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Techno-Economic Study of a New Hybrid Solar Desalination System for Producing Fresh Water in a Hot–Arid Climate

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Abstract: By taking advantage of the obtained experimental data, the impact of employing concentrating solar collectors, using an electric heater, and changing the water height in the basin on the performance of a hybrid solar still system was investigated. Eight different operating modes for the system were studied, while the daily freshwater production in addition to the cost per liter (*CPL*) was considered as the performance criteria. According to the results, the best height of water in the basin is 10 mm. It is the lowest examined height. Moreover, it was found that using the hybrid system with both electric heater and concentrating solar heater brings considerable improvements compared to the other investigated operating modes. For the climatic condition of Sirjan, Iran, which is where the experiments were performed, and water height in the basin of 10 mm, using the hybrid system in the active mode results in 8178 mL/m^2 of fresh water production, and a *CPL* of \$0.04270 per liter.

Keywords: solar still; concentrating solar collector; electric heater; hot–arid environment

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1. Introduction

As the main sources of life, water is the most critical international agenda [1]. During the last decades, there has been a growing demand for pure water [2]. Moreover, there has been a tendency towards using renewable energy resources in different parts of the world [3]. Those issues have encouraged scientists to develop renewable-energy driven desalination technologies [4]. Among different renewable-energy driven solutions for desalination, solar still systems are taken into account as one of the most popular ones [5]. It is because of advantages such as being easy to install and repair, and highly reliable [6].

Considering such a great popularity, solar still desalination systems have been investigated from different perspectives, including modeling, economic, ecological, and technical analyses in several works [7].

For example, Makki et al. [8] simulated the operation of a solar desalination unit in Tehran, Iran by means of a numerical approach. Moreover, considering a case study in the Tochal mountain region, Tehran, Iran, Parsa et al. [9] perused the experimental assessment on a passive type of solar desalination unit. Their results showed that the highest amount of hourly freshwater production was 500 and 720 mL per square meter for Tehran city and Touchal mountain, respectively. Predominantly, many studies focus on the impacts of basic parameters such as ambient conditions, climate type, and available systems on the purification of saline water using solar energy [10].

Sohani et al. [11] utilized experimental investigation to evaluate the enhancement potential of using side mirrors and tracking for a solar still. They found that, compared to a conventional unit, the efficiency during the considered time increased by 22.3 and 36.0% for active and passive conditions, respectively.

Hedayati-Mehdiabadi [12] presented the energy and freshwater production using active solar still equipped with a PV/T collector. They employed phase transition material to produce the drinking water at night, and their experiments were done in the winter and summer days. In addition, they illustrated a numerical method for investigating the impact of preheating on the productivity and efficiency of the system. They claimed that by increasing the mass flow rate which is heated the basin leads to increase the pure water's productivity with the system, especially at night.

Muthu Manokar et al. [13] conducted research on the performance of a solar desalination method for drinking water production by considering the influences of the height of the seawater and insulation of the basin and other equipments of the solar still system. They reported that the isolation and height of the unpureed water play an essential role in the system's performance. For better understanding, they found that increasing the deep of seawater causes decreased productivity, but there was a positive direct effect from isolation on pure water production. As a relevant result, they reported that the system's efficiency with and without isolation is 28.5 and 26.17%.

Parsa et al. [14] focused on pure water production with the aid of a single solar desalination system which is equipped with photovoltaic panels and a thermoelectric device for considering the active condition and preheating. They did their experiment at the height of 13,005 and 3871 ft, thus they reported the effect of the height on the efficiency of seawater purification.

Their result reveals that, at the highest regain, the productivity is improved in comparison with the condition at the city. Thakkar et al. [15] improved the operation of a solar still using a flash evaporator as a device for preheating the unpureed water in the basin. They claimed that the still solar system with and without employing the flash evaporator can produce pure water, at 13.95 kg and 4.29 kg per day in the spring. Hassan [16] presented a comparison study on saline water purification for active and passive solar still systems. They used a parabolic trough collector for the double and single solar systems. They performed their experiment in the summer and winter seasons. They reported that the double active solar still system in the summer has the best efficiency and productivity.

