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Economic analysis of a household solar desalination device integrated with photo thermal and photovoltaic

Ke Yang[a], Xuepan Cheng[a], Teza Mwamulima[a], Hao Guo[c], Changsheng Peng[a,b,*]

[a]*The Key Lab of Marine Environmental Science and Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China, Tel. +86 18300271020, email: 840713242@qq.com (K. Yang), Tel. +86 13255597105, email: chengxuepan@qq.com (X. Cheng), Tel. +86 15865527901, email: 1841174537@qq.com (T. Mwamulima)*
[b]*School of Environmental and Chemical Engineering, Zhaoqing University, Zhaoqing 526061, China, Tel. +86 15853299827, email: cspeng@ouc.edu.cn (C. Peng)*
[c]*Beijing Institute of high-tech Environmental Science, Beijing 101111, China, Tel. +86 15853299827, email: 357951634@qq.com (H. Guo)*

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ABSTRACT

Water shortage is a serious problem in many sea islands and rural areas. Many researchers around the world endeavor to investigate small scale solar desalination systems. Economic analysis is an important factor which affects the consideration in the adoption of various solar desalination systems. However, it is unfair to compare the cost of fresh water between household solar desalination systems and large ones, for the household solar desalination system is applied in special sites such as sea islands and rural areas. Therefore, in order to evaluate the economic feasibility of our solar desalination system, this paper will compare the cost of water and the annual water yield between some small scale solar desalination systems and our system. The results showed that the cost of water produced by our solar desalination system was 16 US$/m^3 and the value is lower than other systems, and the annual water yield is 2625 L, which is 4.75 times higher than the conventional solar systems. The paper has also proved that the cost of water is significantly affected by the capital cost and the annual yield, therefore, the most economic system must find the balance between the two parameters.

Keywords: Economic analysis; Solar desalination; Solar energy; Rural areas

1. Introduction

Despite the fact that most of the Earth's surface is covered with water, only 1% of water is potable. Over exploitation of groundwater and serious water pollution have further resulted in severe water shortage. Therefore, desalination, converting saltwater into freshwater, is a potential method to explore new water source in many counties, especially in coastal areas. As shown in Fig. 1, over the past 50 years, the investments in desalination utilities have been growing rapidly, and the total installed desalination capacity around the world has rapidly grown in recent years.

The reverse osmosis has now been accepted as the mature desalination technology for fresh water supply, but the energy consumption is so high (almost 0.027 ton oil for 1 m^3 fresh water production), which results in additional environmental problem, such as greenhouse gas emission and brine discharge [2]. Some of the oil-rich countries are still using fossil fuel to drive energy-intension desalination plants at present, however, some renewable energies, such as solar, wind, geothermal and wave (tide) for desalination have been considered by scientists, engineers and policy makers as the alternative option.

There are many design and economic factors affecting the consideration in the adoption of renewable desalination device, such as production scale, raw water salinity, remoteness, accessibility of electric power, infrastructure and cost

*Corresponding author.

effectiveness [3]. It is difficult to discern all the influencing factors because desalination systems in different regions have different requirements. Table 1 presents the production cost of water by conventional desalination and solar desalination technologies, it is noticed that solar energy is the most widely used among the renewable sources.

Table 1 shows the cost of conventional desalination systems is still much lower than solar desalination. But the costs of solar desalination are steadily decreasing, while fossil fuel prices are rising, supplies depleting, and concerns about energy security increase. In addition, an inverse correlation between the cost of water and the capacity of the plant in both conventional and solar energy systems is noticeable. For production capacity ranges between 1 and 100,000 m^3/d, the cost of water is reduced from 64 to 0.69 US$/$m^3$. Thus, the cost of small scale desalination is too much higher than large one due to its expensive investment and relatively low output. However, these large plants are usually established in big cities near the sea for supplying a large amount water demand, while the small-scale plant is built for providing freshwater to small communities in isolated arid areas.

