Discover Water

Research

Water desalination using PV panels based on boiling and evaporation

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Abstract

The annual share of water in Egypt has decreased to approximately 500 m^3 per capita, while the annual water scarcity level is 1000 m^3 per capita, which indicates that Egyptians are at a high risk of living. A domestic desalination unit based on solar energy was designed, built, and tested to solve this problem in remote areas that do not have access to fresh water or electricity but have access to salty water. The desalination unit has a new design that depends on boiling salty water using photovoltaic solar cells and then condensing the water vapor through a heat exchanger to obtain freshwater. This new design has not been implemented before and can compete with the solar stills used for domestic applications. The output of the developed unit was compared to those of passive and active solar stills that have been developed and built. The new desalination design produced almost the same amount of daily fresh water, 4 Liter/day, compared to the other solar stills (2–4.75 Liter/day), but the cost per unit volume of the new design, 31 $\$/m^3$, is less by 30% compared to the best performing solar still, 44.55 $\$/m^3$, which produces only 2 Liter/day. The price of the distilled water produced by the new design was 75% lower than the market price at the time of conducting the experiments. Converting a Solar still from a passive system, that is, operating only during sunlight, to an active system operating day and night improves the water productivity rate. However, this is not feasible because of the added accessories that increase the initial cost, consequently increasing the cost of desalination.

Keywords Thermal desalination · Distilled water · Solar stills · Renewable energy

Abbreviations

AC	Alternating current
AMC	Annual operating and maintenance cost
ASV	Annual salvage value
CRF	Capital recovery factor
DC	Direct current
FAC	Fixed annual costs
IC	Initial cost
MENA	Middle East and North Africa
PPM	Parts per million
PV	Photovoltaics
RO	Reverse osmosis
SC	Salvage cost
SFF	Sinking fund factor

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TAC	Total annual cost
W	Watts

List of symbols

i	Interest rate
L_a	Annual freshwater productivity
L_d	Daily freshwater productivity
n	Lifetime of the system

1 Introduction

The world's population at the beginning of 2021 is over 7.7 billion people according to World meters [1]. Although the world has a lot of fresh water for each one, most of it is stored in ice form in the north and south poles, so what is left of the fresh water is stored in lakes and rivers such as the Nile River [2]. There are now about 1 billion people who have water scarcity problems, which means that they have less than 1000 m^3/year per capita of fresh water. The absolute minimum water scarcity level is 500 m^3/year per capita. In contrast, the Middle East and North Africa (MENA) region had an average of 351 m^3/year in 2014. These numbers demonstrate the importance of using water desalination as an alternative source of freshwater, as indicated by El Kharaz [3]. For this reason, in a country such as Egypt, which depends almost 100% on the Nile River for its freshwater source, still has a serious problem in 2023 with the Ethiopian government, when Ethiopia declared to reduce the flow rate of the Nile River by over a third of the average flow rate of 55 billion m^3/year [4]. The Water desalination industry can vary in capacity from a few liters per day from sources such as solar stills [5] to over one million m^3/day in Ras Elkhair, Saudi Arabia, as mentioned by Aquatech [6]. This huge difference made research on the whole sector very difficult unless it was categorized into industrial and domestic scales. The inverse relation between the water price and productivity in three desalination plants is shown in Fig. 1, as have been conducted by Mentis et al. [7]. The best-fit curve was constructed for these three points has been made. If the same curve equation was used to evaluate productivity rates for less than 1 m^3/day, the values would be greater than 67 €/m^3, which is the case for some solar stills, as shown in Table 1 [8]. In addition, because of the high energy requirements of desalination, as indicated by Nassrullah et al. [18] and the 2030 World Agenda for Clean energy sources [19], renewable energy sources should be considered. Although the initial cost of desalination units with renewable sources is still higher than that of nonrenewable sources, the decline in the cost of renewable energy sources, such as PV panels, makes the cost gap between the non-renewable desalination units and the renewable desalination units much smaller [20, 21].

At the industrial scale, there is also a large range of capacities, ranging from approximately 10 m^3/day [22] to over 100 thousand m^3/day. Large-scale desalination systems have several points in common, but the main reason is that the initial cost of the plants is very high, whereas the price of water per m^3 is low [23]. At the industrial scale, there are two main types: (1) thermal-based desalination and (2) membrane-based desalination [24]. Reverse Osmosis (RO) desalination systems depend on pumping water through membranes at high pressures to produce less saline water and brine. RO systems have the largest share in the desalination market, followed by multistage flash distillation [25]. On the other hand, domestic-scale desalination consists mainly of solar stills, as mentioned by Kedar et al. [26]. Unlike most desalination plants, solar stills only use sunlight, unlike the non-renewable sources used by desalination plants. Solar stills are mainly used in the domestic market due to its low initial cost and low complexity, but at the same time the price per

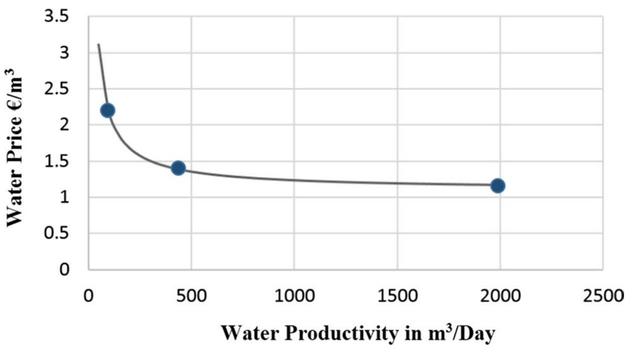


Fig. 1 Water price in €/m^3 verses productivity in m^3/day [7]

