Experimental analysis of innovative designs for solar still desalination technologies; An in-depth technical and economic assessment

Ali Sohani[a], Siamak Hoseinzadeh[b],* and Kiana Berenjkar[a]

[a]Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran
[b]Centre for Asset Integrity Management, Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, 0081, South Africa

Emails:
Ali Sohani. alisohany@yahoo.com; asohani@mail.kntu.ac.ir
*Corresponding author. Siamak Hoseinzadeh. hosseinzadeh.siamak@up.ac.za

Kiana Berenjkar. kianaberenjkar@gmail.com

Highlights

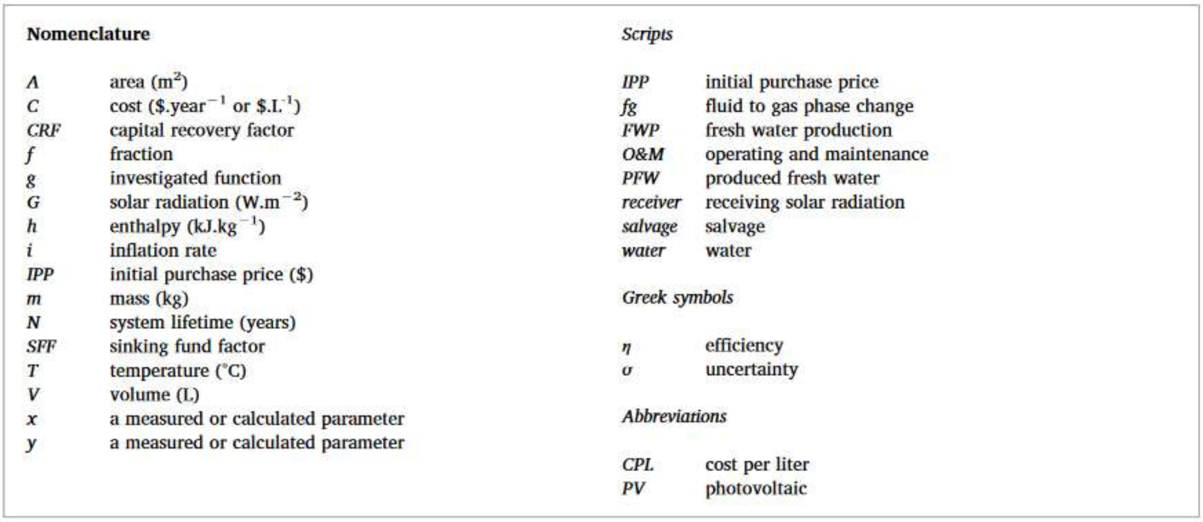
- Water temperature at peak jumps 7.6°C by using side mirrors and sun tracking in passive mode.
- Applying sun tracking and side mirrors leads to 34.3% more distillate at peak in active mode.
- The maximum daily water yield is enhanced 43.1 and 22.2% in passive and active modes.
- 36.0 and 22.3% better daily efficiency are achieved for passive and active operation.
- The enhanced systems in passive and active modes have cost of 0.0319 and 0.0225 $\$.L^{-1}$.

Abstract

Impact of using side mirrors and sun tracking on enhancing the performance of a solar still in both passive and active modes is investigated in details by employing the recorded experimental data. The conventional system, using each improvement strategy individually, and the combination of both strategies together are studied, which leads to having four cases in each mode, and eight cases in total. The eight different cases are compared together from different aspects, including, hourly water temperature in the basin, hourly fresh water production, hourly cumulative yield, daily produced distillate, daily efficiency, and cost per liter. Based on the results, all the investigated performance criteria are improved when sun tracking and side mirrors are employed. For example, by employing both improvement strategies together, the peak temperature of water in the basin goes up by 7.6°C in the passive mode, and the maximum fresh water production increases by 34.3% in the active operation. Moreover, it leads to 43.1 and 22.2% growth in the daily water production, and 36.0 and 22.3% increase in the daily efficiency of the passive and active modes, respectively. Using the combination of sun tracking and side mirrors also imposes the cost per liter of 0.0225 $\$.L^{-1}$ for active operation. It is much lower than the corresponding value in the conventional system.

Keywords: Desalination technology; Economic analysis; Side mirrors; Solar tracker; Solar still; Technical assessment

Nomenclature



Nomenclature

A	area (m^2)
C	cost ($\$$.year^{-1} or $\$$.L^{-1})
CRF	capital recovery factor
f	fraction
g	investigated function
G	solar radiation (W.m^{-2})
h	enthalpy (kJ.kg^{-1})
i	inflation rate
IPP	initial purchase price ($\$$)
m	mass (kg)
N	system lifetime (years)
SFF	sinking fund factor
T	temperature (°C)
V	volume (L)
x	a measured or calculated parameter
y	a measured or calculated parameter

Scripts

IPP	initial purchase price
fg	fluid to gas phase change
FWP	fresh water production
O&M	operating and maintenance
PFW	produced fresh water
receiver	receiving solar radiation
salvage	salvage
water	water

Greek symbols

η	efficiency
σ	uncertainty

Abbreviations

CPL	cost per liter
PV	photovoltaic

1. Introduction

The world population is increasing with a fast speed during the past years. Taking a look at the statistics shows that it reached from 6.143 in 2000 to 7.795 billion people in 2020, which shows the huge increase rate of 26.9% in the period [1].

The growing number of people who are living on the Earth in addition to the significant rising in the standard of living has led to increase in demands for potable water more and more [2], [3], [4], [5]. However, the current growth in the supply is not able to cover the increase in the demand [6], [7], [8], [9]. This point, beside the fact that there are energy crises all around the world have encouraged researchers to develop more efficient desalination technologies, especially the ones which run with renewable energy resources [10], [11], [12], [13].

Among different alternatives as the renewable energy source in a desalination system, solar energy is the most common one [14,15]. The advantages such as higher power density and reliability, as well as lower level of noise compared to other alternatives have made solar energy as the most popular kind of renewable energy [16], [17], [18], [19], and a lot of countries have huge future investment plans for developing their solar energy facilities [20], [21], [22], [23].

One of the cheapest and most energy-efficient ways to remove salts from the impure water by means of solar energy is using solar stills. In a solar still, the radiation from the sun is received, and the received solar radiation provides enough energy for evaporation of a part of the salty water in the basin. The evaporated water moves and it is gathered on the top of the basin. Then, the gathered vapor loses its energy and returns to the liquid phase with this difference now, it is not salty.

Table 1 presents a list of the recent investigations done in the field of solar stills. As observed, in the performed investigations, different components have been used to enhance the productivity of the system. For example, one of the most frequent ones, especially during the last years is photovoltaic (PV) panels or modules. photovoltaic modules have been usually employed in solar still desalination technologies to produce the required electricity of the parts like fans, pumps, and so on. Another popular component is the flat plate solar collector, which has been used to increase the temperature of water in the solar still.

In addition to the studies introduced in Table 1, in another study in the field, Patel et al. [43] conducted experiments in a six month period to evaluate the performance of a triple basin solar still desalination system in which corrugated sheets, evacuated type of heat pipes, and sensible thermal storage substances were used. The authors found that the temperature for the combination of conventional triple basin solar still, evacuated heat pipes, and granite gravel was almost 10°C higher than the stand-alone system.

Moreover, the potential of taking the advantage of calcium stones as the thermal storage system and evacuated tubes to increase the fresh water production in a solar still was investigated by Panchal et al. [44]. The results of that study demonstrated that the average fresh water production was improved by 113.52% when both enhancement ways were applied at the same time.

In another investigation, Essa et al. [45] proposed a solar still desalination technology in which rotating discs were employed to decrease thickness of the impure water and increase evaporation rate. A parametric study was also conducted to find the best rotational speed of discs, which showed that in most of the cases, the foremost operation was seen in the values of 0.05 and 0.1 rpm.

Moreover, a new design for solar still, which was called trays solar still, was presented and experimentally examined by Abdullah et al. [46]. In that study, it was found that employing the new design in combination of mirrors in the top led to enhance the distillate production by 58% compared to the conventional system.

Additionally, in another investigation, Patel et al. [47] introduced a machine for extracting the moisture from the ambient air and assessed the system performance under diverse climatic conditions. The ranges between 0.75 and 4.71 kW per liter and 0.28 and 1.78 liter per hour for specific energy consumption and yield were observed, respectively.

Panchal [48] also considered a double basin solar still desalination system and examined different thermal storage substances in upper basin to improve the performance of that. The measured experimental data was employed for enhancement evaluation, which showed 229.2% growth in the fresh water production compared to the base system. A review paper was also provided by Panchal et al. [49], as well, in which using the thermoelectric-based systems for desalination of groundwater was investigated.

Based on Table 1, as well as other reviewed studies, it is found that valuable studies have been done so far, and different ways to enhance the performance of the solar still desalination system have been examined. However, to best of the Authors' knowledge, some methods for improving the performance have not been investigated and their potential has not been evaluated yet. Two items which seem to have a huge enhancement potential are:

- **Employing Sun tracking technique:** When solar still rotates and it tracks the sun, the possibility of receiving a higher amount of solar irradiation, and consequently, more fresh water production is provided.
- **Using side mirrors:** A lower level of the received energy from the sun is absorbed using side mirrors in a solar still. It also acts as an insulation.

Therefore, the current study is done with the following objectives:

- Design and fabrication of a solar still desalination system in which sun tracking and side mirrors strategies were employed to enhance the performance.
- Testing the performance of the solar still desalination system when the improvement strategies were used in both active and passive modes and recording experimental data.
- Comprehensive technical evaluation of the improvement scenarios by considering the profiles for hourly water temperature in the basin, the hourly fresh water production, and the hourly cumulative yield, as well as the daily produced distillate and the daily efficiency , as the key performance indicators of a solar still desalination system.
- Economic assessment of different cases based on the cost per liter of fresh water.
- In this paper, after presentation of the introduction, which has been done, the methodology is given. Then, the results are presented and discussion about them is carried out. Finally, the most remarkable findings are introduced as the conclusions.

2. Methodology

The methodology employed in this investigation to obtain results are described here.

2.1. Experimental setup

The experiments are done on a single solar still, which is schematically depicted in Fig. 1, in Tehran, Iran, which is located in 51.4 degrees E, 35.7 degrees N.