Manokar et al. [17] designed a solar still system to investigate the passive and active conditions on the purification of the seawater by considering the saline water depth in the basin. Panchal et al. [18] presented the operation of the passive and active solar desalination system during the day and at night for investigation of the exergy and economic responses. They reported that when the depth of saline water decreases, the efficiency of the system is improved. Omara et al. [19] designed a still solar system and equipped it with a reflector. They showed that the productivity of the modified system is improved by 145%.

In a resembling research work, Omara et al. [20] provided a passive solar system by a reflector to enhance drinking water productivity by nearly 57% compared to the traditional solar still. Srivastava and Agrawal [21] performed a series of experiments to investigate the influence of a porous fin in the basin of the passive system, and the addition leads to improve the efficiency of the solar still. Feilizadeh et al. [22] investigated seawater purification using passive and active conditions of a solar still system. For the active system, they employed a straight and spiral tube as water heater. They reported that the values of freshwater production of those systems were 10.22 and 15.25 kg per square meter per day, respectively. Manokar et al. [23] manufactured a solar still system to encounter India's water and energy shortage. Their experiments showed that the equipped system with the PV panel and isolation layer had the best productivity, with about 7.3 kg per day. Hourly glass and seawater, productivity and efficiency for a single slope and two single slope solar stills were performed by Rashildi et al. [24]. Their result showed that the daily total water productions for one and two slope solar stills are 3263 and 3829 cc/m^2 and costs per liter per square for them are 0.0095 and 0.0108 \$/L/m^2, respectively.

Reviewing the conducted investigation has demonstrated that one of the low-cost means of improving the productivity of solar still systems are employing a reflector [25]. Therefore, many studies reported that some materials are applicable and suitable for considering the reflector's property, some of which are steel, aluminum, and mirrors [26]. Among the listed items, the mirrors have been found as the best material that leads to the highest increase in the freshwater productivity. This point has been reported in several works, such as Kumar et al.'s [27] and Tanaka et al.'s [28] studies.

According to the literature that has been reviewed so far, in the present study, a novel configuration for a solar still in which a concentrating solar collector and electric heater are utilized are proposed. Eight cases were analyzed in which the impacts of employing concentrating solar collector, using electric heater, and height of seawater in the pan were investigated. The investigation was done by utilization of the obtained experimental data by the authors. It is worth mentioning that proposing a novel configuration has been the novelty of several research works done in the field of solar stills. The studies of Sohani et al. [11], Hedayati-Mehdiabadi [12], Parsa et al. [14], and Thakkar et al. [15] could be given as four example of such investigations.

2. Case Study

A single solar system is employed in Sirjan city at 3850 ft elevation from the sea level. Sirjan is located in the southeast of Iran. The location of this city is presented in Figure 1.

Figure 1. The location of Sirjan City on the map.

3. Experimental Setup

The experimental setup is shown in Figure 2. Considering the fact that the Middle East, especially Iran, enjoys high levels of the received solar radiation during the year [29] and in such regions, cost is very important [30], a single-stage solar still is chosen. Such a system could be solely utilized, or it could be integrated with a concentrating solar collector and an electric heater. Figure 2 demonstrates the hybrid system.