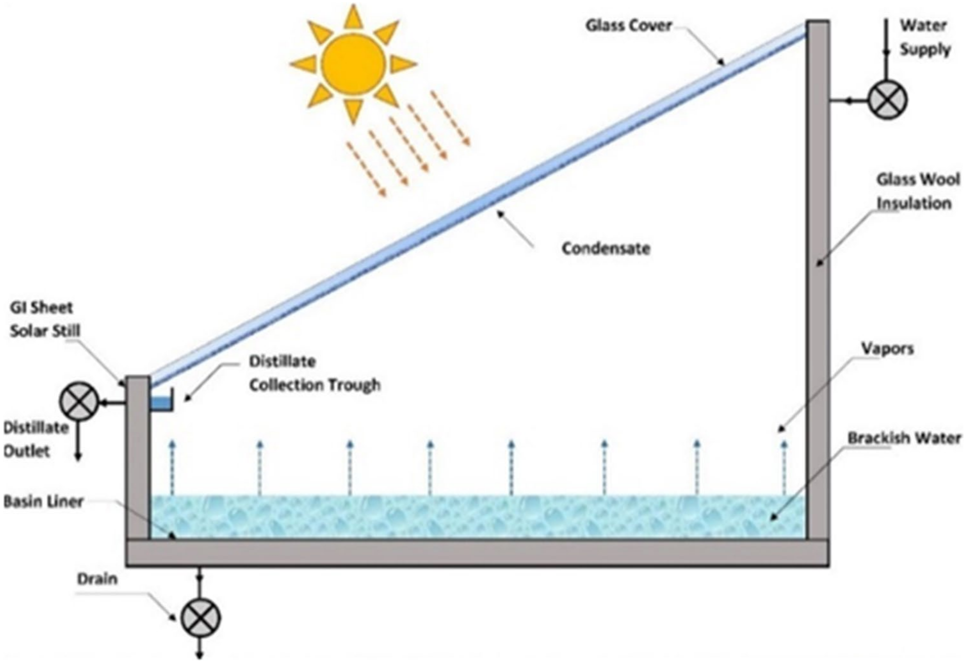
Table 1 Water desalination prices based on solar stills (S.S.) [8]

$/m^3	Maximum (Liter/m^2)	Description	References
243	3.41	S.S. using shape stabilized PCM	[9]
25.2	4.62	S.S. with thermoelectric cooling and nanofluid	[10]
24	4.71	Tubular S.S. with parabolic concentrator	[11]
15.3	6.56	S.S. with PCM and heat pipe	[12]
12.1	6.3	Inverted absorber S.S	[13]
12	68 (using motor and fan)	S.S. with solar heater	[14]
5.8	6.1	S.S. with parabolic solar collector	[15]
20	3.63	Tilted wick type S.S	[16]
32.2	Not available	Dual effect tubular S.S	[17]

liter is much higher compared to the systems in the industrial scale as shown in Table 1. In some cases, the reported daily freshwater production is only 2 L [27]. Solar stills desalinate saline water using sunlight to evaporate the water in a basin filled with saline water. Subsequently, the water vapor rose and condensed on a tilted glass at the top of the basin. Because the glass is tilted, freshwater droplets go down the glass until they are collected and stored, as shown in Fig. 2. This type of solar still is called passive solar still. This process has a very low water-production rate. Although some solar stills have different geometries, their production rates are still low compared to those of other types of active solar stills. Active solar stills are more complex than passive stills because they use electric devices such as heaters to increase the evaporation rate, as shown in Fig. 3. The heater power can come from typical electrical outlets; however, in the case of remote locations, batteries or any other source of power not connected to the grid can power the heaters. PV panels can be used as a source of energy for power devices to increase their production rate. Simultaneously, the cost of the devices associated with the PV panels, such as the inverter, batteries, and charge controllers, increases the initial price of the entire system, thereby reducing the main advantage of solar stills.

The purpose of this study is to improve the feasibility of domestic-scale water desalination units, that is, to reduce the price per liter of distilled water. A new design for water desalination units for domestic applications was developed based on the boiling of salty water and then condensing the water vapor into fresh water. The source of electrical energy to power the heaters was PV panels. In addition, a traditional solar still system for water desalination, based on the evaporation of water, was built to compare the output with that of the developed system. The designed solar still is based on up-to-date solar stills, which use additional heaters to increase the evaporation rate, consequently increasing

Fig. 2 Schematic diagram of a conventional passive solar still [28]



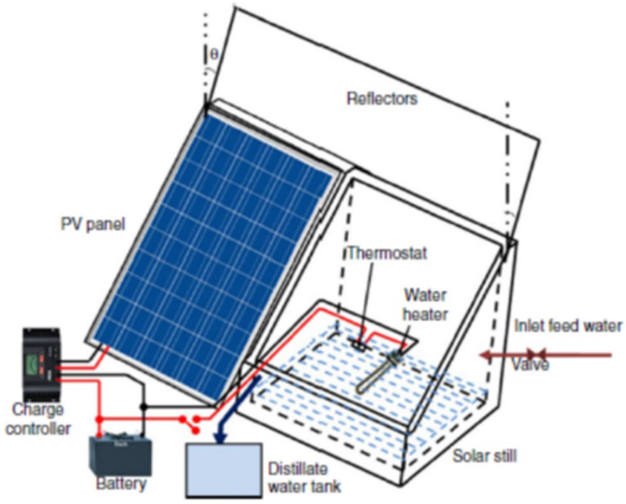


Fig. 3 Active solar still with PV powered heater [29]

water production, and the source of electrical energy is again PV panels. The new domestic water desalination design was compared to solar stills in terms of output water productivity, overall costs, and price per unit volume. The purpose of this comparison is to determine which system is more efficient in terms of the price per unit volume, which is an important economical variable that determines with great accuracy which system is better economically and practically. All experiments were performed on the same days so that the comparison is made under the same operating conditions of solar irradiance and ambient temperature. The average results were recorded and used to perform calculations to determine the best-performing water desalination system.