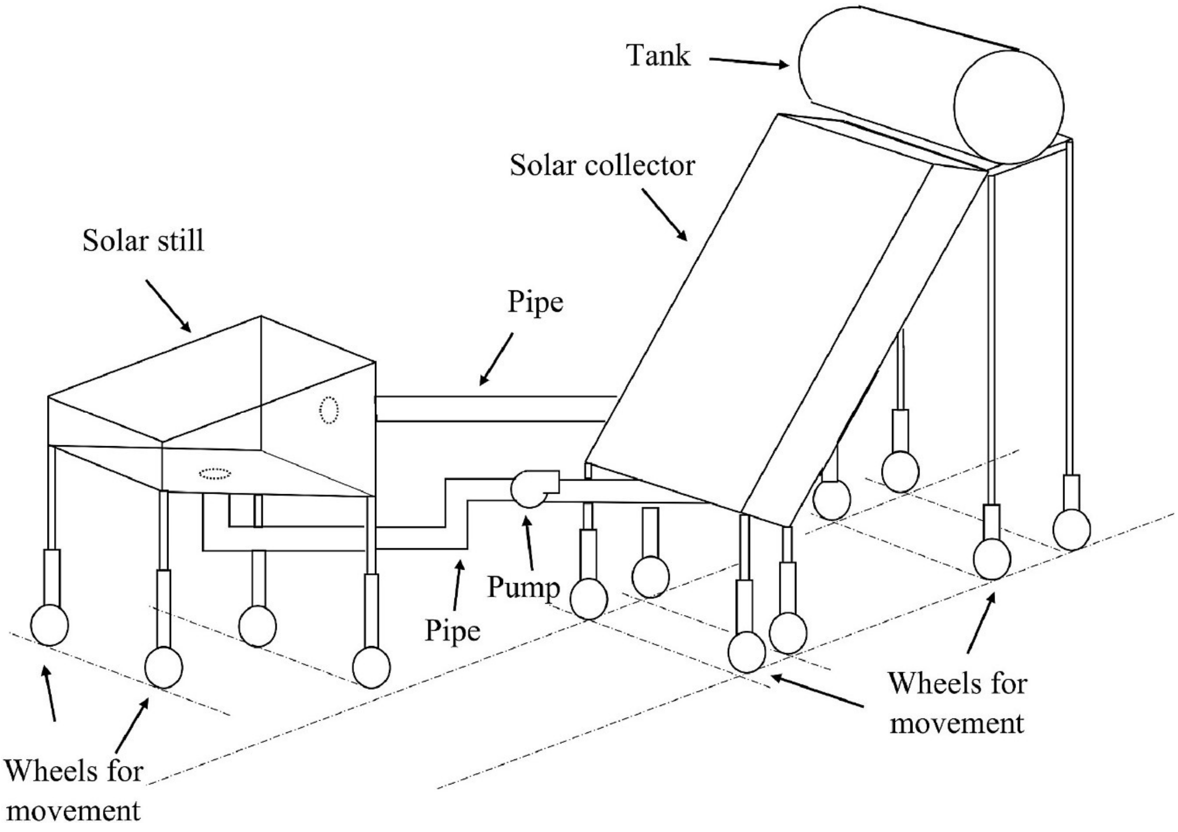
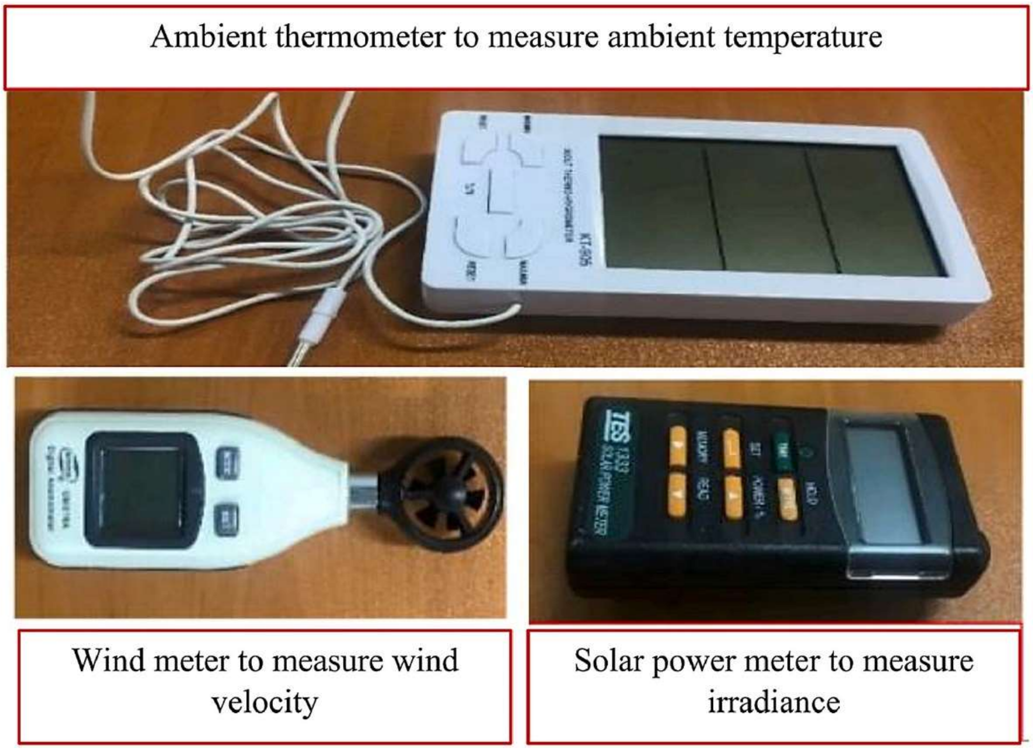


Fig. 1. Schematic of the investigated experimental setup for solar still.

Fig. 2 also shows some of the measurement devices employed to record data from the performance of the solar still. As seen in Fig. 1, the experimental setup is composed of a solar still and a flat plate solar collector. The two mentioned parts are connected together by pipeline. In addition, for operation of the system in the active condition, a pump is also considered, which gives enough energy from the network grid in the experiments. Moreover, there are two reservoirs, one for the salty water, which is connected to the solar still and another for water above the solar collector. There is a place for accumulation of the fresh water, as well.


Ambient thermometer to measure ambient temperature

Wind meter to measure wind velocity

Solar power meter to measure irradiance

Fig. 2. Some of the measurement devices employed to record data from the performance of the solar still.

The bottom of the solar still is painted black, which leads to absorbing a higher level of solar radiation. The solar still has the area of 1.4 m^2, and consists of glass, basin, isolation cover, polycarbonate box, and the fresh water collection half pipe. Additionally, the 3 m^2 flat plate solar collector is covered with glass wool insulator and the pipes in the heat transfer circuit from the steel pipe, which provides the possibility of both a long life-time and high level of heat transfer rate.

The experiments were done on eight different days. Having the similar fashion as the studies like [28, 31, 34], the experiments were done on an hourly basis. It is an acceptable time resolution to report data for solar stills. On each day, the operation of system, and consequently, data recording, starts at 8:00 and finishes ten hours later, i.e., at 18:00. In order to obtain each set of experimental data, measuring is done six times with ten seconds intervals, and the average value is reported. The description of the conducted experiments is presented in Table 2.

Table 2. Description of the conducted experiments.

Case	Date	Passive/Active	Using side mirrors/Not using side mirrors	Using sun tracking/Not using sun tracking
Case 1	Sep 1, 2019	Passive	Not using side mirrors	Not using sun tracking
Case 2	Sep 2, 2019	Passive	Not using side mirrors	Using sun tracking
Case 3	Sep 3, 2019	Passive	Using side mirrors	Not using sun tracking
Case 4	Sep 4, 2019	Passive	Using side mirrors	Using sun tracking
Case 5	Sep 6, 2019	Active	Not using side mirrors	Not using sun tracking
Case 6	Sep 7, 2019	Active	Not using side mirrors	Using sun tracking
Case 7	Sep 8, 2019	Active	Using side mirrors	Not using sun tracking
Case 8	Sep 9, 2019	Active	Using side mirrors	Using sun tracking

The devices introduced in Table 3 were employed for measurement. The recorded values of the weather characteristics, including ambient temperature, solar radiation, and wind velocity are reported in the results and discussion part of the paper, i.e., Section 3.

Table 3. Introducing the devices employed to measure the experimental data.

Devises	The measured parameter	Range	Uncertainty
K-type Thermocouple	water temperature in the basin	0-1000°C	± 0.6°C
Ambient thermometer	ambient temperature	0-80°C	± 0.1°C
Solar power meter	solar irradiation	0-2000 $W.m^{-2}$	± 10 $W.m^{-2}$
Wind meter	wind velocity	0-10 $m.s^{-1}$	± 0.2 $m.s^{-1}$
Graduated cylinder	fresh water production	0–2000 mL	± 5 mL

It is worth mentioning that as observed in Fig. 1, the solar still and flat plate solar collector were installed on the wheels, and the wheels are connected to the solar still by rods. The rods are built in a way that the length of them can be changed. By changing the length of the rod, the distance between the wheels and basin or collector, and consequently, the slope changes. In addition, the wheels can be also employed to rotate the solar basin and collector around N-S axis.

2.2. Calculated parameters

By obtaining the measured parameters from the experiments, they can be employed to determine the values of some other indicators based on the calculations, which are called calculated parameters here. This part provides a brief description about the way to calculate them. In addition, the details about the economic analysis and calculating the economic and technoeconomic criteria are also provided in this part.

2.2.1. Technical parameters

Efficiency of the solar still (η) is taken into account as the most important dimensionless technical parameter of that. Efficiency of a solar still is determined from Eq. (1) [29]:

$$\eta = \frac{m_{PFW} h_{fg,water}}{A_{receiver} G} \tag{1}$$

where m_{PFW} is the mass of the produced fresh water, and G is the received solar radiation. $h_{fg, water}$ also represents the required heat of vaporization of water for changing phase from liquid to gas. $h_{fg, water}$ is dependent on the temperature of water, as Eq. (2) shows [50]:

$$h_{fg,water} = h_{g,water} - h_{f,water} = (2501.3 + 1.82T_{water}) - 4.196T_{water} = 2501.3 - 2.376T_{water} \tag{2}$$

Moreover, $A_{receiver}$ in Eq. (1) denotes the area which receives solar radiation. In the passive mode, $A_{receiver}$ only comes from the solar still. However, for an active solar still, the area of preheating collector should be also considered to calculate the efficiency. In addition, as another important notification, it should be noted that based on the definition and given parameters as the input of Eq. (2), the efficiency can be calculated hourly or daily basis. In this study, the latter, i.e., daily efficiency is employed.