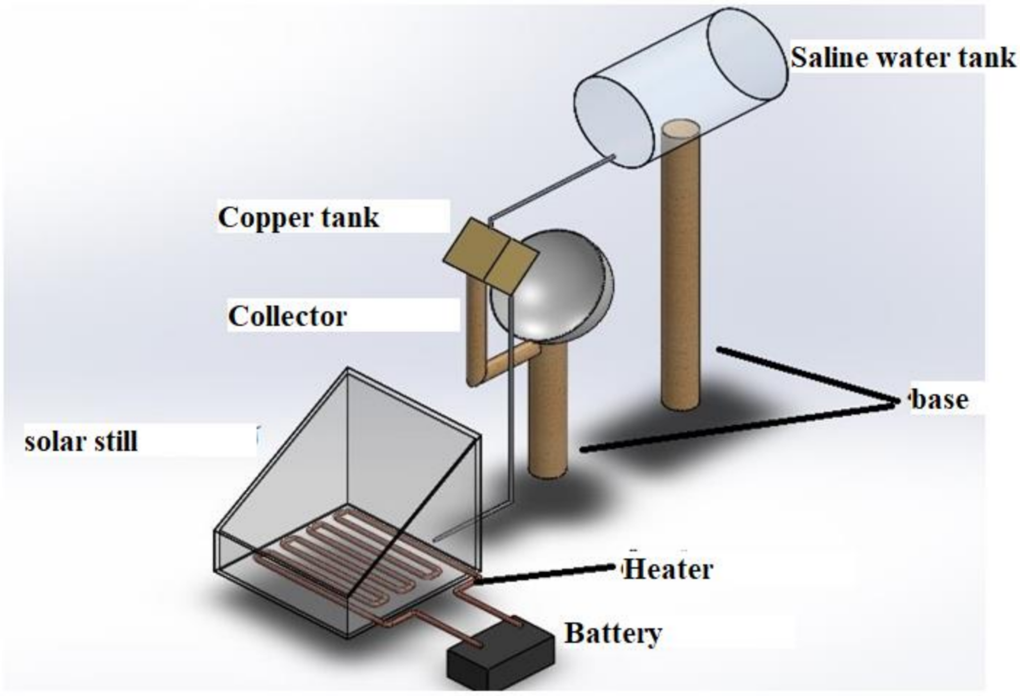

Figure 2. The experimental setup for the solar still.

As shown in Table 1, eight cases (conditions) for the experimental setup have been examined in this study. In cases 1 to 4, the solar still system is considered passive and the height of water in basin changes from 40 to 10 mm. In a similar way, for cases 5 to 8, the system is studied in the active mode and water height in the basin varies. Moreover, the system has the area of 1 m^2.

Table 1. The information of the case study tests.

Case	Date	Passive/Active	Height of Salt Water (mm)
1	8/1/2020	Passive	40
2	8/2/2020	Passive	30
3	8/3/2020	Passive	20
4	8/4/2020	Passive	10
5	8/5/2020	Active	40
6	8/6/2020	Active	30
7	8/7/2020	Active	20
8	8/8/2020	Active	10

In order to measure important parameters such as temperature, saline water flow, and fresh water volume, devices such as thermocouples, level gauges, etc., have been employed. Table 2 provides the details regarding those parameters.

In this design, a copper heater is used. Copper pipes are spirally placed on the surface of the basin. The diameter of these pipes is equivalent to 5 mm. The voltage used for the heater is supplied by a 220 V battery.

Table 2. Devices for measuring important parameters.

Measure Important Parameters	Device	Type	Error Percentage (%)
Temperature	Thermocouple	Type K	2–3
data logger	Advantech	USB-4718	5–7
Sea water level	Level controller	BTC L 500	4–5
Wind speed	Turbine wind speed	AM-4901	4–5
Solar radiation	Pyranometer	Sl100	5–6
TDS	sclerometer	HM digital	2

4. Results

Because of the critical role of the ambient conditions on the freshwater production with solar still, for eight cases, in Figures 3 and 4, and in Tables 3 and 4, the variation of the solar radiation, ambient temperature, and wind velocity are reported.

Table 3. Ambient temperature for eight cases.