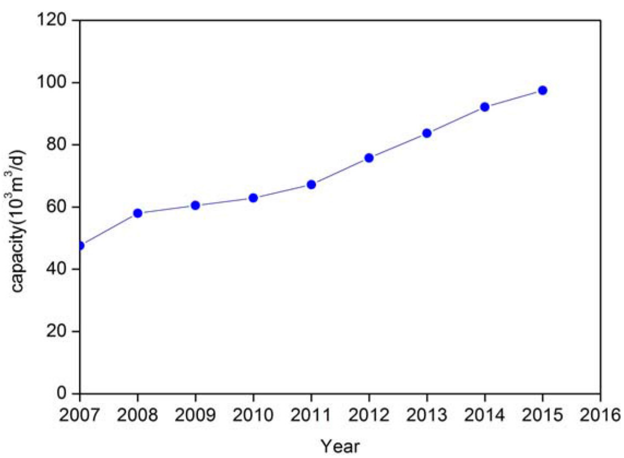

Fig. 1. Total installed desalination capacity, 2007–2015 [1].

Recently, the demand for small scale plants which supplies fresh water for dozens of people to thousands of people has become more and more popular. The kind of desalination technology used in small-scale plants significantly affects their water cost and system stability, general, cost evaluation is essential for decision-making about adoption of a small-scale desalination system in a certain area, Therefore, in this paper, we will introduce our solar desalination system and present a comprehensive economic analysis for it, then we will also study some recent small-scale devices which have made significant enhancements on productivities, finally, we will carry out a detailed cost comparison in consideration of all the economic parameters among these works to estimate the economic feasibility of our developed desalination system in remote regions.

2. Factors affecting the cost

The cost of fresh water is affected by many factors, such as capital investment, maintenance costs, operational and energy costs [5,6]. Table 2 shows the summary of the factors for cost of small scale desalination units.

The cost comparison of conventional desalination system and renewable one is shown in Table 3. It can be seen that the capital investment costs account for 90% of total costs for renewable energy desalination system, which means the capital investment is always the chief concern for the cost of a small solar desalination plant.

3. Description of some laboratory desalination system

3.1. Our desalination system

The solar thermal MSF and MED technologies are always popular in economic -developed towns and cities, however,

Table 1
Water cost for conventional and solar desalination pilot plants

Type	Capacity (m^3/d)	Cost of water (US$/$m^3$)	Description	Ref.
SWRO		0.76		[4]
MSF	23,000–52,8000	0.52–1.75		[5]
Solar-MED	100,000	0.69	PTC; 16 stages	[6]
MSF powered by solar pond	10,000	1.84	Pond size: 800,000 m^2	[7]
MSF powered by solar pond	1000	2.85	Pond size: 80,000 m^2	[7]
Solar-MSF	90	6.4		[8]
Solar–MED	85	7–10		[9]
Solar–MED	72	2		[10]
Triple basin solar still	17	64	TBSS with PDC, cover cooling with charcoal in fins	[11]
Solar Multi-effect still	10	28.8	24–h operation; hybrid	[12]
PV-RO	8	7.8–8.3	With an energy recovery device	[13]
Solar still	1	12		[14]

Table 2
The factors affecting the cost of small scale desalination units in remote regions

Factors	Description
Meteorological	• Solar radiation
	• Wind intensity
	• Average annual precipitation
	• Climatic circumstances
Site conditions	• Land
	• Accessibility for water source
	• Proximity to users
	• Electric power availability
Energy	• The availability of inexpensive sources
	• Auxiliary equipment consumption
Quality of feed water	• Salinity, temperature, intake arrangement and required
Labor	• The availability of qualified and trained
Financing	• Direct capital cost
	• Indirect capital cost
	• Annual operating cost
	• Annual maintenance cost
System infrastructure	• Access to appropriate desalination technology
	• Access to materials, components and supplies
	• Possible pumping systems for the saline water and fresh product water
	• Brine disposal location

Table 3
Cost comparison between conventional desalination system and renewable one

Type of process	Investment costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22	15	63
Conventional (MSF)	25	40	35
Renewable energ	90	10	0

these concepts do not match well for remote regions or sea islands with limited power infrastructure. Photovoltaic powered reverse osmosis system (PVRO) is considered to be the most mature commercial solution to the clean water problems but yet presents some important limitations. In fact，it is relatively much more technologically advanced, complex and possibly restricted in its domains of applicability. It also needs trained operators and technicians, which is not applicable for remote communities. Unlike the PVRO, solar distillation is very simple to operate, but low fresh water production is its main drawback.

In our lab, an innovative and compact solar distillation system was intended to increase the fresh water yield. The system is composed of three main parts: evacuated solar collectors (ETCs), a tubular solar still (TSS) and a PV panel. The three parts cost 23 US$, 165 US$ and 150 US$ respectively, and they were integrated in a stainless stand as shown in Figs. 2a and 2b. The total cost of our system is 424 US$ which includes other auxiliary equipment.