2.2.2. Economic parameters

The annualized cost of the solar still desalination system (C_{system}) is obtained from Eq. (3):

$$C_{system} = C_{IPP} + C_{O\&M} - C_{salvage} \tag{3}$$

In Eq. (3), C_{IPP} denotes the annualized cost imposed from buying the system at the beginning of the time, which is determined by Eq. (4) [31]:

$$C_{IPP} = CRF \times IPP \tag{4}$$

IPP is the initial purchase price of the system. *IPP* is calculated based on the information found in Table 4. In addition, *CRF*is the cost recovery factor by which the lumped payment of *IPP* becomes annualized. When the system life-time (*N*) and inflation rate (*i*) are available, *CRF* can be determined from Eq. (5) [51]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} = \frac{i}{1-\left(\frac{1}{1+i}\right)^N} \tag{5}$$

Table 4. Cost of components which are used to calculate the initial purchase price of the system; the values are obtained based on the inquiry from local providers in Iran.

Devises	**Cost ($)**
Solar collector (the flat plate type)	172.93
Water tank	29.77
Pipes	7.19
Wheels and rods	7.46
Isolation layers	12.19
Polycarbonate body	75.38
Channel	19.86
Glass	8.42
Pump	22.24
Other parts	19.22

For a solar still desalination system *N* can be considered 15 years [31] while based on the information of [52], the value of 5% for *i* is taken.

in Eq. (3) is also the operating and maintenance cost. In general, in all the energy systems like solar stills, is assumed to be a fraction of C_{IPP}. Therefore [31]:

$$C_{O\&M} = f_{O\&M} \times C_{IPP} \tag{6}$$

Following the same fashion as the studies in the literature, including [31], $f_{o\&M}$ is chosen 15%.

The income gained by selling the components which have the potential of the further usage at the end of lifespan is indicated by $C_{salvage}$. Similar to $C_{O\&M}$, $C_{salvage}$ is also considered to be a fraction of C_{IPP} [53], this time 20% of that. As result, and knowing the fact that $C_{salvage}$ will be paid at the end of lifespan, it is computed from Eq. (7) [31]:

$$C_{salvage} = f_{salvage} \times C_{IPP} \times SFF \tag{7}$$

where *SFF* is the sinking fund factor, which is determined via Eq. (8) [31]:

$$SFF = \frac{i}{(1+i)^{N} - 1} \tag{8}$$

2.2.3. Techno-economic parameters

In order to provide a fair comparison with the previously published research items on solar stills, the same criterion as them is taken into account as the investigated techno-economic parameter. The fresh water production cost (C_{FWP}), which is defined by Eq. (9), is chosen. C_{FWP} is the most frequent reported techno-economic parameter for a solar still, and several studies like [31,34] used the concept of C_{FWP}.

$$C_{FWP} = \frac{C_{system}}{V_{PFW}} \tag{9}$$

In Eq. (9), V_{FWP} stands for the volume of the produced fresh water. V_{FWP} during a year is calculated based on the obtained daily experimental data and by following the same fashion of the references like [34]. C_{system} is the imposed cost of the desalination system, as well. The way to calculate C_{system} has been presented in Section 2.2.2.

2.3. Uncertainty analysis

Conducting uncertainly analysis has to be done in each experimental work to guarantee the accuracy and correctness of the recorded data. In other words, the reported data in each experimental work is valid only when the uncertainty of the data recording stands in an acceptable level [54].

In order to conduct the uncertainty analysis, similar to the studies like [54], for the parameters measured directly the reported values in their catalogues of the measurement devices are used while the propagation of uncertainty rule is employed for the ones which are calculated based on the directly measured data. According to the propagation of uncertainty rule, when the parameter g is calculated based on the parameters x and y, which are measured directly or calculated, the uncertainty of g, which is shown by σ_g, could be obtained from Eq. (10) [55]:

$$\sigma_g = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial g}{\partial y}\right)^2 \sigma_y^2} \tag{10}$$

where σ_x and σ_y are the known values of the uncertainty of the directly measured or calculated parameters of x and y, respectively. $\left(\frac{\partial g}{\partial x}\right)$ and $\left(\frac{\partial g}{\partial y}\right)$ also represent the partial derivative of the function g with respect to x and y, respectively.

3. Results and discussion

Here, the results of the study are given and the discussion about them is carried out. Initially, the recorded data for the weather characteristics, including the ambient temperature, wind velocity, and solar radiation, as well as the performance criteria such as produced fresh water, are presented in part 3.1. Then, in section 3.2, the hourly profiles of key performance criteria for the eight investigated modes are plotted and analyzed and after that, the eight different modes are compared together from the daily fresh water production, cost per liter (*CPL*), and daily efficiency perspectives, as well. Finally, the uncertainty values for the directly measured and calculated parameters are reported in part 3.3.

3.1. The recorded experimental data

The hourly values of ambient temperature, solar radiation, wind velocity, and fresh water production for eight different cases are reported in Table 5a, Table 5b, Table 5c, and Table 5d, respectively.. Moreover, Table 5e provides the hourly values of water temperature in the basin recorded during the experiments. For providing a clear presentation, the values of ambient temperature and received solar radiation for each day are also depicted as the hourly profiles in Fig. 3 and Fig. 4, respectively.

Table 5a. The values of ambient temperature for eight different investigated cases; the unit of the reported values are °C.

Hour	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
8:00	25	25	23	22	24	25	23	18
9:00	25	26	24	24	26	29	25	20
10:00	26	27	27	25	28	29	26	23
11:00	28	28	29	26	29	30	28	24
12:00	29	29	29	28	30	31	29	25
13:00	29	31	30	29	30	31	29	26
14:00	30	31	31	30	31	32	31	27
15:00	31	32	33	30	31	33	31	28
16:00	31	32	34	30	32	33	31	29
17:00	32	32	33	30	33	33	31	28
18:00	32	32	33	30	32	33	31	28

Table 5b. The values of solar radiation for eight different investigated cases; the unit of the reported values are W.m^{-2}.

Hour	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
8:00	279.8	277.9	276.3	274.4	270.7	268.8	266.8	264.9
9:00	456.7	455.3	453.3	451.5	447.7	445.8	443.8	442.0
10:00	623.1	621.2	619.5	617.6	614.0	612.0	610.2	608.2
11:00	753.3	751.5	749.5	747.7	743.4	741.8	739.8	737.5
12:00	826.5	824.6	822.4	820.1	815.7	813.6	811.4	808.9
13:00	830.8	828.4	825.9	823.4	818.0	815.4	812.7	809.8
14:00	765.4	762.5	759.4	756.4	750.1	747.0	743.9	740.4
15:00	641.0	637.5	634.0	630.7	623.6	619.9	616.0	612.4
16:00	477.9	474.5	470.7	466.9	459.0	454.9	451.2	447.0
17:00	301.2	297.4	293.3	289.6	281.8	278.0	273.8	270.1
18:00	134.4	130.9	276.3	274.4	270.7	268.8	266.8	264.9

Table 5c. The values of wind velocity for eight different investigated cases; the unit of the reported values are m.s^{-1}.

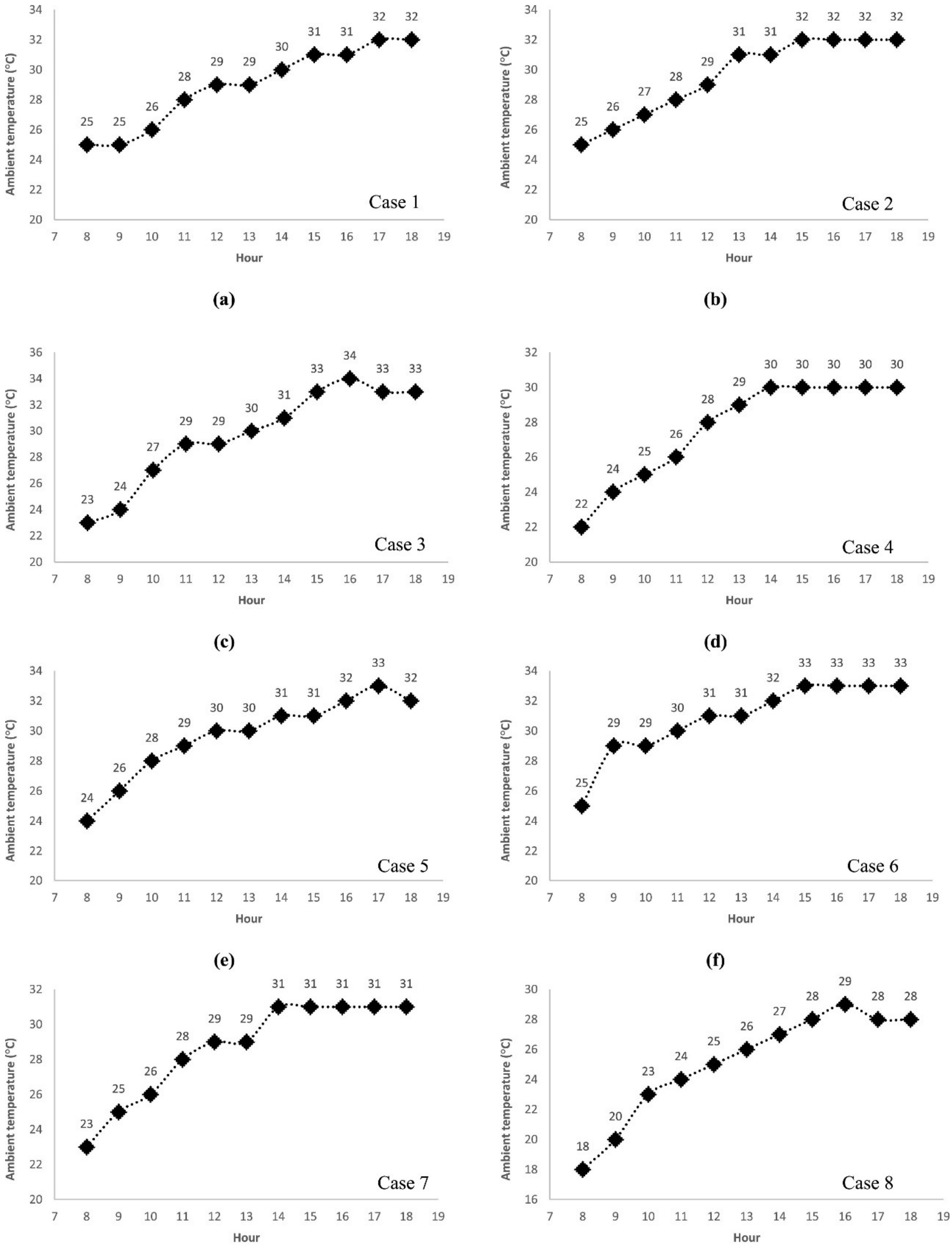
Hour	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
8:00	0.0	1.0	1.5	1.0	1.0	1.0	2.1	1.0
9:00	1.0	2.1	2.1	1.5	1.0	0.0	2.1	2.1
10:00	2.1	1.0	1.0	2.1	1.0	1.5	2.6	1.5
11:00	2.1	2.6	1.0	2.1	2.1	2.1	2.1	1.5
12:00	2.1	2.1	2.1	1.5	2.1	2.1	2.6	1.5
13:00	3.1	2.1	3.1	1.0	2.1	2.6	1.0	1.5
14:00	2.6	3.1	3.6	2.6	2.6	2.6	1.5	1.0
15:00	2.6	2.1	3.1	1.5	2.1	2.6	1.0	1.0
16:00	1.5	1.5	4.6	2.1	1.5	0.0	1.5	1.0
17:00	1.0	2.1	3.6	1.0	1.0	2.1	2.1	2.1
18:00	2.1	1.0	5.1	1.5	1.5	1.5	3.6	2.6