Time	Ambient Temperature (°C)							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
6	20	24	23	24	23	22	21	23
7	25	29	28	29	28	27	26	28
8	26	33	32	33	32	28	30	32
9	30	35	32	35	34	32	32	32
10	35	39	37	39	38	37	36	37
11	38	42	40	42	41	40	39	40
12	37	43	39	42	42	39	39	39
13	35	44	37	43	43	37	40	37
14	30	40	40	39	39	32	36	40
15	28	35	39	34	34	30	31	35
16	27	38	34	37	37	29	34	38
17	25	36	37	35	35	27	32	36
18	24	35	35	34	34	26	31	35
19	23	29	34	28	28	25	25	29
20	20	28	28	27	27	22	24	28

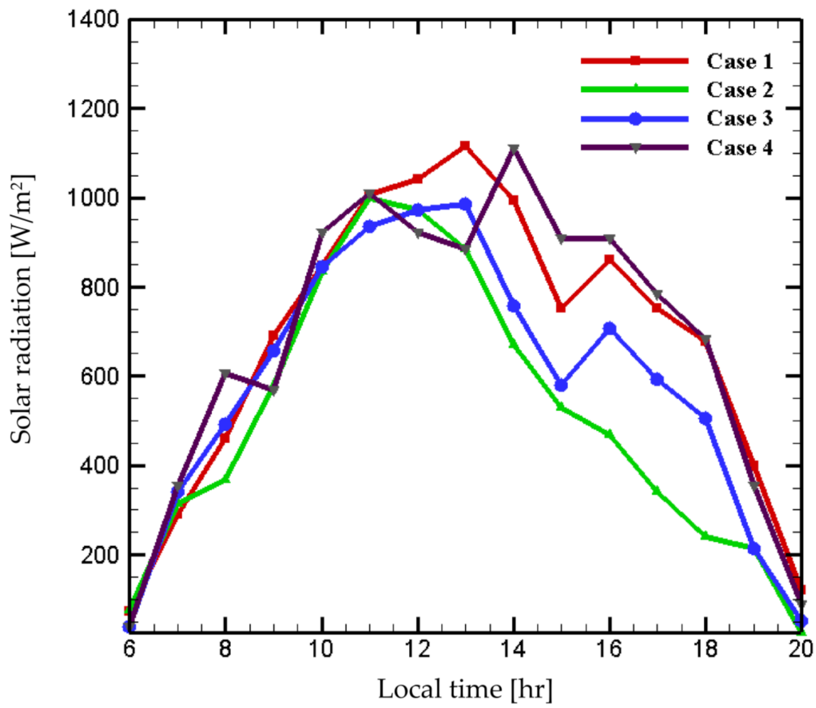

Figure 3. Solar radiation for 4 cases (1 to 4) during the day time.