2 Experimental setup

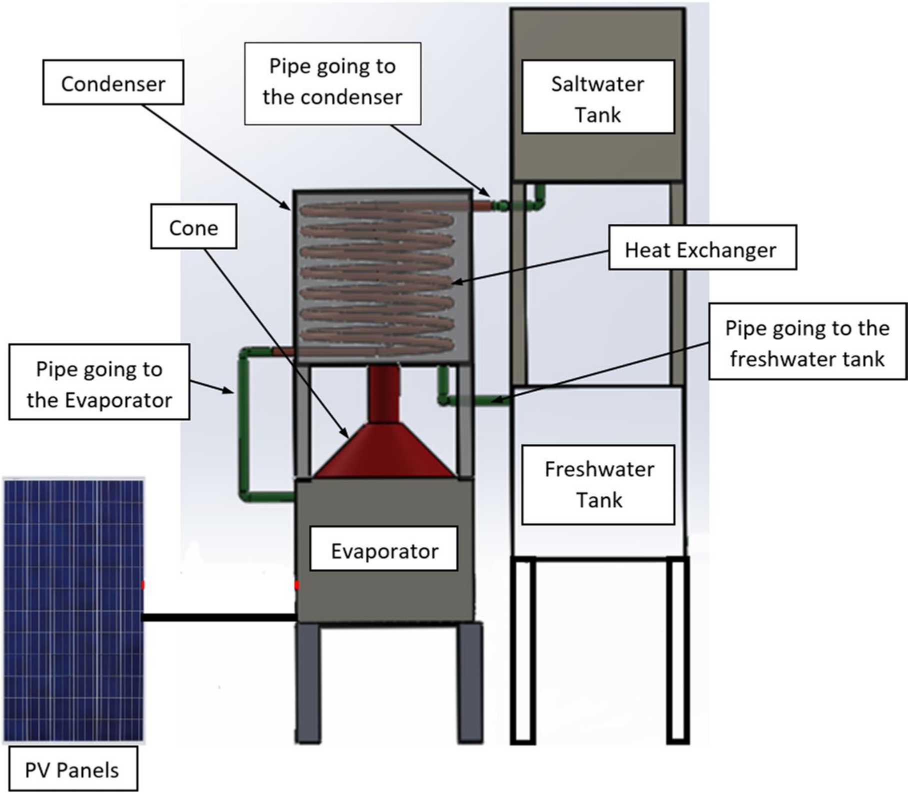
Two water desalination systems were developed: System 1 was based on the boiling of salty water, and System 2 was based on water evaporation. Both systems are discussed below.

2.1 Water desalination system based on boiling (first system)

The first water desalination system, system 1, depends on water boiling and consists of a saltwater tank, condenser, freshwater tank, and an evaporator, as shown in Figs. 4 and 5. The saltwater tank is placed above the water vapor condenser, and the condenser is placed above the water evaporator. The saltwater tank is a19-liter tank bottle, which is placed upside down to allow the salty water to flow downwards by gravity, in order to prevent the use of a water pump and reduce the overall cost of the system. The salty water flows from the saltwater tank into a heat exchanger, which is placed inside the water vapor condenser and then to the evaporator, as can be seen in Figs. 4 and 5. The first medium of the heat exchanger is the cold salty water from the saltwater tank, which passes through the tubes of the heat exchanger until it reaches the evaporator. The second medium of the heat exchanger is the hot water vapor rising from the evaporator, which flows externally over the tubes of the heat exchanger. As the water vapor passes over the cold tubes of the heat exchanger it transfers its latent heat of condensation to the incoming salty water, such that the vapor condenses to liquid on the tubes and fins of the heat exchanger while the salty water is heated. The heat exchanger of the condenser has a dual function, i.e. preheating the salty water before it enters the evaporator and condensation of the water vapor, which is coming from the evaporator. This preheating step of the salty water reduces the electrical power of the evaporator heater as well as the PV panels. Afterwards, the condensed water vapor then falls down to the bottom surface of the condenser. The bottom surface of the condenser is inclined at an angle of 30° such that the condensed freshwater can flow downwards by gravity into the freshwater tank, which is positioned below the level of the condenser, as shown in Fig. 4.

After the salty water passes through the heat exchanger of the condenser and is preheated, it flows downwards by gravity into the evaporator, as shown in Fig. 4. The evaporator contains an electric heater and a siphon pipe. The purpose of the siphon pipe is to close and open automatically the salty water flow coming from the condenser. There are

Fig. 4 Schematic of system 1



two limits in the siphon pipes, as shown in Fig. 6. The first limit occurs when the rod holding the floating ball makes an angle 9° below the horizontal. At this point, the salty water level has reached the maximum height in the evaporator, and the water inlet valve is fully closed so that no more water could enter the evaporator until some water is boiled. The second limit is reached when the rod makes an angle of 29° below the horizontal, such that the water inlet valve is fully opened and the salty water can flow into the evaporator. The siphon pipe reduces the overall cost of the system by eliminating the need for a level sensor and motor to control the flow of the salty water into the evaporator. After the salty water gains thermal energy in the heat exchanger of the condenser and is heated directly through the electric heater in the evaporator, water turns into steam. The generated steam exits the evaporator through the cone directly into the condenser, as shown in Figs. 4 and 5.

The electric heater of the evaporator is operated by a set of PV panels of a total power of 520 W. The main difference in the mentioned system over solar stills of the same capacity size is that this system heats the water to the boiling point, whereas solar stills use a heater to increase the evaporation rate. The main obstacle facing small-capacity desalination systems that use heaters for boiling water is fouling, that is, the accumulation of salts on the heater surface. When the accumulation increased, an insulation layer was created between the water and heater. This insulation layer reduces the overall productivity of freshwater, particularly in heat-driven desalination. In addition, if the system is not designed to handle the accumulation, the production rate can reach zero, as the salts block the heat transfer from the heater to the water. This problem has been addressed in large-scale desalination systems such as Membrane Distillation [30]. On the other hand, small-scale production units, such as solar stills, do not handle this problem because the heater is used only to increase the evaporation rate, and after a while, the brine is thrown away from the basin of the still. This is the first time that fouling has been handled using the electric shock method in small-scale desalination [31, 32]. This is done by simply letting the heater run for 5 min without water and then turning it off, such that the heater contracts more than the fouling layers because of the difference in the coefficient of thermal expansion, causing cracks in the layer and falling off the heater's surface. Then the evaporator is flushed by opening the drain pipe at the bottom side of the evaporator to allow the fallen salts to come out together with the flushing water. This cleaning process could be done weekly or monthly depending on the salinity of the salty water.