Table 5d. The values of the fresh water production for eight different investigated cases; the unit of the reported values are mL.

Hour	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
8:00	1.7	2.1	1.8	2.4	6.1	6.7	6.5	7.5
9:00	16.9	21.3	33.4	44.2	190.9	166.4	166.8	274.9
10:00	91.4	123.4	98.9	131.3	333.2	356.3	353.2	417.7
11:00	172.8	248.2	169.5	225.8	641.8	685.1	671.5	790.4
12:00	242.8	299.1	234.4	367.9	883.2	977.1	939.4	1007.4
13:00	290.4	367.7	348.3	415.5	996.9	1123.1	1052.1	1339.2
14:00	254.8	308.4	278.9	373.2	946.3	1081.0	982.2	1035.8
15:00	201.6	232.8	218.1	282.6	727.8	797.0	838.9	875.4
16:00	139.2	151.1	153.1	197.6	505.2	545.4	505.9	636.4
17:00	80.8	99.5	88.2	115.7	295.0	340.6	316.9	369.4
18:00	38.6	47.3	41.9	54.5	142.4	158.0	218.3	176.5

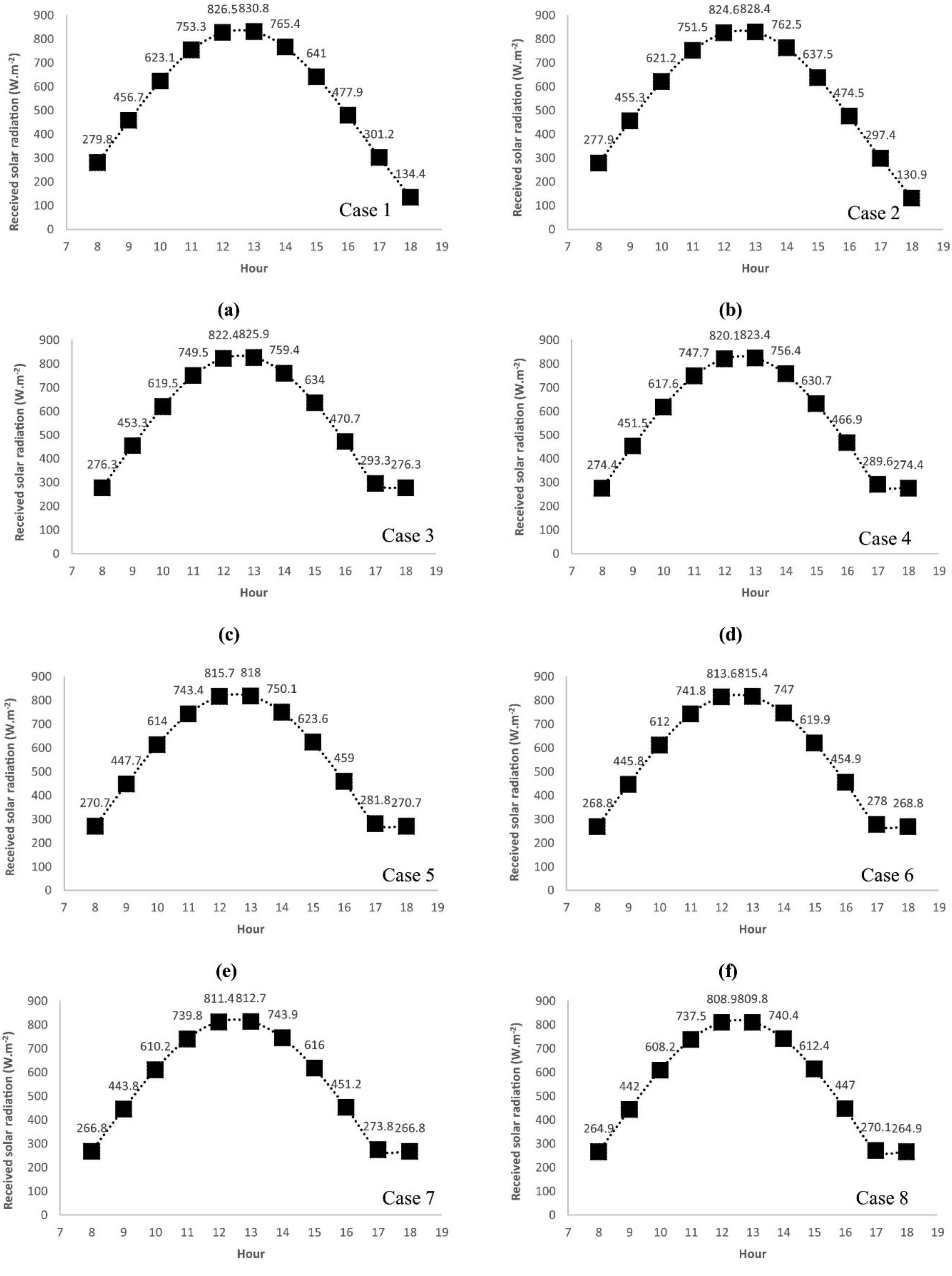
Table 5e. The values of the water temperature in the basin; the unit of the reported values are °C.

Hour	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
8:00	21.6	28.2	21.4	27.5	36.5	35.2	36.6	39.0
9:00	26.5	32.9	28.1	31.7	40.9	42.8	41.5	43.8
10:00	29.1	37.2	32.7	34.2	42.7	45.7	44.1	47.0
11:00	36.8	45.0	37.4	41.2	51.4	51.5	56.8	54.6
12:00	42.9	49.9	43.5	53.8	62.5	63.7	64.9	64.5
13:00	54.5	60.8	55.4	62.1	68.9	68.6	69.5	72.1
14:00	50.5	54.9	51.2	58.4	63.7	65.2	65.6	68.5
15:00	47.6	51.8	48.2	55.5	61.7	60.2	62.6	65.0
16:00	45.1	48.4	46.1	53.0	60.8	55.5	60.2	62.4
17:00	42.2	45.6	42.8	49.9	55.9	53.9	57.2	60.1
18:00	39.7	40.1	38.7	46.9	55.0	54.3	54.7	57.3



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 3. Hourly profiles for the ambient temperature (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Fig. 4. Hourly profiles for the received solar radiation (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8.

3.2. Comparing the performance criteria of the eight investigated cases

In this part, the eight considered cases are compared together from different aspects. The investigated performance criteria are the main characteristics of a solar still desalination system.