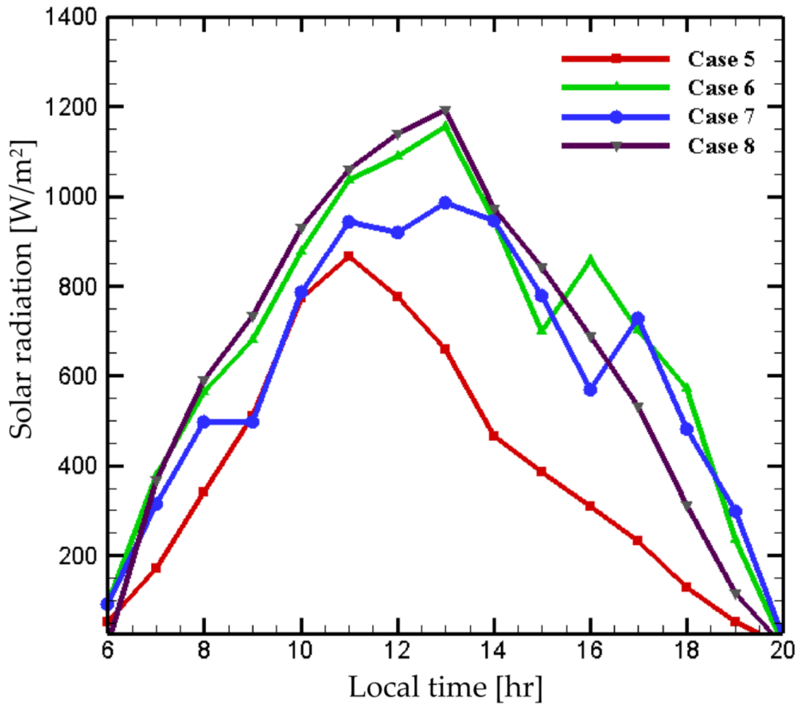

Figure 4. Solar radiation for 4 cases (5 to 8) during the day time.

Table 4. Wind velocity for eight cases.

Time	Wind Speed (m/s)							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
6	2.2	0.1	0.3	0.2	0.4	1.8	1.5	0.9
7	0.7	0.1	1.2	1.1	0.8	1.7	1.6	0.9
8	1.9	0.7	0.9	1.5	0.4	1.4	1.3	0.6
9	1.3	0.1	0.4	1.5	0.6	1.3	1.5	0.8
10	1.5	0.8	1.8	0.6	0	1.2	1.4	0.6
11	0.8	0.6	1.1	0.7	0.6	1.2	1.1	1
12	0.3	0.5	1.7	0.3	0	1.4	1.4	1
13	2.2	0.1	0.3	0.2	0.4	1.8	1.5	0.9
14	2.4	0	2.4	0.2	0.4	1.2	1.2	0.8
15	1.1	0.3	0.3	0.7	0	1.1	1.9	0.6
16	1.4	0.5	2.6	0.2	0	1.3	1.5	0.8
17	0.8	0.3	2.8	0.5	0	1.5	1.2	1.4
18	3.5	2	1.3	0.4	0.4	1.5	1.9	0.6
19	4	0.8	0.2	1.8	0.8	1.4	1.6	1.2
20	1.2	1.5	0.2	0.8	0.6	1.3	1	0.6

Figure 5 shows the impact of the height of the saline water in the basin on the freshwater production of the system. Four levels of sea water, 10, 20, 30, and 40 mm, are considered. As shown in Figure 5, by increasing the amount of saline water in the basin of the solar still system, the productivity is decreased exponentially. The reason is that a higher mass of water absorbs the heat, which means less temperature increase. The lesser increase in the temperature of water in the basin is accompanied by a reduction in the water evaporation, and consequently, in the yield. Based on the obtained results, the fresh water productivity for the cases 1 and 4 with the see water height of 40 and 10 mm are 3292 and 4089 gr/m^2, respectively.

As indicated, the reason for such a behavior is that the smaller thickness the water in basin has, the greater amount of energy the mass of water could be absorbed. The more heat water in the basin is absorbed, the higher the evaporation is, and as a result, freshwater production is seen. Additionally, according to Figure 6, for the corresponding active cases, i.e., 5 and 8, the impact of height is much greater, where the yield is equal to 6419 and 8178 gr/m^2 (mL/m^2), respectively.