Fig. 5 Full view of the developed water desalination system, which consists of a salty water tank, condenser and an evaporator. In the zoomed picture of the Evaporator, (1) is the electric heater, (2) is the Siphon pipe and floating ball and (3) is the cone going from the evaporator to the condenser

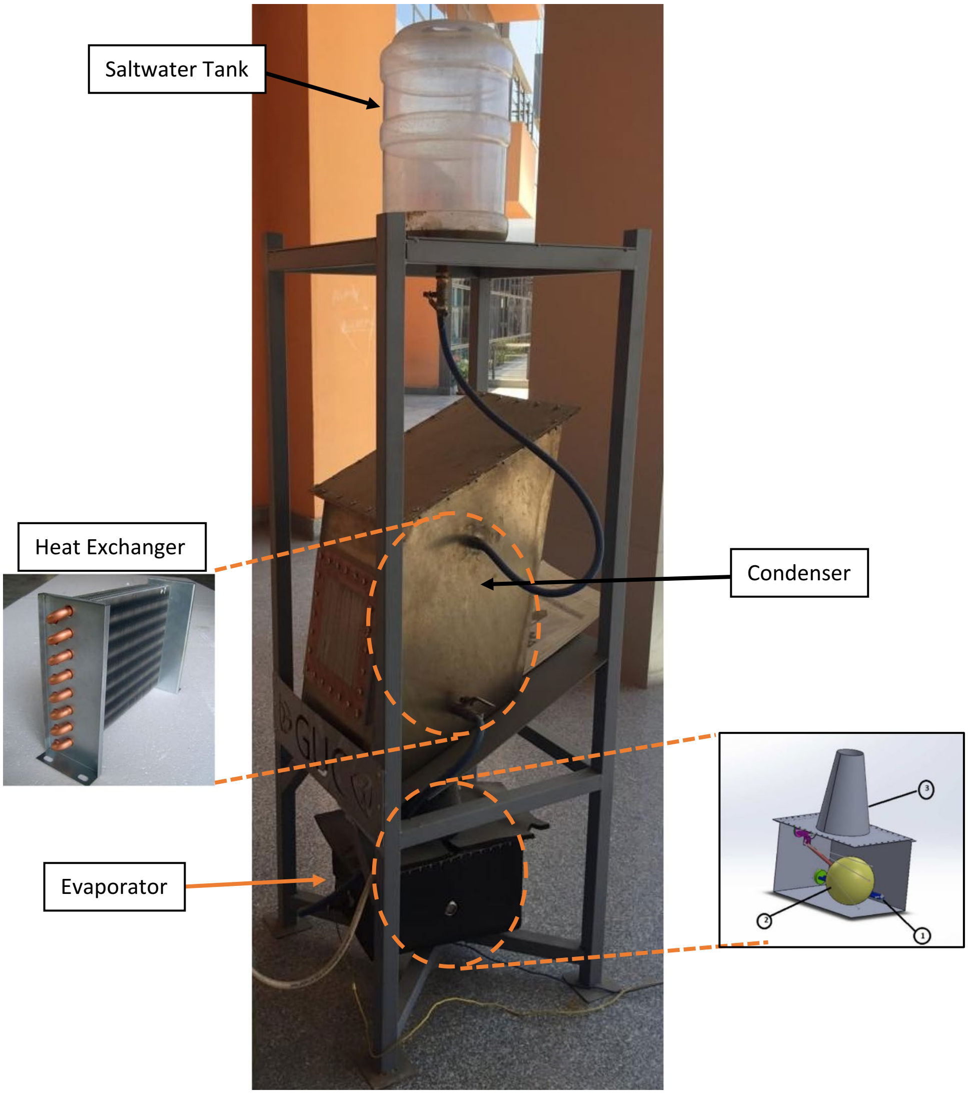
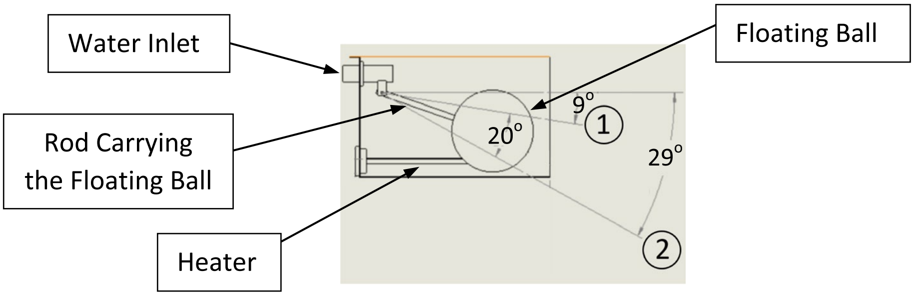


Fig. 6 Floating ball positions: (1) the water inlet is fully closed and (2) is fully opened



2.2 Water desalination system based on evaporation (second system)

The second desalination system was based on water evaporation and consisted of one solar still, as shown in Fig. 7. The solar still was tested under two conditions: first, when it was not connected to the PV panels, that is, the passive case, and when it was connected to the PV panels, that is, the active case. The Solar Still has an inclination angle of 30° towards the south for the glass cover and a basin area of 0.5 m^2. The enclosure is made of plywood to provide heat insulation because plywood is a poor conductor of heat. Subsequently, the enclosure is covered with foam boards to provide an extra insulation layer so that no heat loss occurs through the walls or the basin of the entire system. The