3.2.1. Temperature of water in the basin

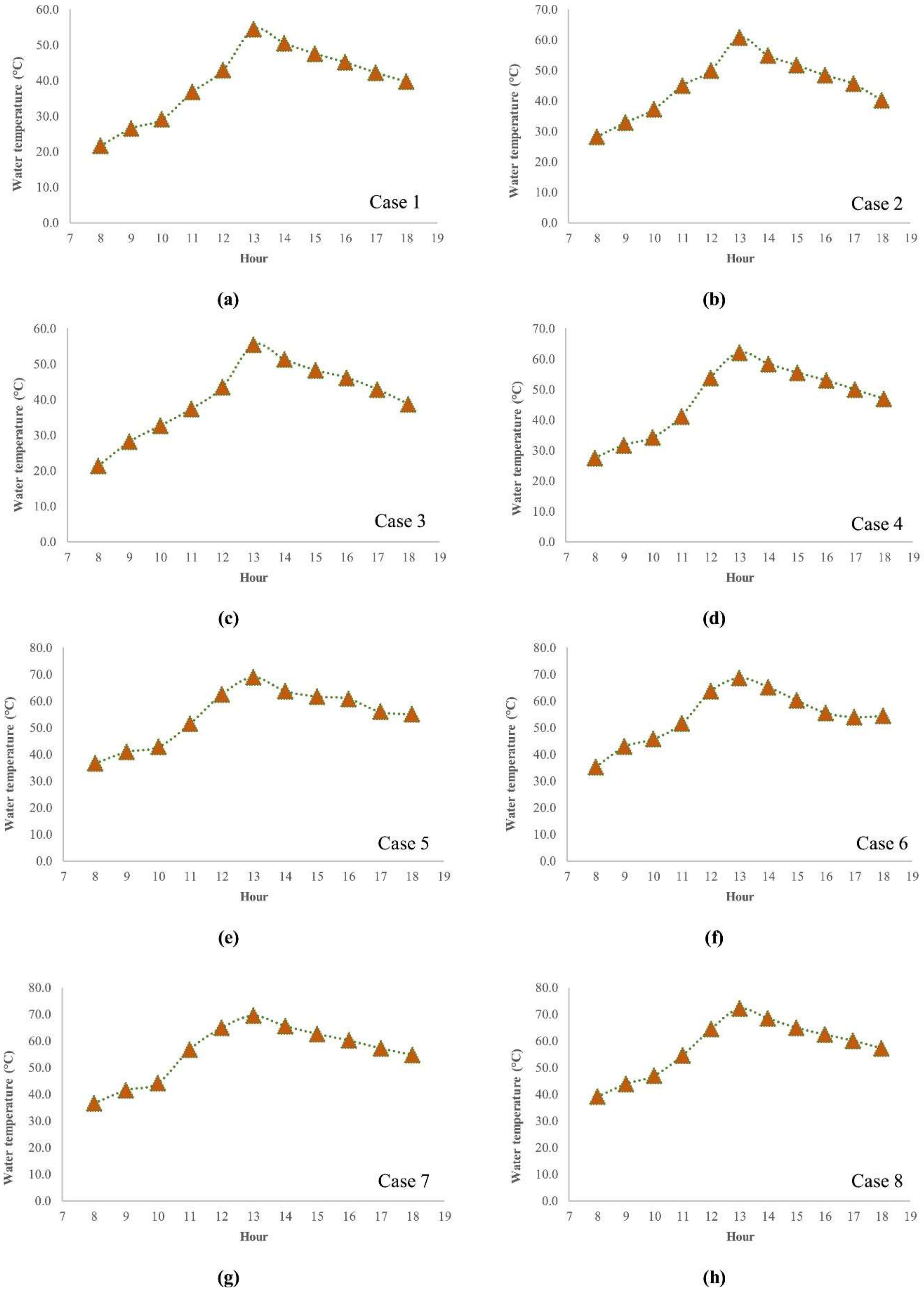
Fig. 5 present the recorded data for water temperature in the eight different cases. This figure reveals that in general, the water temperature in the basin has an upward trend from 8 to 13, i.e., in the first half of the day, and then, goes down in the second half, i.e., 13 to 18. However, the rate of decrement is not as high the increase rate. The reason is the temperature of water in the basin is a function of both received solar radiation and ambient temperature; the high irradiance and ambient temperature are, the higher temperature water in the basin has, and since the ambient temperature in the afternoon is higher than morning, a condition with the same solar radiation in the afternoon has a more water temperature level. For example, the temperature of water in the basin goes up from 27.5 to 62.1°C from 8 to 13, and reduces from 62.1 to 46.1°C from 13 to 18 for case 4. It shows the average increment and decrement rates for this case are 6.92 and 3.20°C per hour, respectively. It highlights the fact that using the active mode or other pre-heating methodologies in the morning is more important than the afternoon to have a more water temperature in the basin.

Moreover, when other factors are kept constant, changing the working mode from the passive to active condition leads to almost 8-15°C increase in the temperature of water in the basin. For example, the peak temperature, which occurs at 13, for the passive cases of 1, 2, 3, and 4 are 54.5, 60.8, 55.4, and 62.1°C. The corresponding values for the cases 5, 6, 7, and 8, are 68.9, 68.6, 69.5, and 72.1°C, which shows 14.4, 7.8, 14.1, and 10.0°C growth, respectively.

Fig. 5a-5d also demonstrate that using both the side mirrors and sun tracking can increase the water temperature level in the basin significantly in the passive mode. When both enhancement strategies are employed, the maximum water temperature in the solar still jumps from 54.5 to 62.1°C, which means the considerable increase of 7.6°C. Furthermore, comparing the results in the passive mode shows that between side mirrors and sun tracking, taking the advantage of sun tracking is more effective and causes a higher water temperature increase.

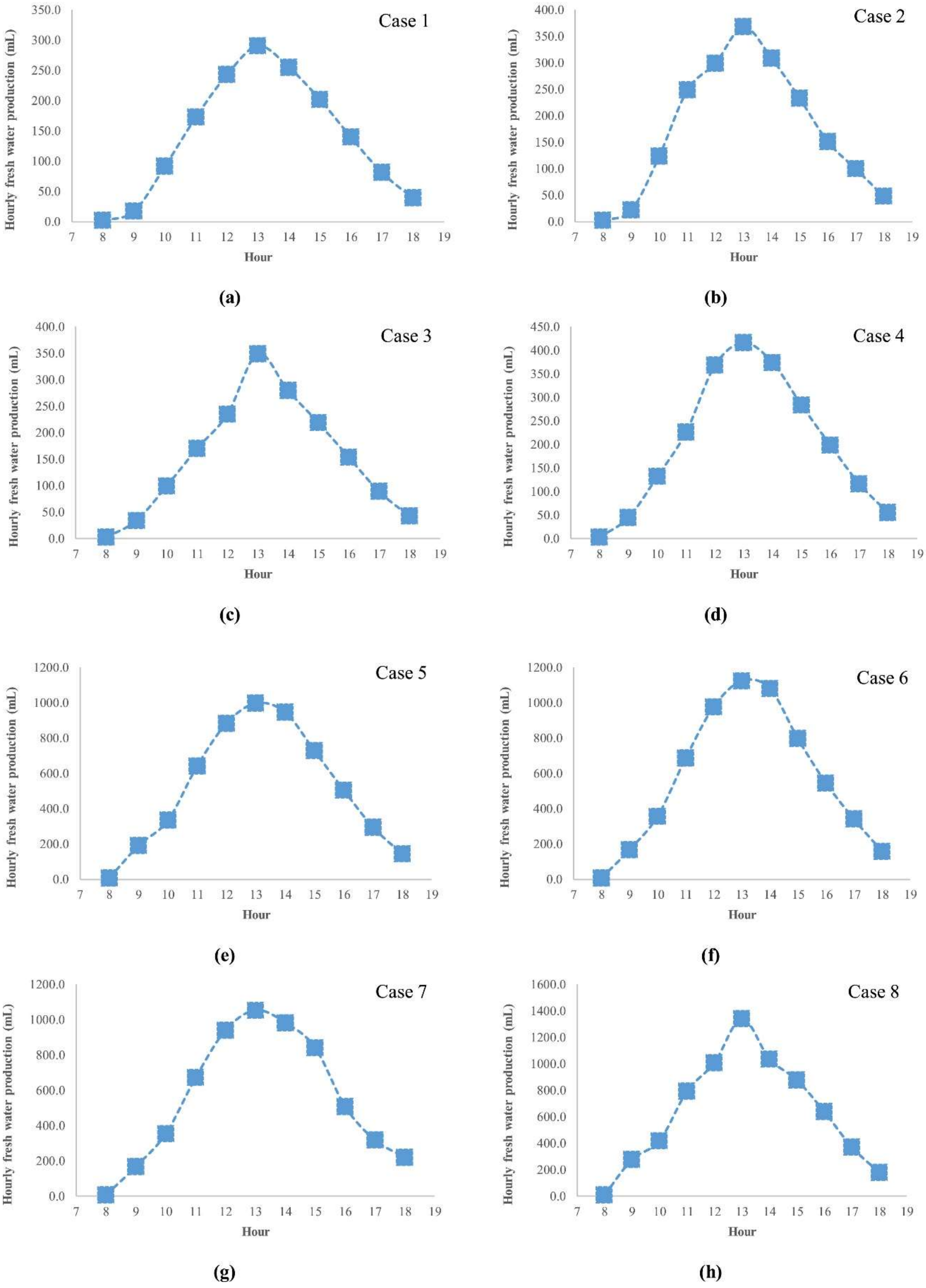
3.2.2. Hourly fresh water production

As the main technical characteristics of a solar still, the hourly profiles of fresh production of the system, which is also known as yield, are depicted in Fig. 6 for the eight considered cases. Fig. 6 brings the important point into the attention that in low radiation levels, especially in the morning, using the active mode is necessary to have an acceptable fresh water productivity. For instance, at 9, the amount of the hourly yield in the cases 1, 2, 3, and 4, which are all passive, are 16.9, 21.3, 33.4, and 44.2 mL. The values become much more considerable when it is switched to the active mode where for the cases 5, 6, 7, and 8, which are the active modes of cases 1, 2, 3, and 4, the hourly fresh water production reaches 190.9, 166.4, 166.8, and 274.9 mL at 9, respectively. In addition, the significant positive role of using the employed enhancement ways is proven by comparing the values of the pure water production before and after taking the advantage of them.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 5. Hourly profiles for temperature of water in the basin (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 6. Hourly profiles for hourly fresh water production (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8.

As another example of huge improvement in the hourly yield, the peak values, i.e., values at 13, could be given. Based on Fig. 6a-6d, using sun tracking and side mirrors individually leads to have 1.27 and 1.20 times greater fresh water production, while taking the advantage of both enhancement methods is accompanied by 1.43 times bigger hourly pure water yield. In this case, like the temperature of water in the basin, sun tracking has a higher impact on the amount of the produced fresh water in the passive mode. However, the higher impact of sun tracking in this case is not as big as the previous case, i.e., temperature of water in the basin.

Moreover, despite the fact that temperature of water in the basin does not return to the morning level in the afternoon and stays in a higher level than morning, the hourly water yield values returns to the morning level in the afternoon. In case 4, for instance, the fresh water productivity at 10 is 131.3 mL while at 17 it has the value of 115.7 mL. This is because the fact that the water productivity is a stronger function of the received solar radiation than the temperature of water in solar basin, and in this case, ambient temperature is not as effective as water temperature in the basin.