An evacuated tube collector array aims at heating seawater to 50–70°C, consists of 10 concentric borosilicate tubes with 1.65 m^2 collector areas. The PV panel with 1 m^2 collector area aims at supplying electricity to an electric water heater. The TSS was manufactured for the purpose of evaporation and condensation, the detailed construction of the TSS is shown in Figs. 2c and 2d.

The schematic view of our desalination system is illustrated in Fig. 2e. The cooling seawater is pumped into the TSS through 1, and the heated seawater is evaporated and the vapor is condensed in the condensation chamber. Some parts of the cooling water are discharged from 5, and the other cooling water flows into the evaporation chamber through the ball float. Finally, the brine water is discharged from 8. A polyurethane board, between the outlet of fresh water and the ball float, is designed to keep the evaporator heat from losing into the condensation chamber. A electric water heater powered by the PV panel is consistently heating the seawater until the temperature reaches 80°X, the PV panel works whole day ,continues absorbing solar energy and store it in some batteries. If the solar irradiation is weak or the weather is bad, those batteries would ascertain the desalination system work normal and produce fresh water consistently.

The system starts to work at 8:00 am, given that the solar irradiation is too low to heat the seawater, (as shown in Fig. 3, the solar irradiation at 8:00 am is 449 W/m^2 the electric water heater heats the water and quickly increases water temperature to 80°C, after 10:00 am, the heater stops working and the system is completely powered by solar energy, the function of the electric heater is shorten the water heating time and produces more fresh water at lower solar irradiation , when the electric water heater is off, the water temperature dropped to 74.1°C rapidly and increased proportional to the solar irradiation, the maximum water temperature was 84.2°C at 15:00 and after sunset, the temperature dropped slowly and the minimum value was 46.5°C at 4:00 am. Fig. 3 shows the measured sunlight hours are from 8:00 to 19:00, the maximum solar irradiation was 863 W/m^2 at 12:00, and the daily solar irradiation was 12.15 KW/m^2.

It is found in Fig. 4 that a positive correlation between the water temperature and the hourly water yield, the maximum hourly yield was 0.77 L at 15:30, given that the better thermal insulation, the evaporator chamber temperature drops slowly and thus the desalination system could operates during night time. The minimum hourly yield was 0.173 L at 4:00, and the total daily yield was 9.38 L.

In order to calculate the annual yield of the solar system, the seasonal variations were also considered, and all