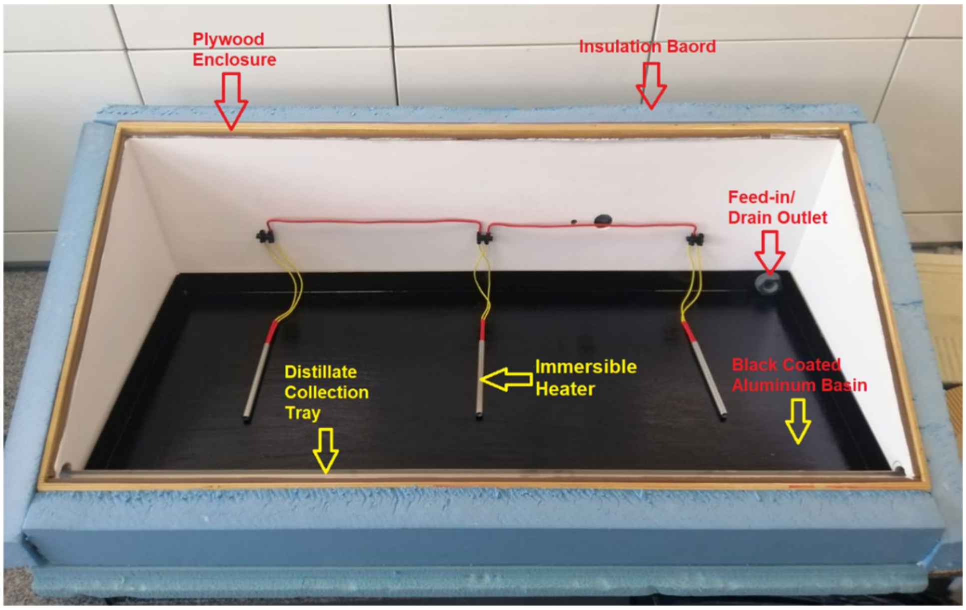


Fig. 7 The second setup is an active solar still which contains an electric heater

solar still basin was coated with black light. The black coating provided the maximum possible absorption of sunlight to maximize salty water heating. At the bottom of the basin, there was a drain for leftover brine after desalination was complete. The active solar still had three electric heaters immersed in a saltwater basin to increase the evaporation rate. The heaters were powered by four 130 W PV panels. The power from the panels was passed through a solar charge controller. This charge controller is connected to a set of two batteries and an inverter to convert the current from DC to AC. Batteries are used to maintain the evaporation of salty water for several hours after the sun is down and under dim-light conditions. A temperature controller was used to set a predetermined water temperature for saline water in the basin.

In the experiments conducted on the active solar still, one and two fans of 5 W power were installed inside the enclosure to increase the airflow of the air inside the solar still. This was performed to increase the water condensation rate, that is, the freshwater productivity rate. The flow of water was as follows: first, the salty water was placed in the basin. Subsequently, when the sun shines on the solar still and PV panels, the water starts to evaporate. The evaporation rate in the active solar still case is higher than that in the passive solar still case. The reason for this increase is that the water in the active case was heated using direct solar energy, in addition to the thermal energy coming through the heater. When the water vapor reached the glass surface, it began to condense. At this time, the condensed water was fresh, and the remaining water was highly saline, that is, brine. Fresh water was collected using a tube placed at the bottom of an inclined glass in both solar stills. When the sun goes down, evaporation in the first passive solar still stops, and it continues in the second one, that is, the active solar still, because of the charged batteries that continue the evaporation process even after the sun sets. When the energy in the batteries is finished, evaporation stops in the active solar still. At this time, the drain outlet shown in Fig. 7 was opened to remove the brine and allow new salty water to enter and begin the process all over again on another day.

3 Results

The water productivity rate of the water desalination systems, based on boiling and evaporation, was recorded for four days; then, the average was calculated, and the results are presented in Fig. 8. The presented results are for water desalination based on boiling using System 1 and evaporation using a solar still, that is, System 2, in the case of no night heating (system 2-passive), night heating without a fan (System 2, active) with one fan (System 2, active with one fan), and with two fans (System 2, active with two fans). The two vertical lines in Fig. 8 represent sunrise and sunset times, respectively. It can be seen that the water productivity continued after sunset, which is the case for System 2 with the active condition cases. This is because System 2 has batteries installed in it, such that productivity continues throughout the night until all the energy of the batteries is consumed by the heaters and fans. The maximum water productivity per day in the

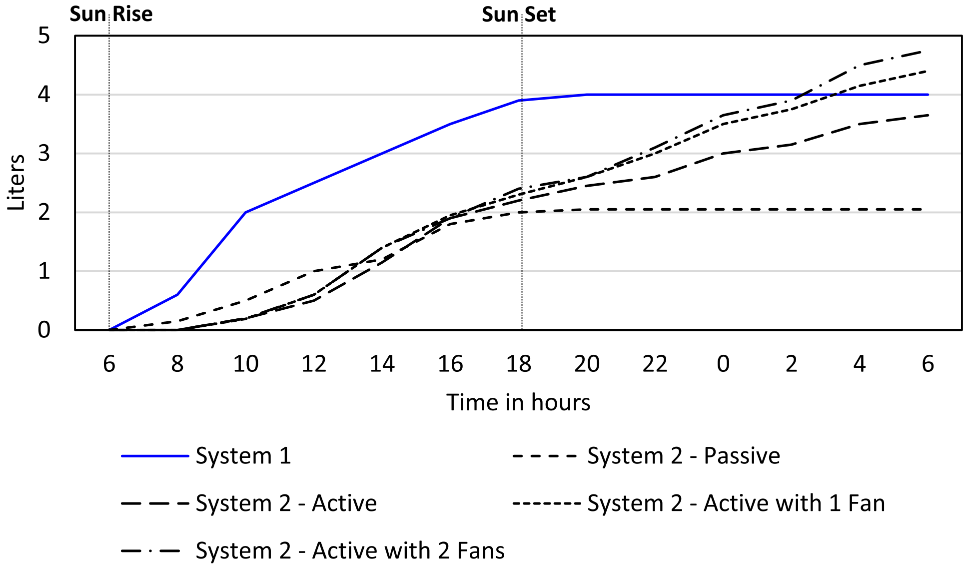


Fig. 8 Average Fresh water productivity based on boiling using system 1, and evaporation using a solar still, i.e. system 2, in case of passive heating, active night heating, and active night heating with 1 fan and 2 fans