3.2.3. Cumulative fresh water production

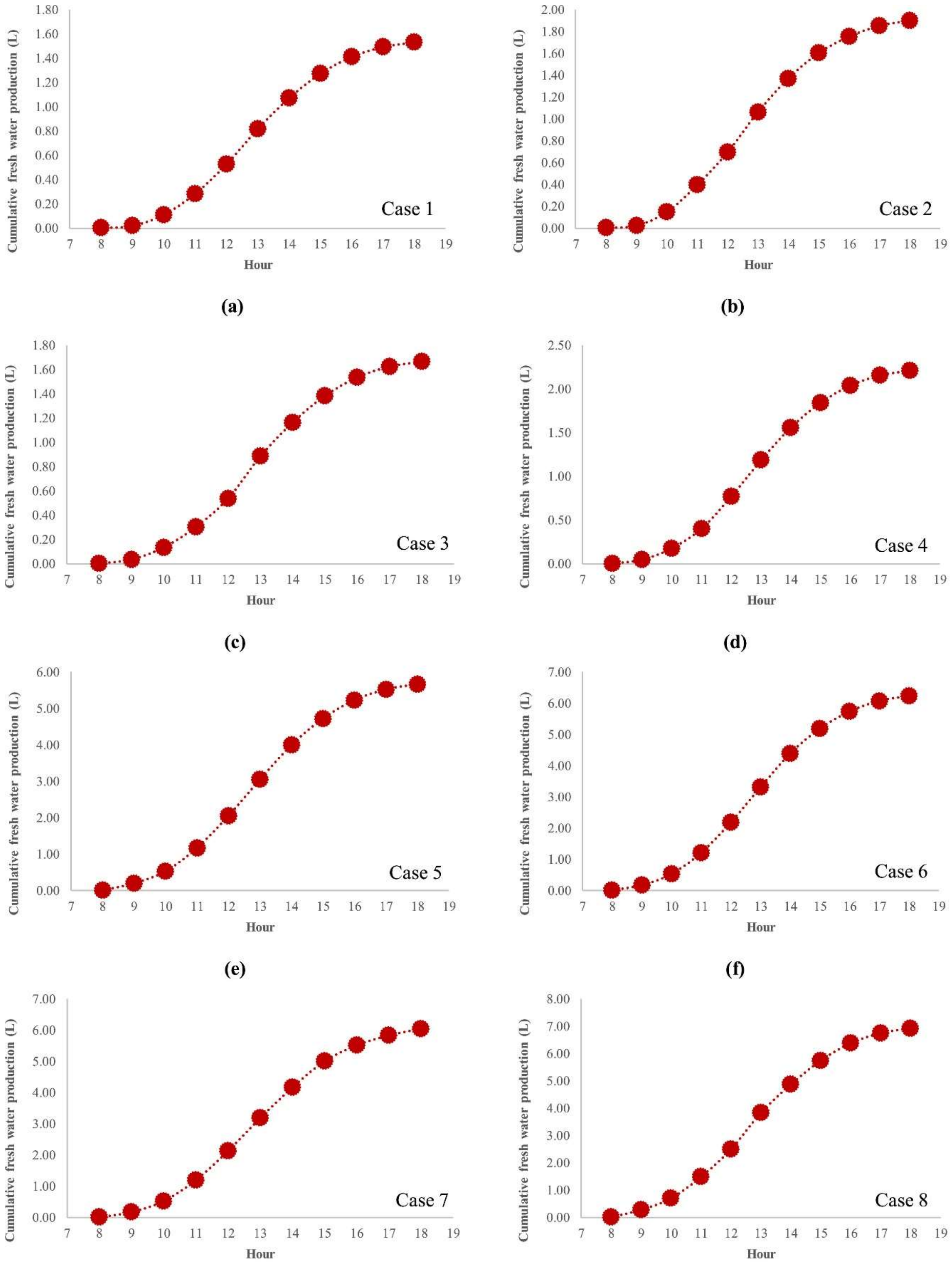
Fig. 7 reveals that although using the enhancement ways does not almost change the behavior of cumulative fresh water production, it improves the values significantly. For example, taking the advantage of sun tracking increases the cumulative yield at 13 from 0.82 to 1.06 L. Using side mirrors also leads to enhancing the value at the same time to 0.89 L while by employing the combination of sun tracking and side mirrors, the cumulative yield of 1.19 L is provided at 13. Comparison of the values not only for this time but also other time points shows the higher positive impact of sun tracking compared to side mirrors in enhancement of cumulative water production.

Furthermore, as per Fig. 7, switching from the passive to the active mode brings a huge improvement in the values of the cumulative water production. For instance, the cumulative production yield of case 8 at 14 is 4.87 L. This value is 3.12 times bigger than case 4, which is the passive mode of case 8. The cumulative fresh water production of case 4 is 1.56 L.

Evaluating the hourly profiles for different cases reveals some other points, as well. One point is that in spite of the fact that the amount varies from a case to another one, the water production for two time periods are not considerable. They are the periods between 8 and 10, and 16 and 18, in which the solar radiation is not high. It highlights the fact that in order to improve the performance of a solar still, in addition to the considered strategies of this study, the techniques to enhance the given input for such hours should be found, as well.

3.2.4. The daily productivity

The amounts of distillate provided by each of the investigated cases are compared together in Fig. 8. This figure shows that using even one of the employed enhancement strategies leads to a considerable increase in the daily productivity of systems in either passive or active mode. Compared to the conventional passive case, i.e., case 1, applying the sun tracking enhances the daily productivity from 1.53 to 1.90 L, which means the significant growth of 24.18%. The improvement gets even more by taking the advantages of both side mirrors and sun tracking at the same time, where 2.19 L distillate is produced and 43.14% increase happens.



(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Fig. 7. Hourly profiles for cumulative fresh water production (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8.

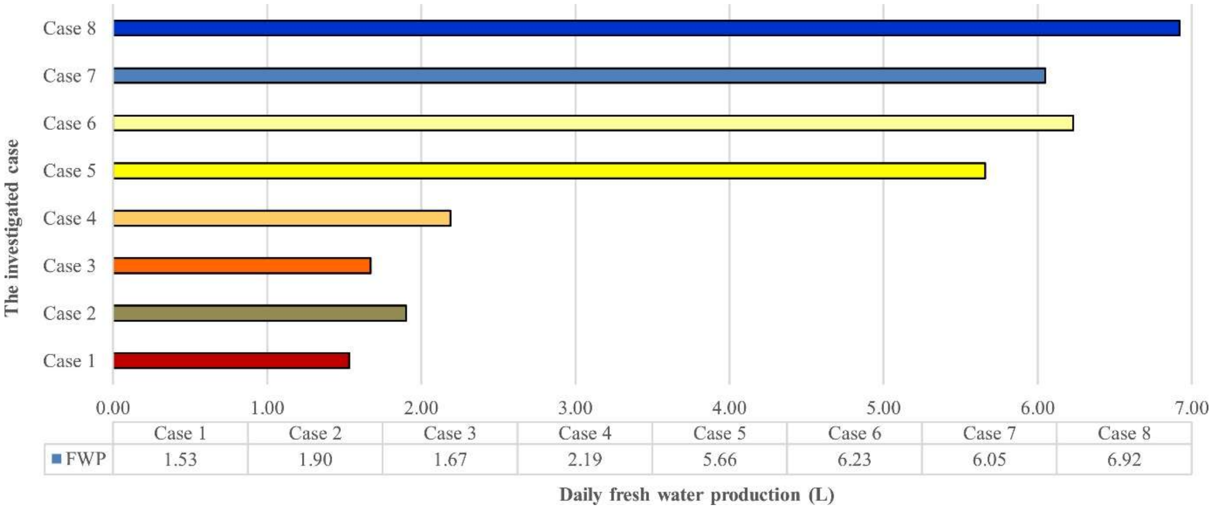


Fig. 8. Comparing the daily fresh water production of the different investigated cases.

The suggested strategies to enhance the performance of the solar still also provides remarkable improvements in fresh water production in the active mode. The daily yield for the conventional active system (case 5) is 5.66 L, while it reaches 6.05 L by employing the side mirrors (case 7). In case 6, in which the sun tracking is used, the fresh water production enhances to 6.23 L per day. Taking both the improvement techniques increases the daily distillate production to 6.92 L, as well. It means 0.57, 0.39, and 1.26 L growth in the daily pure water production for cases 6, 7, and 8, which is accompanied by 10.07, 6.89, and 22.26% improvement compared to the conventional active mode (case 5), respectively. In addition, case 8 has 352.29% higher yield than case 1.

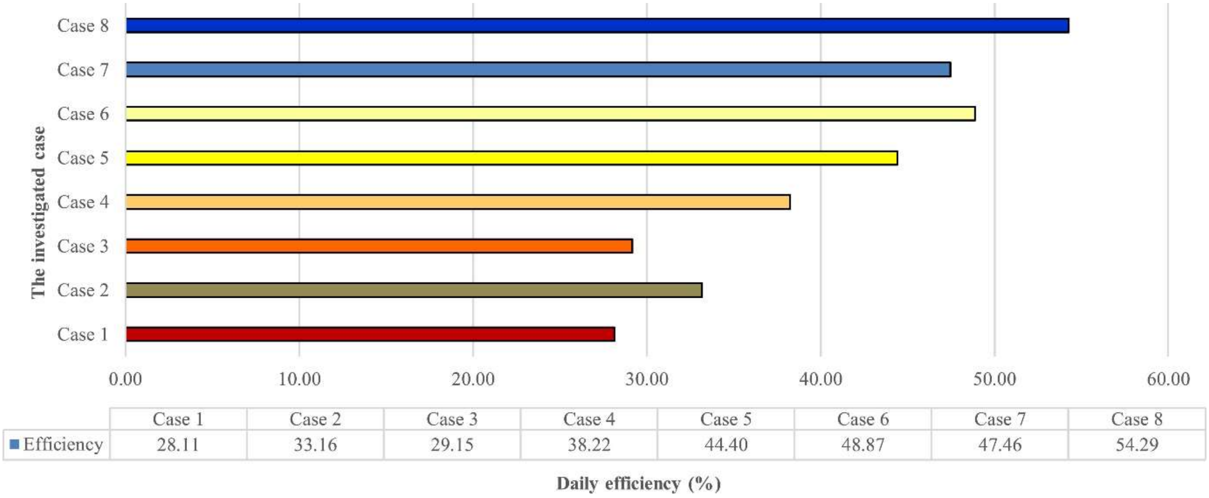


Fig. 9. Comparing the daily efficiency of the different investigated cases.

3.2.5. Daily efficiency

The daily efficiency of the eight different investigated cases are calculated and the results are presented in Fig. 9. According to Fig. 9, the efficiency varies in the range of 28 to 55%, and for a conventional passive solar still (case 1), the efficiency value is 28.11%, which is close to the reported values in the literature [34]. In addition, based on the obtained results, it is found that using the suggested techniques in the both passive and active modes is accompanied by almost considerable enhancement in the efficiency of the solar still.

In the passive mode, using sun tracking individually increases the efficiency from 28.11 to 33.16%, while the value of 29.15% is achieved by taking the advantage of side mirrors. Employing both enhancement strategies together also leads to having the daily efficiency of 38.22% in case 4, which shows the growth rate of 35.97% compared to the conventional system, i.e., case 1.

The efficiency levels in the active mode are higher as expected. Here, however, the improvement in the daily efficiency when the side mirrors and sun tracking strategies are applied are much closer together. For cases 6 and 7, daily efficiency values are equal to 48.87 and 47.46%, respectively. In addition, like the passive mode, a significant increment in efficiency happens in case two strategies are applied together. Reaching from 44.40 to 54.29%, daily efficiency experiences 22.27% enhancement in case 8 compared to case 5.

