1095.75	1262.25	1632.2
Environmental parameter (ton CO_2/year)	6.342	11.394	6.899	12.237	6.752	10.630	33.02	38.35	19.057
Enviroeconomic parameter CO_2 (\$/year)	91.963	165.254	100.038	177.443	97.910	154.148	478.8	556.15	276.33

Table 13. Energy payback time (EPBT) and energy production factor (EPF) for all considered systems

Parameter	(CH)	(TEH)	(SWH)	Parsa.[35]	Joshi.[32]
Annual yield (kg)	466.25	438.75	375.25	530.7	2190
Embodied energy (kWh)	2390.77	2384.11	635.84	2244.34	7824
En_{out} (kWh) annual	319.91	337.86	245.47	396.27	1482
Ex_{out} (kWh) annual	33.62	43.85	17.65	66.40	114
$EPBT_{en}$	7.45	7.07	2.59	5.66	5
$EPBT_{ex}$	70.89	54.52	36.01	33.79	68
EPF_{en}	0.134	0.141	0.386	0.176	0.2
EPF_{ex}	0.014	0.018	0.027	0.029	0.014

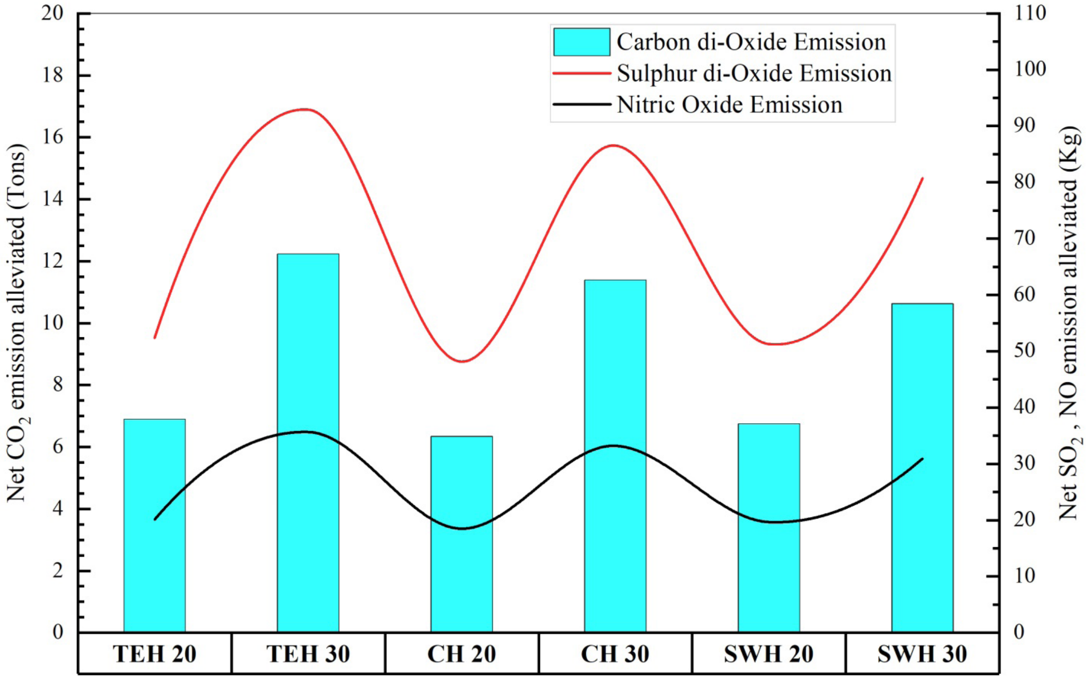

Figure 6. CO_2, SO_2, and NO emission alleviated during the lifetime of the solar stills.

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.

NOMENCLATURE

Abbreviation

A	Area (m^2)
CH	Copper Heater
CPL	Cost Per Liter ($)
CR	Capital Recovery Factor
ED	Electrodialysis
En	Energy
EPBT	Energy Payback Time (Years)
EPF	Energy Production Factor
	Exergy
FAC	First Annual Cost ($)
HDH	humidification-dehumidification
I(t)	Solar radiation intensity (W/ m^2)
LCCE	life cycle conversion efficiency
LHV	Latent heat of evaporation (J/kg)
$\dot{m}$	Amount of water distillate (kg)
MED	multi effect desalination
MENA	Middle East and North Africa
MSF	multi-stage flash
N	Number
N	Lifetime (Years)
P	Partial pressure (N/m^2)
Pm	Annual power obtained
PR	Price ($)
PV	Photovoltaic
PV/T	Photovoltaic Thermal
RO	Reverse osmosis
SV	Salvage value
SFF	Sink Fund Factor
SWH	Solar Water Heater
SS	Solar still
T	Temperature (°C)
t	Time
TEH	Thermoelectric Heating solar still
TVC	Thermal-vapor compressio
UAC	Uniform Annual Cost of the system ($)
YMC	Yearly Maintenance Cost ($)
YSV	Yearly Salvage Value ($)
zCO_2	Price of carbon in the international market ($)
$Z'CO_2$	Enviroeconomic parameter ($)

Subscripts

a	Ambient
en	Energetic
ev	Evaporative
ex	Exergetic
exgo	Exergoeconomic
g	Glass
i	Interest Rate
in	Inlet
out	Output
s	Surface
tot	Total
w	Water

Greeks Symbols

α	Absorption coefficient
η	Efficiency

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