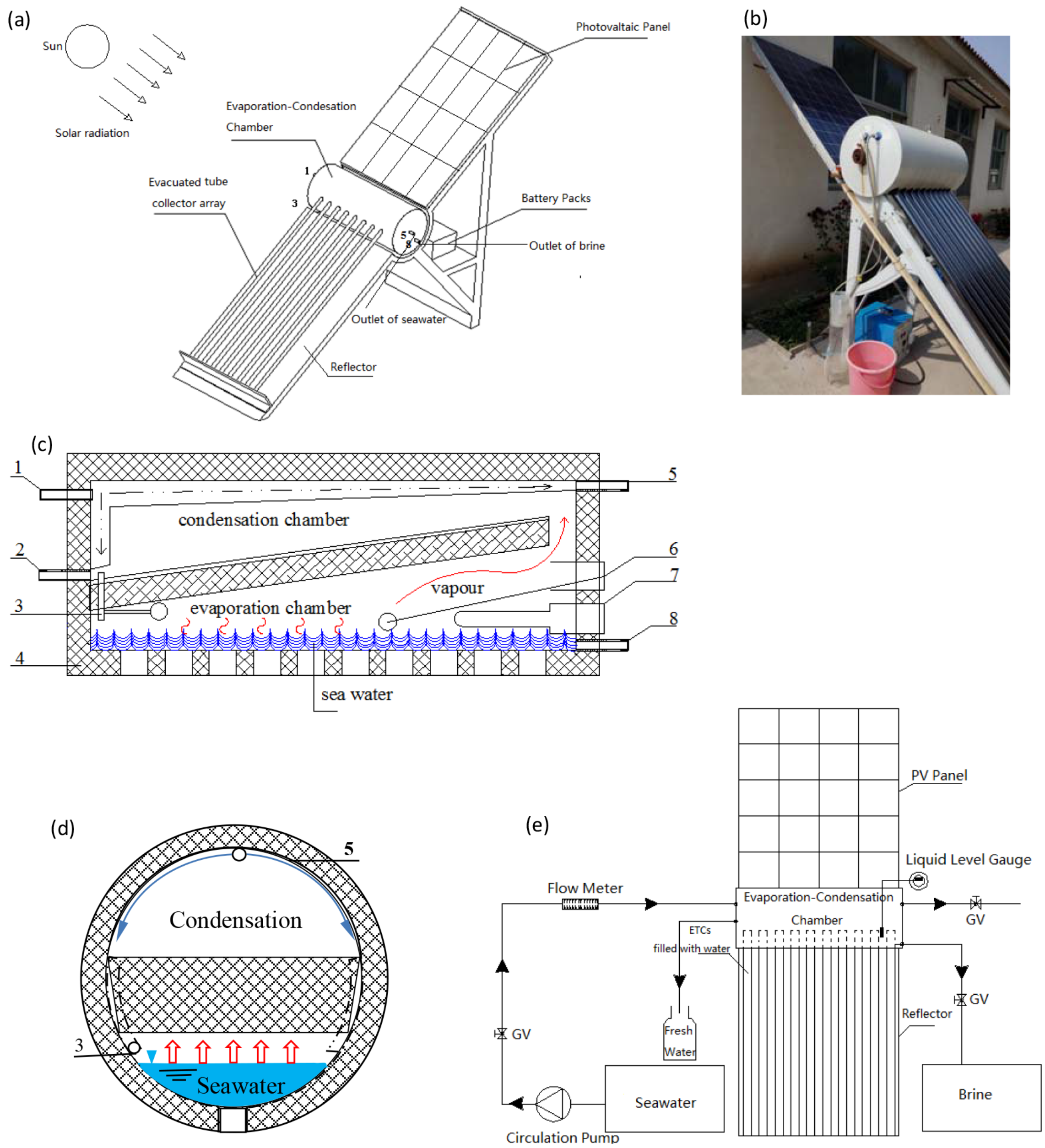

Fig. 2 (a) 3D view of TSS with ETCs and PV panel, (b) pictorial view of the TSS with ETCs and PV panel, (c) and (d) Detail view of TSS, (e) Schematic view of our desalination system.

the experiments were conducted in the clear days in April, July and November under the metrological conditions in Qingdao (36.04°N, 120.19°E), China. It was calculated that the average daily water yield of our system in spring, summer, autumn and winter was 8.2, 9.37, 7.7 and 4.9 L respectively, and the average daily water yield was 7.5 L.

3.2. Other desalination systems

In order to analyze the cost efficiency of our solar desalination system, some similar solar desalination systems published in journals were selected to compare with us, and the comparative result are shown in Table 4.

As observed from Table 4, the highest water productivity was carried by Kabeel et al. They use various nanomaterials to enhance the solar absorption and provide a vacuum evaporation condition, which significantly enhances both productivity and efficiency of the still. However, this modification inevitable increases the system capital cost and in turn raise the productivity cost. The second-highest water productivity is obtained by a compound parabolic concentrator- tubular solar system (CPC-TSS), the system performance is enhanced by integrating another pyramid-type solar still, the much higher water productivity results from the large collector area (tubular and pyramid solar still). our systems daily yield was 7.5 l, which is better than most systems list above, and

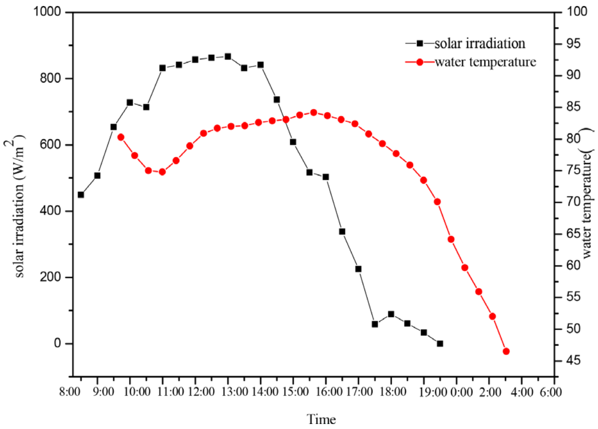

Fig. 3. Solar irradiation and water temperature.