3.2.6. Cost per liter

As mentioned earlier, the cost per unit of the produced fresh water, C_{FWP}, is taken into the most important techno-economic performance criteria of a solar still desalination technology. Usually, the unit for the volume of distillate (V_{FWP}) in the equation to calculate C_{FWP} (Eq. (9)) is expressed in liters, and in such cases, C_{FWP} is known as cost per liter (*CPL*). *CPL* is calculated for the eight investigated cases based on the method introduced in Sections 2.2.2 and 2.2.3, and the values are reported in Fig. 10 while the details of calculations are given in Table 6.

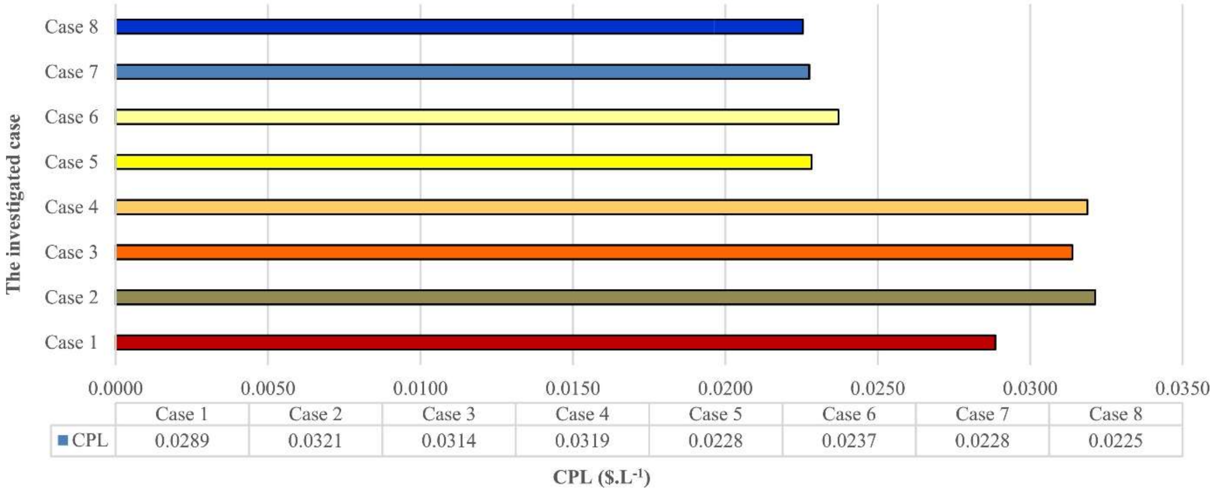


Fig. 10. Comparing cost per liter (*CPL*) of the different investigated cases.

Table 6. The details of calculations of *CPL*.

Case	Daily water production on the investigated day (L)	Annual water production (L)	Annualized cost ($)	CPL ($.L^{-1})
Case 1	1.53	459	13.2	0.0289
Case 2	1.90	570	18.3	0.0321
Case 3	1.67	501	15.7	0.0314
Case 4	2.19	657	20.9	0.0319
Case 5	5.66	1698	38.8	0.0228
Case 6	6.23	1869	44.3	0.0237
Case 7	6.05	1815	41.3	0.0228
Case 8	6.92	2076	46.8	0.0225

The results show that generally, the passive systems (cases 1 to 4) have much higher values of *CPL* in comparison to the active ones (cases 5 to 8). According to Table 6, which reports the details of calculations, although passive systems imposes a lower level of annualized cost, they suffer from a much less amount of fresh water production, as well. On the other hand, the active systems enjoy a much greater distillate production level, which overcomes the extra imposed annual cost. For example, for case 4, the amount of water production and the imposed annual cost are 657 L.year^{-1} and 20.9 $.year^{-1}, which results in having *CPL* of 0.0319 $.L^{-1}. Case 8, which is case 4 in the active mode, has 2.24 times greater annual cost, but also 3.16 times bigger fresh water production, which is accompanied by 29.46% cheaper *CPL*. *CPL* for this case is 0.0225 $.L^{-1}. This value is a bit more than the one mentioned in the studies like [56], but the proposed system of this study is less complicated and has fewer parts, which provides a higher reliability level.

In addition, the techno-economic assessment for the active systems reveals that there is a small difference between the *CPL* of using side mirrors and sun tracking when each one is employed individually. Employing sun tracking has *CPL* of 0.0237 $.L^{-1}, while this value for taking advantage of side mirrors is 0.0228 $.L^{-1}. Nonetheless, because of higher water production rate, sun tracking technique is recommended if only one of the enhancement ways is going to be chosen. Additionally, as a very significant point, using the side mirrors and sun tracking techniques together does not impose additional *CPL* compared to the conventional system and even reduces it. As Fig. 10 shows, for case 8, *CPL* has the value of 0.0225 $.L^{-1}, while *CPL* for the conventionial passive system, i.e., case 1, is 0.0289 $.L^{-1}. Therefore, the technoeconomic benefit of using both suggested strategies together for the active mode is proven. This point, in addition to the other previously discussion shows that using active mode in combination with the two proposed enhancement strategies not only brings a higher level of temperature in the water basin and water production rate, but also is totally economically justifiable.

3.3. Uncertainty values

Following the similar fashion as the recent studies like [54], values of the relative uncertainty are given to evaluate the accuracy of the reported information. Table 7 gives the results where the uncertainty values are found very close to the previously done investigations such as [31,34]. Therefore, the accuracy of the reported data in the paper is verified.

Table 7. The relative uncertainty of the reported parameters.

Parameter	Average relative uncertainty (%)
Ambient temperature	0.863
Solar radiation	0.022
Wind velocity	0.034
Temperature of water in solar still	0.258
The fresh water production	1.087

4. Conclusions

The enhancement potential of using sun tracking and side mirrors to improve the performance of a solar still was evaluated through conducting experiments. Investigation was done for the conventional system, employing each enhancement strategy individually, and taking the advantage of both sun tracking and insulation at the same time in passive and active modes, which led to having eight different cases. Different key performance criteria, including the hourly profiles of water temperature in the basin, fresh water production, and cumulative yield, as well as the daily obtained pure water and efficiency for eight cases were compared together. In addition, eight cases were evaluated based on cost per liter, as well. The following items could be mentioned as the most remarkable findings of the study:

- All the performance criteria were enhanced when either one or two enhancement ways were employed in both modes. In most of the cases, the improvement was considerable, which proved the effectiveness of the suggested enhancement strategies.
- By applying both side mirrors and sun tracking techniques, the peak water temperature increased by 7.6°C in the passive mode. Changing the mode from the passive to active while two aforementioned techniques were used at the same time also was also accompanied by 10°C higher maximum temperature of water in the basin.
- The hourly yield at the peak and daily produced fresh water was enhanced both 43.1% in the passive mode, and 34.3 and 22.2% in the active mode when the two proposed improvement strategies were employed simultaneously.
- The daily efficiency also jumped 36.0% in the passive mode after taking the advantage of sun tracking and side mirrors at the same time, while the corresponding value for the active operation was 22.3%.
- Although using side mirrors in addition to sun tracking imposes higher annualized cost compared to the conventional system, it leads to having a lower cost per liter in the active mode. The reason is the higher increase rate of the produced water compared to the annualized cost, which reduced cost per liter from 0.0228 to 0.0225 $\$.L^{-1}$. It showed that for active operation, the improvement ways were economically justifiable, as well.

Declaration of Competing Interest

None.

References

[1] Worldmeter Website. World population by year https://www.worldometers.info/world-population/world-population-by-year; Accessed on August 9, 2020. (2020).

[2] R. Tariq, N.A. Sheikh, J. Xamán, A. Bassam. An innovative air saturator for humidification-dehumidification desalination application. Appl. Energy, 228 (2018), pp. 789-807.

[3] A. Rafiei, R. Loni, S.B. Mahadzir, G. Najafi, S. Pavlovic, E. Bellos. Solar desalination system with a focal point concentrator using different nanofluids. Appl. Therm. Eng., 174 (2020), Article 115058

[4] A. Abubakkar, P. Selvakumar, T. Rajagopal, A. Tamilvanan. Development of concentrating dish and solar still assembly for sea water desalination. Mater. Today: Proc. (2020).

[5] H.M. Wilson, D.J. Ahirrao, S. Raheman Ar, N. Jha. Biomass-derived porous carbon for excellent low intensity solar steam generation and seawater desalination . Sol. Energy Mater. Sol. Cells, 215 (2020), Article 110604

[6] A.R. Razmi, A. Arabkoohsar, H. Nami. Thermoeconomic analysis and multi-objective optimization of a novel hybrid absorption/recompression refrigeration system. Energy (2020), Article 118559.

[7] M. Zeynalian, A.H. Hajialirezaei, A.R. Razmi, M. Torabi. Carbon dioxide capture from compressed air energy storage system. Appl. Therm. Eng., 178 (2020), Article 115593.

[8] S.M. Babaei, A.R. Razmi, M. Soltani, J. Nathwani. Quantifying the effect of nanoparticles addition to a hybrid absorption/recompression refrigeration cycle. J. Clean. Prod., 260 (2020), Article 121084.

[9] M. Soltani, M.H. Nabat, A.R. Razmi, M.B. Dusseault, J. Nathwani. A comparative study between ORC and Kalina based waste heat recovery cycles applied to a green compressed air energy storage (CAES) system. Energy Convers. Manage., 222 (2020), Article 113203.

[10] R. Yargholi, H. Kariman, S. Hoseinzadeh, M. Bidi, A. Naseri. Modeling and advanced exergy analysis of integrated reverse osmosis desalination with geothermal energy. Water Supp., 20 (2020), pp. 984-996

[11] S. Hoseinzadeh, R. Yargholi, H. Kariman, P.S. Heyns. Exergoeconomic analysis and optimization of reverse osmosis desalination integrated with geothermal energy. Environ. Prog. Sustainable Energy (2020) e13405.

[12] S. Hoseinzadeh, R. Ghasemiasl, M.A. Javadi, P.S. Heyns. Performance evaluation and economic assessment of a gas power plant with solar and desalination integrated systems. (2020).