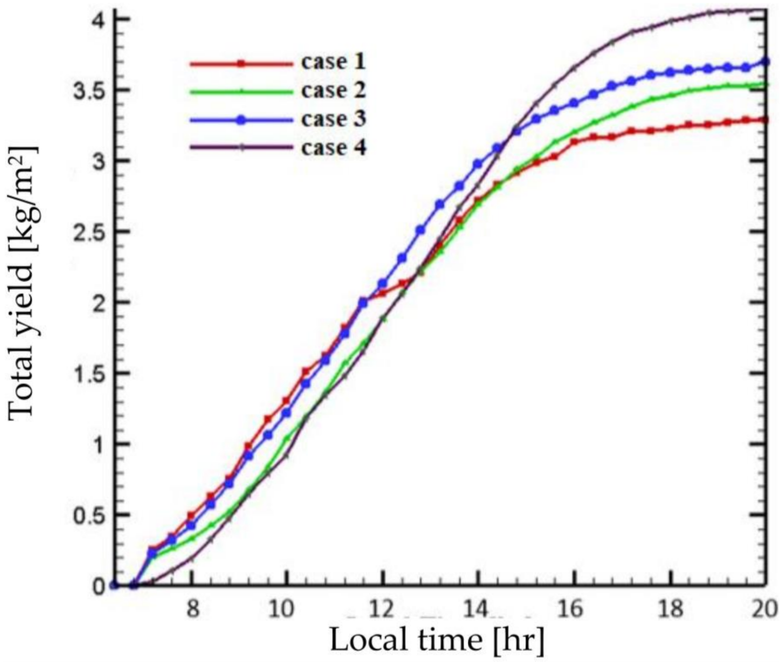

Figure 5. The total freshwater production for cases 1–4.

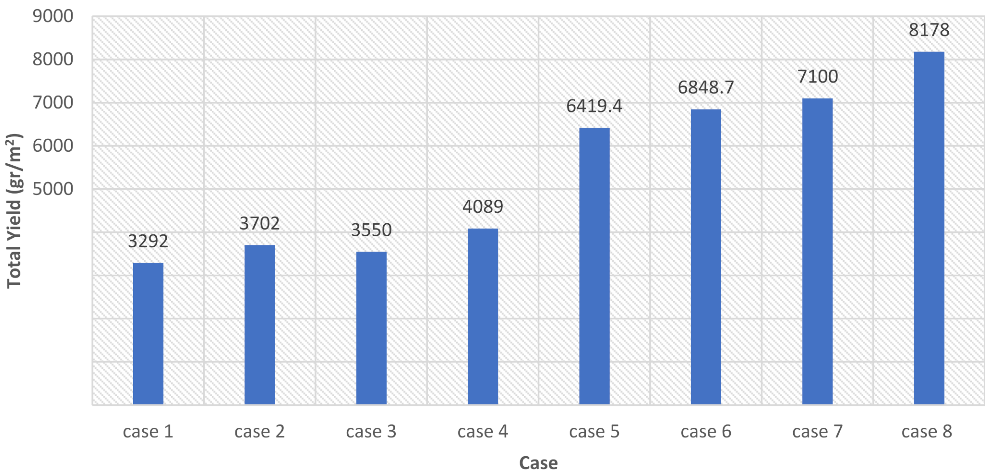

Figure 6. The total freshwater production for all the investigated cases.

In addition to finding the effects of height on the system yield, an economic analysis was also carried out. For this purpose, initially, some required data and equations were introduced, and subsequently, the achieved results were obtained and are provided.

Table 5 provides the required information to calculate the initial cost.

Based on the provided information in Table 4, the initial cost of the active solar desalination system is \$213. The initial (capital) cost for the passive system is also equal to \$108. As seen in this table, in the present work, in order to determine the initial cost, the whole used materials and components, as well as the manufacturing cost of the solar still are taken into account. It covers the channel, body (polycarbonate), pipes, basement, isolation layers, flat plate solar collector, water reservoir, pump, glass, etc. Furthermore, the maintenance costs, annual salvage values, sinking fund factor, and interest rate per year are considered in the computation process.

Table 5. The required information to calculate the initial cost.