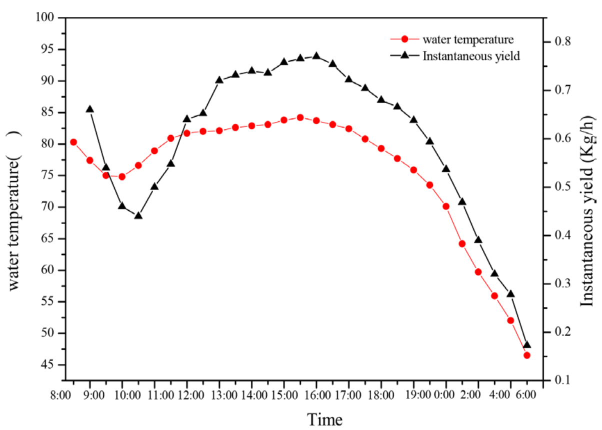

Fig. 4. Water temperature and instantaneous yield.

the collector area was 1.75 m^2, which is relatively lower than some desalination stills with similar daily yields.

4. Economic analysis

Since different solar desalination systems are applied in different areas, it is too hard to point which one is better. Thus, economic analysis of each system may be a rational comparative method. Many researchers have put forward different economic analytical methods for calculating the water cost of solar desalination systems. However, a cost evaluation method proposed by Goosen [25] was adapted widely in single desalination system. In order to calculate the cost per liter (CPL) of fresh water, it is necessary to determine the annual water yield of solar still (M) and the total cost of the system, including capital, operating and maintenance costs over a certain period of time. The total cost of the desalination system as a function of the actual annual cost (AC) can be expressed as

Actual annual cost (AC) = The first annual cost (FAC) + Annual operating and maintenance cost (AMC) – Annual salvage value (ASV) (1)

In Eq. (1), if P is the capital cost of the system and CRF is the capital recovery factor, the first annual cost of system, FAC, can be determined as

$$FAC = P \times CRF \tag{2}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

Table 4
Characteristic of the different solar desalination systems

Type of solar still	Collector areas, m^2	Average daily productivity, l	Location	Operation hours, h	Ref.
CPC-TSS with pyramid solar still	3	7.8	India	8	[15]
CPC-TSS with single slope still	2.25	6.5	India	8	[15]
Compound parabolic concentrator- tubular solar still (CPC-TSS)	2	5	India	8	[15]
Solar still integrated with ETCs	1	3.78	India	23	[16]
Square fin type with wicks	1	3.29	India	9	[17]
Fin type solar still powered by fin type solar pond	1	3	India	8	[18]
Basin solar still with flat plate collector	0.648	3.5	India	9	[19]
Conventional solar still integrated with a solar parabolic trough	1	1.55	Egypt	11	[20]
Still coupled with vacuum fan and using cuprous oxide nanoparticles	0.5	9	Egypt	8	[21]
Solar still with a separate air-cooled condenser working at sub-atmospheric	0.25	7.2	Egypt	11	[22]
Solar still integrated to evacuated tube collectors and thermoelectric modules	1	6.2	Iran	8	[23]
TSS coupled with a ETCs and PV panel	1.75	7.5	China	24	Our system

where i is the interest rate of the lending bank, which is 4.6% in this study; n — the number of life years, which is assumed as 15 years.

The annual operating and maintenance costs (AMC) are the total yearly costs of operating and maintaining the desalination system, including amortization or fixed charges, operation and maintenance and parts replacement costs. According to Goosen's suggestion, a fixed percentage of the first annual cost (FAC) has been considered.

$$\text{AMC} = 0.05\text{FAC} \tag{4}$$

The salvage value (S) of the system is the expected market value at the end of useful life of system, this usually considered to be 20% of the usable material cost, the annual salvage value, ASV, can be determined as

$$ASV = S \times SFF \tag{5}$$

$$\text{S} = 0.2\text{P} \tag{6}$$

where SFF is the sinking fund factor

$$\text{SFF} = \frac{\text{i}}{(1+\text{i})^{\text{n}} - 1} \tag{7}$$

Finally，the cost per liter (CPL) as a function of the actual annual cost (AC) and annual water yield can be expressed as

$$\text{CPL} = \frac{\text{AC}}{\text{M}} \tag{8}$$

Based on the equations mentioned above, the CPL of our desalination system is determined by the AC and the M, considered that the AC and P are closely linked, thus the CPL can be determined by P and M. The P usually overs the cost of equipment, auxiliary equipment, land, installation charges and water pre-treatment. The P of our solar desalination system can be expressed as follows:

$$P_{Total} = P_{TSS} + P_{ETC} + P_{PV} + P_{auxiliary\ equipment} \tag{9}$$

In our desalination system part, the P_{TSS}, P_{ETC}, P_{PV}, $P_{auxiliary\ equipment}$ have been calculated, are 165 US$, 23 US$, 150 US$ and 86 US$ respectively. Thus, the P of our system is 424 US$. Given that the system will be out of operation for 15 days for maintenance purposes during the year, so the annual water yield, M, can be calculated for 350 days using the average daily yield.