case of system 1 was 4 lit, and in the case of system 2 without night heating, that is, the passive case, it reached 2.05 lit. However, the water productivity in the case of system 2 with night heating, i.e., the active case, has reached 3.65 lit, and increased to 4.4 lit and 4.75 lit in the case of adding 1 fan and 2 fans inside the solar system, respectively. Forcing air to the glass cover of the solar still increases the condensation rate compared to its dependence on natural circulation. The PPM of distilled water achieved by system 1 was 4 ppm and that for system 2 was 14 ppm.

The main factor that differs between desalination systems from another one is the price per unit volume of desalinated water. The solar still systems and the new design system are compared based on the water price per unit volume, which is an important economical variable. An economic study was conducted to determine the price of distilled water per m^3 for both techniques presented in this paper, based on boiling and evaporation, and then the results were compared to the market price. The assumptions made to determine the cost per unit volume in this economic study are listed in Table 3. The lifetime of the system, n, is assumed to be 10 years, the interest rate, i, is assumed to be 12%, and the Salvage Cost (SC) is the cost of the system at the end of its lifetime; this variable is assumed to be 20% of the Initial Cost (IC) [33]. Assuming that the initial cost of the system is borrowed, the Capital Recovery Factor (CRF) provides the percentage of money that should be paid each year [34], that is, the loan annual installments that should be paid to the bank. The Sinking Fund Factor (SFF) is used to calculate the future value of a product in terms of annual cash cheques [35]. The Total Annual Cost (TAC) is the overall cost the system needs to maintain operation in terms of Fixed Annual Costs (FAC) and annual operating and Maintenance Costs (AMC) minus the Annual Salvage Value (ASV). The values used in the cost analysis were based on the Egyptian environment, as discussed by Kabeel et al. [33].

Table 2 lists the price breakdowns for the individual components used in Systems 1 and 2. The prices mentioned in this table assume that the lifetime of the system is 10 years. Battery Blocks, for example, have a lifetime of 4 years with a price tag of 150$ so the final price that was used in the table is adjusted so that the battery blocks will be used for 10 years. This is done by multiplying 150$ by 10/4 to 375$, as presented in Table 2. The same procedure was performed for everything used, which had a lifetime of < 10 years.

The PV panels used were a set of four panels, each with a power of 130 Watt. Two individual Varta car battery blocks were used such that each had a capacity of 70 AH and nominal voltage of 12 V. The Ep Solar Tracer 4210RN MPPT 1000W(24 V) was used as the charger controller. The MW Mean Well, power inverter, 600 W, 12VDC/230VAC, was used as the DC/AC Power Inverter.

A cost analysis for each system studied in this research is presented in Table 4, which is based on the assumptions listed in Table 3, and the final Initial Cost prices of Systems 1 and 2 listed in Table 2. It can be concluded from the presented cost analysis that system 1 has the lowest desalination price, i.e., 31 $/m^3$, compared to system 2. Although system 2-active with one and two fans has a higher productivity rate than system 1, the desalination cost of system 2 is higher than that of system 1, which is due to the installed batteries and charger controller that resulted in a higher desalination price. The price of deionized water in the market is about 0.125 $/L [36]; however, the highest desalination price achieved in this research, which is of System 2 & Active, is 0.093 $/L, which is approximately 25% less than that available in the market,

Table 2 Price breakdown of each system

Item description	System 1	System 2, i.e., solar still, with			
		No night heating (Passive)	Night heating (Active)	Night heating and one fan	Night heating and two fans
PV Panels	200	0	200	200	200
Thermostat	0	0	25	25	25
*Battery blocks	0	0	375	375	375
Solar charger controller	0	0	80	80	80
DC/AC power inverter	0	0	100	100	100
heaters	22	0	66	66	66
Solar still unit	0	193	193	193	193
System 1 unit including supports	203	0	0	0	0
Wires and cables	11	0	24	24	24
Solar still supports	0	128	128	128	128
Fans	0	0	0	13	25
Total	436	321	1191	1204	1216

All costs are in $

*The given prices are based on a lifetime of 10 years

Table 3 The assumptions and models used for water desalination cost analysis are listed in Table 4

Exchange rate	18.5 EGP/USD, rate in May 2022	Sinking fund factor (SFF)	$SFF = \frac{i}{(1+i)^n-1}$
Life time of system, n	10 Years	Fixed annual cost (FAC)	FAC = CRF X IC
Interest per year, i	12%	Annual operating and maintenance cost (AMC)	10% × FAC
Salvage cost (SC)	20% of the initial cost (IC)	Annual salvage value (ASV)	ASV = SFF × S
Capital recovery factor (CRF)	$CRF = \frac{i(1+i)^n}{(1+i)^n-1}$	Total annual cost (TAC)	TAC = FAC + AMC −ASV
Annual cost per liter (CPL) of distilled water produced, $CPL = \frac{TAC}{L} X1000$ (\$/m^3)			