No.	Devises	Cost ($)
1	40 liter water source	5
2	20 liter salt water source	10
3	Copper cube box	15
4	1 meter steel base	20
5	Desalinate for water	10
6	Faucet	5
7	Tarpaulin fabric and insulation	25
8	Half tube for collecting fresh water	3
9	Concentrating solar collector with insulation equipment	75
10	1 inch tube	10
11	Galvanized iron sheet and painting	10
12	Glass	15
13	glass wool	10
Total cost of an active solar still		213

The capital recovery factor (*CRF*), which is a required parameter for the economic calculations, is computed in terms of the interest per year (i), the lifetime of the systems (n), and the costs in the first year of system operation (*FAC*), as in Equations (1) and (2) [30]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{1}$$

$$FAC = P(CRF) \tag{2}$$

where the initial cost of the system is shown by P. It should be mentioned that the values of 14% and 12% are assumed for the interest (i) and lifetime (n), respectively [31]. Moreover, the salvage value (S) is taken as one-fifth of P [32]:

$$S = 0.2P \tag{3}$$

The annual salvage value and Sinking fund factor are also found based on Equations (4) and (5), respectively [33]:

$$SSF = \frac{i}{(1+i)^n - 1} \tag{4}$$

$$ASF = (SSF)S \tag{5}$$

In addition, the annual maintenance cost is assumed as 15% of FAC [34]:

$$AMC = 0.15(FAC) \tag{6}$$

Consequently, the annual cost (AC) could be determined [35]:

$$AC = FAC + AMC - ASV \tag{7}$$

Having determined AC, the cost imposed to produce one liter of freshwater (CPL) can be calculated as [36]:

$$CPL = \frac{AC}{VOL_{fresh\ water}} \tag{8}$$

Table 6 demonstrates that, generally, because of the production of a higher amount of freshwater, the cases with active operation have a better CPL, even though they are more expensive. Case 8 enjoys the highest *CPL*, in which this parameter is equal to \$0.04270 for each liter. Among the cases with passive condition, the best *CPL* is seen for case 1. It offers a *CPL* of \$0.05494 per liter.

Table 6. The details of economic calculations.

No.	*CRF*	*FAC*	*SSF*	*ASV*	*AMC*	*AC*	*M* (mL/m^2)	*CPL* (\$/L)
Case 1	0.176669	19.1392	0.036669	0.794502	2.870877	21.21555	3292	0.05494
Case 2	0.176669	26.5004	0.036669	1.10008	3.97506	29.37538	3702	0.06221
Case 3	0.176669	22.8198	0.036669	0.947291	3.422968	25.29547	3550	0.05997
Case 4	0.176669	30.1810	0.036669	1.252869	4.527152	33.45529	4089	0.06025
Case 5	0.176669	55.9453	0.036669	2.322391	8.391793	62.01469	6419	0.04432
Case 6	0.176669	63.3065	0.036669	2.627968	9.495976	70.17452	6848	0.04352
Case 7	0.176669	59.6259	0.036669	2.47518	8.943885	66.0946	7100	0.04378
Case 8	0.176669	66.9871	0.036669	2.780757	10.04807	74.25443	8178	0.04270

5. Conclusions

The results of this study demonstrated the high improvement potential of using concentrating solar collector and electric heater together to enhance the performance of a solar still desalination system. In addition, it was found that by adjusting the water height in the basin in the minimum level for that hybrid desalination unit, the highest evaporation, and as a result, the highest freshwater production took place. Therefore, using the proposed hybrid water desalination technology in which the water in the basin has the lowest height is recommended. The gathered experimental data for Sirjan, Iran, demonstrated that in that condition (case 8), the yield of 8178 mL/m^2 was achieved, while *CPL* had a value of \$0.04270 per liter. As observed, both values are much better than the base case (case 1), i.e., 3292 mL/m^2 and \$0.05494 per liter. Two items could be figured out as the significance of this work:

One is finding the point that running a solar still at the lowest possible height will result in much more productivity than higher water levels. This could be considered as a good rule of thumb for better operation of solar stills.

Another item is that the amounts of added cost and fresh water production due to the system modification are in a way that *CPL* goes down. Therefore, a more economically justifiable system than the conventional solar still is achieved when concentrating solar collector and electric heater are utilized together. It introduces the proposed system as a good item from a techno-economic perspective in the market.

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