[13] H. Kariman, S. Hoseinzadeh, P.S. Heyns. Energetic and exergetic analysis of evaporation desalination system integrated with mechanical vapor recompression circulation. Case Stud. Therm. Eng., 16 (2019), Article 100548

[14] A. Sohani, H. Sayyaadi. Providing an accurate method for obtaining the efficiency of a photovoltaic solar module. Renewable Energy, 156 (2020), pp. 395-406

[15] S. Hoseinzadeh, M.H. Ghasemi, S. Heyns. Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems. Renewable Energy, 160 (2020), pp. 323-332.

[16] A. Sohani, M.H. Shahverdian, H. Sayyaadi, D.A. Garcia. Impact of absolute and relative humidity on the performance of mono and poly crystalline silicon photovoltaics; applying artificial neural network. J. Clean. Prod., 276 (2020), Article 123016.

[17] A. Badiei, Y. Golizadeh Akhlaghi, X. Zhao, S. Shittu, X. Xiao, J. Li, *et al.* A chronological review of advances in solar assisted heat pump technology in 21st century. Renewable Sustainable Energy Rev., 132 (2020), Article 110132.

[18] Y. Fan, X. Zhao, J. Li, G. Li, S. Myers, Y. Cheng, *et al.* Economic and environmental analysis of a novel rural house heating and cooling system using a solar-assisted vapour injection heat pump. Appl. Energy, 275 (2020), Article 115323.

[19] M. Majidi Nezhad, D. Groppi, F. Rosa, G. Piras, F. Cumo, D.A. Garcia. Nearshore wave energy converters comparison and Mediterranean small island grid integration. Sustainable Energy Technol. Assess., 30 (2018), pp. 68-76.

[20] I. Ustun, C. Karakus, H. Yagli. Empirical models for estimating the daily and monthly global solar radiation for Mediterranean and Central Anatolia region of Turkey. Int. J. Glob. Warming, 20 (2020), pp. 249-275.

[21] R. Tariq, J. Xamán, A. Bassam, L.J. Ricalde, M.A.E. Soberanis. Multidimensional assessment of a photovoltaic air collector integrated phase changing material considering Mexican climatic conditions. Energy, 209 (2020), Article 118304.

[22] A. Refiei, R. Loni, G. Najafi, A.Z. Sahin, E. Bellos. Effect of use of MWCNT/oil nanofluid on the performance of solar organic Rankine cycle. Energy Rep., 6 (2020), pp. 782-794

[23] A. Heydari, M. Majidi Nezhad, E. Pirshayan, D. Astiaso Garcia, F. Keynia, L. De Santoli. Short-term electricity price and load forecasting in isolated power grids based on composite neural network and gravitational search optimization algorithm. Appl. Energy, 277 (2020), Article 115503.

[24] S. Rashidi, N. Rahbar, M.S. Valipour, J.A. Esfahani. Enhancement of solar still by reticular porous media: experimental investigation with exergy and economic analysis. Appl. Therm. Eng., 130 (2018), pp. 1341-1348.

[25] H. Mousa, J. Naser, A.M. Gujarathi, S. Al-Sawafi. Experimental study and analysis of solar still desalination using phase change materials. J. Energy Storage, 26 (2019), Article 100959.

[26] L. Xiao, R. Shi, S.-Y. Wu, Z.-L. Chen. Performance study on a photovoltaic thermal (PV/T) stepped solar still with a bottom channel. Desalination, 471 (2019), Article 114129.

[27] W.M. El-Maghlany, A.H. Abdelaziz, A.A. Hanafy, A.E. Kabeel. Effect of continuous and discrete makeup water on the productivity of conventional solar still. J. Energy Storage, 28 (2020), Article 101223.

[28] A.R. Abd Elbar, H. Hassan. An experimental work on the performance of new integration of photovoltaic panel with solar still in semi-arid climate conditions. Renewable Energy, 146 (2020), pp. 1429-1443.

[29] A.E. Kabeel, R. Sathyamurthy, A.M. Manokar, S.W. Sharshir, F.A. Essa, A.H. Elshiekh. Experimental study on tubular solar still using graphene oxide nano particles in phase change material (NPCM's) for fresh water production. J. Energy Storage, 28 (2020), Article 101204.

[30] V.S. Vigneswaran, G. Kumaresan, B.V. Dinakar, K.K. Kamal, R. Velraj. Augmenting the productivity of solar still using multiple PCMs as heat energy storage. J. Energy Storage, 26 (2019), Article 101019.

[31] P. Dumka, A. Jain, D.R. Mishra. Energy, exergy, and economic analysis of single slope conventional solar still augmented with an ultrasonic fogger and a cotton cloth. J. Energy Storage, 30 (2020), Article 101541.

[32] M. Abu-Arabi, M. Al-harahsheh, M. Ahmad, H. Mousa. Theoretical modeling of a glass-cooled solar still incorporating PCM and coupled to flat plate solar collector. J. Energy Storage, 29 (2020), Article 101372.

[33] A.R.A. Elbar, M.S. Yousef, H. Hassan. Energy, exergy, exergoeconomic and enviroeconomic (4E) evaluation of a new integration of solar still with photovoltaic panel. J. Clean. Prod., 233 (2019), pp. 665-680.

[34] A.E. Kabeel, W.M. El-Maghlany, M. Abdelgaied, M.M. Abdel-Aziz. Performance enhancement of pyramid-shaped solar stills using hollow circular fins and phase change materials. J. Energy Storage, 31 (2020), Article 101610.

[35] B. Ghorbani, M. Mehrpooya, A. dadak. Thermo-economic analysis of a solar-driven multi-stage desalination unit equipped with a phase change material storage system to provide heating and fresh water for a residential complex. J. Energy Storage, 30 (2020), Article 101555

[36] A.E. Kabeel, M. Abdelgaied. Performance enhancement of a photovoltaic panel with reflectors and cooling coupled to a solar still with air injection. J. Cleaner Prod., 224 (2019), pp. 40-49.

[37] S.M. Parsa, D. Javadi Y, A. Rahbar, M. Majidniya, M. Salimi, Y. Amidpour, *et al.* Experimental investigation at a summit above 13,000ft on active solar still water purification powered by photovoltaic: a comparative study. Desalination, 476 (2020), Article 114146.

[38] A.S. Abdullah, F.A. Essa, Z.M. Omara, Y. Rashid, L. Hadj-Taieb, G.B. Abdelaziz, *et al.* Rotating-drum solar still with enhanced evaporation and condensation techniques: comprehensive study. Energy Convers. Manage., 199 (2019), Article 112024.

[39] M.E.H. Attia, Z. Driss, A.M. Manokar, R. Sathyamurthy. Effect of aluminum balls on the productivity of solar distillate. J. Energy Storage, 30 (2020), Article 101466.

[40] Q. Zhao, H. Zhang, Z. Hu, S. Hou. A solar driven hybrid photovoltaic module/direct contact membrane distillation system for electricity generation and water desalination. Energy Convers. Manage., 221 (2020), Article 113146.

[41] R. Chauhan, S. Sharma, R. Pachauri, P. Dumka, D.R. Mishra. Experimental and theoretical evaluation of thermophysical properties for moist air within solar still by using different algorithms of artificial neural network. J. Energy Storage, 30 (2020), Article 101408.

[42] A.E. Kabeel, K. Harby, M. Abdelgaied, A. Eisa. Augmentation of a developed tubular solar still productivity using hybrid storage medium and CPC: an experimental approach. J. Energy Storage, 28 (2020), Article 101203.

[43] M. Patel, C. Patel, H. Panchal. Performance analysis of conventional triple basin solar still with evacuated heat pipes, corrugated sheets and storage materials. Groundwater Sustainable Dev., 11 (2020), Article 100387.

[44] H. Panchal, S.S. Hishan, R. Rahim, K.K. Sadasivuni. Solar still with evacuated tubes and calcium stones to enhance the yield: an experimental investigation. Process Saf. Environ. Prot., 142 (2020), pp. 150-155.

[45] F.A. Essa, A.S. Abdullah, Z.M. Omara. Rotating discs solar still: new mechanism of desalination. J. Clean. Prod., 275 (2020), Article 123200.

[46] A.S. Abdullah, M.M. Younes, Z.M. Omara, F.A. Essa. New design of trays solar still with enhanced evaporation methods – comprehensive study. Sol. Energy, 203 (2020), pp. 164-174

[47] J. Patel, K. Patel, A. Mudgal, H. Panchal, K.K. Sadasivuni. Experimental investigations of atmospheric water extraction device under different climatic conditions. Sustainable Energy Technol. Assess., 38 (2020), Article 100677.

[48] H. Panchal. Annual performance analysis of various energy storage materials in the upper basin of a double-basin solar still with vacuum tubes. Int. J. Ambient Energy, 41 (2020), pp. 435-451.

[49] H. Panchal, K.K. Sadasivuni, C. Prajapati, M. Khalid, F.A. Essa, S. Shanmugan, *et al.* Productivity enhancement of solar still with thermoelectric modules from groundwater to produce potable water: a review. Groundwater Sustainable Dev., 11 (2020), Article 100429.

[50] Y.A. Cengel, M.A. Boles. Thermodynamics: an Engineering Approach 6th Editon (SI Units). The McGraw-Hill Companies, Inc., New York (2007).

[51] A. Sohani, S. Rezapour, H. Sayyaadi. Comprehensive performance evaluation and demands' sensitivity analysis of different optimum sizing strategies for a combined cooling, heating, and power system. J. Clean. Prod., 279 (2021), Article 123225.

[52] A. Sohani, H. Sayyaadi, M. Azimi. Employing static and dynamic optimization approaches on a desiccant-enhanced indirect evaporative cooling system. Energy Convers. Manage., 199 (2019), Article 112017

[53] A. Sohani, H. Sayyaadi. End-users' and policymakers' impacts on optimal characteristics of a dew-point cooler. Appl. Therm. Eng., 165 (2020), Article 114575

[54] A. Sohani, H. Sayyaadi. Employing genetic programming to find the best correlation to predict temperature of solar photovoltaic panels. Energy Convers. Manage., 224 (2020), Article 113291.

[55] H.W. Coleman, W.G. Steele. Experimentation, Validation, and Uncertainty Analysis for Engineers. John Wiley & Sons (2018).

[56] A.E. Kabeel, M. Abdelgaied. Observational study of modified solar still coupled with oil serpentine loop from cylindrical parabolic concentrator and phase changing material under basin. Sol. Energy, 144 (2017), pp. 71-78.