Table 4 Cost analysis of different desalination systems presented in this study

	System 1	System 2, i.e. Solar still, with			
		No night heating (Passive)	Night heating (Active)	Night heating and one fan	Night heating and two fans
Initial cost (IC)	436.00	321.00	1191.00	1204.00	1216.00
Salvage cost (SC)	87.20	64.20	238.20	240.80	243.20
Interest rate, %	12.00	12.00	12.00	12.00	12.00
Capital recovery factor (CRF) %	11.10	11.10	11.10	11.10	11.10
Sinking fund factor (SFF)	0.09	0.09	0.09	0.09	0.09
Fixed annual cost (FAC)	48.30	35.63	132.20	133.64	134.98
Annual operating and maintenance costs (AMC)	4.84	3.56	13.22	13.36	13.50
Annual salvage value (ASV)	7.96	5.86	21.75	21.99	22.20
Total annual cost (TAC)	45.27	33.33	123.67	125.02	126.27
Daily freshwater productivity, L_d	4.00	2.05	3.65	4.40	4.75
Annual freshwater productivity, L_a	1460.00	748.25	1332.25	1606.00	1733.75
Annual cost per m^3 of distilled water in \$/m^3	31	44.55	92.83	77.85	72.83

All costs are in USD ($)

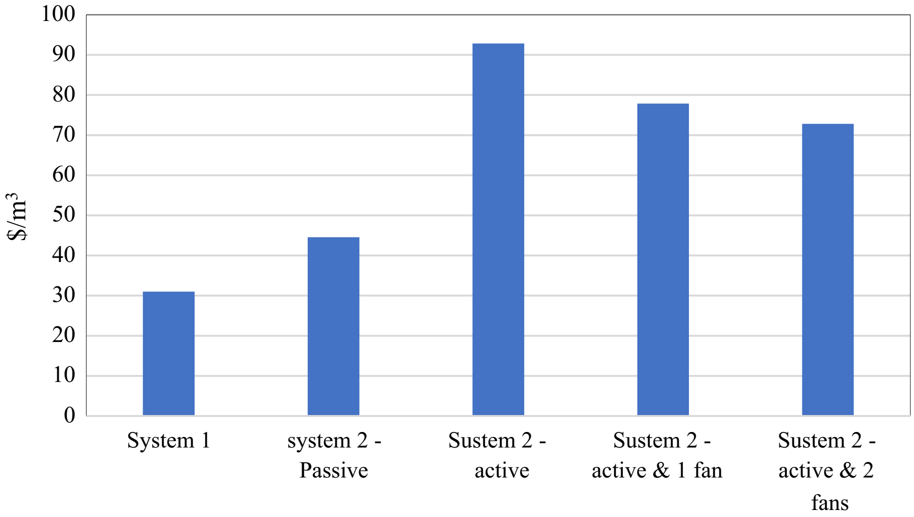


Fig. 9 Desalination price based on the developed desalination systems

while the lowest desalination price achieved, that is, System 1, is 0.03 \$/L, which is more than 75% less than the market price. This indicates that the price of distilled water in system 1 is four times less than that of the market, which makes system 1 a feasible system for distilled water production. In addition, the distilled water produced can be mixed with the water source in a specific ratio to obtain fresh drinkable water.

4 Discussion of results

Installing fans on an active solar still, that is, system 2-active, proved to be effective as it increased the water productivity by 20% in the case of installing one fan and by 30% in the case of installing two fans, over the active solar still with no fans. Moreover, the installed fans reduced the price per unit volume of distilled water compared to the no fan case by 16% in case of one fan and by 22% in the case of two fans. The use of fans and batteries proved to have produced more liters per day, as shown in Fig. 9, yet the overall cost per unit volume was much higher than that of the passive solar still owing to the high initial cost of the batteries and inverter.

It can be concluded that converting a solar still from a passive system operating only during sunlight to an active system operating day and night improves the water productivity rate. However, this is not feasible owing to the added accessories, which increases the initial cost and consequently increases the cost of desalination. It should be noted that system 2 (passive) is cheaper in terms of the initial cost compared to system 1, yet the overall price per unit volume of distilled water is higher than that of system 1 by more than 30% owing to the high productivity rate of system 1 over system 2.

5 Conclusions

A new design for water desalination that uses boiling and condensation has been developed and implemented, and it proves to be more feasible than conventional solar stills in terms of the cost per unit volume. Four different types of solar stills were compared with each other and with the new design for water desalination. The water output of the systems varied between (2–4.75) Liter/day. The price per unit volume of the new design is 31 $\$/m^3$ which is less by 30% less than the best performing solar still, 44.55 $\$/m^3$, and 75% less than the worst-performing solar still. These numbers prove that this new design can compete in the domestic desalination market because it has a better price per unit volume than all four solar stills. Although it is more complex to build than conventional solar stills, it is a good option for water desalination, as the price of distilled water is four times less than the market price. Converting a Solar still from a passive system, that is, operating only during sunlight, to an active system operating day and night improves the water productivity rate; however, it is not feasible because of the added accessories that increase the initial cost, consequently increasing the cost of desalination.

Author contributions JI and OS performed the experiments, methodology, analysis and wrote the paper, while NEM and MSA tasks were conceptualization, supervision, writing—review and editing.

Data availability The authors declare that the data supporting the findings of this study are available within the paper.