Based on the equations mentioned above, the calculating process of the CPL of our system is listed in Table 5, it is show that the CPL of our desalination system is 0.016 US$/L. This cost is still high, however, if the cost of transportation and environment is considered, our system shows high feasibility for application in rural area and island.

This paper analyses the cost performance of other desalination systems using the above method. The results are listed in Table 6. It can be seen that the P of 140$ for the conventional desalination system seems to be the lowest, but the M of this system is very low, resulting to a relatively high CPL of about 0.046 US$/L [3], our system has the highest capital cost, P, about 424 US$/L, but because of the high M, the CPL is relatively low, therefore, CPL is not proportional to the P. Both P and M affect the economic feasibility of the solar desalination system.

5. Conclusion

This paper presented a novel solar desalination system and evaluated its economic feasibility by comparing the CPL of previous solar desalination systems. It is unfair to compare the CPL of small scale desalination system with a lager one, because rural areas and islands can only established a small scale system. Taking into account the limited power infrastructure and the transportation costs, small scale solar desalination system is well adapted in these special areas.

Our system is composed of three main parts, and the P was 435 US$ while the M was 2625 L, so the CPL was calculated as 0.016 US$/L, which is a rational price compared with other solar desalination.

The CPL is significantly affected by two parameters, one is the P, the other is the M. The most economic system must find the balance between the P and M.

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Table 5
Calculating process of the CPL of our system

Input	Formula	Output	Input	Formula	Output
PTSS, PETC, PPV, P auxiliary equipment	(9)	P = 424 US$	SFF,S	(5)	ASV = 4.0 US$
i = 4.6%	(3), (7)	CRF = 0.094	FAC, P, AMC,	(1)	AC = 41.7 US$
n = 15		SFF = 0.048	ASV		
CRF,P	(2)	FAC = 39.8 US$	D = 250 days	(10)	M = 2625 l
FAC	(4)	AMC = 6.0 US$	AC, M	(8)	CPL = 0.016 US$
P	(6)	S = 84.8 US$			

Table 6
Cost analysis of different solar desalination systems

NO	n (y)	i (%)	P ($)	CRF	FAC ($)	S ($)	SFF	ASV ($)	AMC ($)	AC ($)	M (L)	CPL (US$)	Ref.
1	15	6	279	0.103	28.7	55.8	0.043	2.4	4.3	30.6	1625	0.019	[15]
2	15	6	319	0.103	32.8	63.8	0.043	2.7	4.9	35.0	2113	0.017	[15]
3	15	6	359	0.103	37.0	71.8	0.043	3.1	5.5	39.4	2535	0.016	[15]
4	10	12	381	0.177	67.4	76.2	0.057	4.3	10.1	73.2	983	0.074	[16]
5	30	12	154	0.124	19.1	30.8	0.004	0.1	2.9	21.9	755	0.029	[17]
6	5	12	154	0.277	42.8	30.8	0.157	4.9	6.4	44.3	905	0.049	[17]
7	10	12	310	0.177	54.9	62.0	0.057	3.5	8.2	59.6	780	0.076	[18]
8	10	12	192	0.177	33.4	38.4	0.057	2.2	5.1	37.0	910	0.041	[19]
9	10	12	140	0.177	24.8	14	0.057	0.8	1.2	25.2	553	0.046	[20]
10	10	12	268	0.177	47.4	53.6	0.057	3.1	7.1	51.5	2340	0.022	[21]
11	10	12	195	0.177	34.5	19.5	0.057	1.1	1.7	35.1	643	0.055	[22]
12	20	10	235	0.117	27.6	23.5	0.017	0.4	4.1	31.3	2258	0.014	[23]
13	15	4.6	424	0.094	39.8	84.8	0.048	4.0	6.0	41.7	2625	0.016	Our system

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