Declarations

Ethics approval and consent to participate All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Competing interests The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

References

1. Boretti A, Rosa L. Reassessing the projections of the world water development report. NPJ Clean Water. 2019;2(1):1–6.
2. Shiklomanov IA. The world's water resources. In Proceedings of the international symposium to commemorate, vol. 25, 1991. pp. 93–126.
3. Kharraz DJE. Desalination as an alternative to alleviate water scarcity and a climate change adaptation option in the MENA region, Tech. Rep. ISBN 978-3-95721-811-7, 2020.
4. Wheeler KG, Jeuland M, Hall JW, Zagona E, Whittington D. Understanding and managing new risks on the Nile with the Grand Ethiopian Renaissance Dam. Nat Commun. 2020;11(1):1–9.
5. Omara AA, Abuelnuor AA, Mohammed HA, Khiadani M. Phase change materials (PCMs) for improving solar still productivity: a review. J Therm Anal Calorim. 2020;139(3):1585–617.
6. Angelakis AN, Valipour M, Choo KH, Ahmed AT, Baba A, Kumar R, Wang Z. Desalination: from ancient to present and future. Water. 2021;13(16):2222.
7. Mentis D, Karalis G, Zervos A, Howells M, Taliotis C, Bazilian M, Rogner H. Desalination using renewable energy sources on the arid islands of South Aegean Sea. Energy. 2016;94:262–72.
8. Chauhan VK, Shukla SK, Tirkey JV, Rathore PKS. A comprehensive review of direct solar desalination techniques and its advancements. J Clean Prod. 2021;284: 124719.
9. Cheng WL, Huo YK, Nian YL. Performance of solar still using shape-stabilized PCM: experimental and theoretical investigation. Desalination. 2019;455:89–99.
10. Nazari S, Safarzadeh H, Bahiraei M. Performance improvement of a single slope solar still by employing thermoelectric cooling channel and copper oxide nanofluid: an experimental study. J Clean Prod. 2019;208:1041–52.
11. Elashmawy M. An experimental investigation of a parabolic concentrator solar tracking system integrated with a tubular solar still. Desalination. 2017;411:1–8.
12. Faegh M, Shafii MB. Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes. Desalination. 2017;409:128–35.
13. Dev R, Abdul-Wahab SA, Tiwari GN. Performance study of the inverted absorber solar still with water depth and total dissolved solid. Appl Energy. 2011;88(1):252–64.
14. Siddiqui FR, Elminshawy NA, Addas MF. Design and performance improvement of a solar desalination system by using solar air heater: experimental and theoretical approach. Desalination. 2016;399:78–87.
15. Arunkumar T, Velraj R, Ahsan A, Khalifa AJN, Shams S, Denkenberger D, Sathyamurthy R. Effect of parabolic solar energy collectors for water distillation. Desalin Water Treat. 2016;57(45):21234–42.
16. Munisamy, TK, Mohan A, Veeramanikandan, A. Experimental investigation of tilted wick solar still using fabrics. Aust J Mech Eng. 2017;17(3):185-190.
17. Yan T, Xie G, Sun L, Du M, Liu H. Experimental investigation on a two-effect tubular solar still operating under vacuum conditions. Desalination. 2019;468: 114057.
18. Nassrullah H, Anis SF, Hashaikeh R, Hilal N. Energy for desalination: a state-of-the-art review. Desalination. 2020;491: 114569.
19. Falcone PM, Hiete M, Sapio A. Hydrogen economy and sustainable development goals: review and policy insights. Curr Opin Green Sustain Chem. 2021;31: 100506.
20. Al-Husban Y, Al-Ghriybah M, Handam A, Al Smadi T. Residential solar energy storage system: state of the art, recent applications, trends, and development. J Southwest Jiaotong Univ. 2022; 57(5):750–769.
21. Schmidt O, Hawkes A, Gambhir A, Staffell I. The future cost of electrical energy storage based on experience rates. Nat Energy. 2017;2(8):1–8.
22. Liponi A, Tempesti C, Baccioli A, Ferrari L. Small-scale *desalination* plant driven by solar energy for isolated communities. Energies. 2020;13(15):3864.

23. Berenguel-Felices F, Lara-Galera A, Muñoz-Medina MB. Requirements for the construction of new desalination plants into a framework of sustainability. Sustainability. 2020;12(12):5124.
24. Xu P, Cath TY, Robertson AP, Reinhard M, Leckie JO, Drewes JE. Critical review of desalination concentrate management, treatment and beneficial use. Environ Eng Sci. 2013;30(8):502–14.
25. Eke J, Yusuf A, Giwa A, Sodiq A. The global status of desalination: an assessment of current desalination technologies, plants and capacity. Desalination. 2020;495: 114633.
26. Kedar SA, Kumaravel AR, Bewoor AK. Experimental investigation of solar desalination system using evacuated tube collector. Int J Heat Technol. 2019;37(2):527–32.
27. Omara ZM, Hamed MH, Kabeel AE. Performance of finned and corrugated absorbers solar stills under Egyptian conditions. Desalination. 2011;277(1–3):281–7.
28. Rufuss DDW, Iniyan S, Suganthi L, Davies PA. Solar stills: a comprehensive review of designs, performance and material advances. Renew Sustain Energy Rev. 2016;63:464–96.
29. Kabeel AE, Abdelgaied M, Mahmoud GM. Performance evaluation of continuous solar still water desalination system. J Therm Anal Calorim. 2021;144(3):907–16.
30. Lu X, Peng Y, Ge L, Lin R, Zhu Z, Liu S. Amphiphobic PVDF composite membranes for anti-fouling direct contact membrane distillation. J Membr Sci. 2016;505:61–9.
31. Schlumpberger S, Smith RB, Tian H, Mani A, Bazant MZ. Deionization shocks in crossflow. AIChE J. 2021;67(8): e17274.
32. Bishara E, Abd-Elhady MS, Halim MA. Influence of thermal shock on fouling of smooth, rough and finned tubes. Energy. 2015;93:354–60.
33. Dawood MMK, Omar AH, Shehata AI, Samir Shehata A, Taha AAE, El-Shaib MN, Mohamed MK. 3E enhancement of freshwater productivity of solar still with heater, vibration, and cover cooling. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-20340-9.
34. Haas R, Ajanovic A, Ramsebner J, Perger T, Knápek J, Bleyl JW. Financing the future infrastructure of sustainable energy systems. Green Finance. 2021;3(1):90–118.
35. Mann GR. Replacement allowance: modified sinking fund method. Apprais J. 1990;58(4):486.
36. https://www.ubuy.com.eg/en/product/1B8YZ1MY-chemworld-type-ii-deionized-water-2x1-gallons.