

Research Article

Studying Safe Water Production using Conventional Solar Distillation Stills (CSSs) Integrated with Direct Current Apparatuses and Photovoltaic Modules- A Mini Review

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ARTICLE INFO	Abstract
<p>Received date: 7 Oct 2024 Accept date: 8 May 2025 Published date: 8 May 2025</p> <p>Keywords: Forced Convection, Photovoltaic Modules, Solar Desalination Still, Water Production.</p>	<p>Safe water is free from pathogenic agents, harmful chemical substances, and color, odor, and taste, making it usable for domestic purposes. One of the low-cost water treatment techniques used to produce freshwater for remote and rural communities was the conventional solar still (CSS), which utilized only solar energy. Recently, integrating low-voltage direct current (DC) machines powered by photovoltaic modules with the CSSs to increase the CSS yield has received considerable attention in countries with abundant sunny days and a shortage of freshwater annually. Accordingly, this work reviews the performances of DC apparatuses integrated with CSSs, examining the enhancement of CSSs' basin water temperatures and productivities, and the potential elimination of pathogenic organisms from the basin water. The review method includes additional related studies, focusing on the application of CSS and DC, which were conducted worldwide 10 years ago. It was revealed that the DC apparatuses such as a DC fan, a DC heater, a DC rotating shaft motor, four DC stirrers and two DC rubber scrapers integrated with different designs of the conventional solar stills (CSSs) were effective to increase the basin water temperatures, evaporation rates and hence, the CSSs' freshwater production. Moreover, it was concluded that designing and constructing a CSS with a smaller-scale basin or absorber and having a low water capacity in its basin, while integrating with DC machines, is vital to achieve higher working temperatures and prevent the transfer of pathogens and viruses to the CSS's distillates.</p>

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1. Introduction

Impacts of climate changes, global population growth and industrial developments resulted in pollution of the water bodies and declining the available amount of safe freshwater per capita by a fifth over two decades (Tabrizi et al., 2010; Liu et al., 2024) and rising the clean freshwater demand throughout the world, particularly in remote and rural communities whom lack access to the clean water and electricity, but having plenty of annual daily sunshine hours (Sánchez-Lozano et al., 2025). By 2023, approximately 1.6 billion people will need to survive without access to hygienic drinking water (UNICEF & WHO, 2020). Safe water is the water that is usable for domestic purposes and is free from pathogenic agents, harmful chemical substances, color, and odor (Terefe et al., 2024). Microbial contamination is a common issue, affecting all types of water resources in several developing countries (Bagordo et al., 2024). The transmission of waterborne diseases in surface water and groundwater resources has also generated public health concerns in rural regions of Africa, India, and East Asia, posing health risks to villagers who consume the water without further decontamination (WHO, 2012; Pal et al., 2018; Adio et al., 2021). Waterborne diseases—such as cholera, dracunculiasis, infectious hepatitis, typhoid, bacillary dysentery, paratyphoid, colibacillosis, giardiasis, salmonellosis, filariasis, cryptosporidiosis, and amoebiasis—are transmitted in water bodies such as flowing rivers, groundwater, and runoff water from rooftops of the aforementioned rural areas by pathogenic microorganisms such as bacteria, viruses, fungi, and protozoa (Adio et al., 2021). Access to safe water, sanitation, and hygiene is fundamental to human health. Infants and children are more likely to die due to a lack of access to safe water (WHO, 2012). Many diarrheal diseases are transmitted through contaminated water and inadequate sanitation. These conditions, along with poor hygiene, can also cause deadly waterborne diseases such as cholera and typhoid fever. Cholera has been reported in 47 countries worldwide. It will likely affect the poorest and most vulnerable populations, including young children and older adults, who often lack access to safe, potable water. Around 1.7 billion children under 5 years old, 3 and 11 million people are infected with diarrheal, cholera, and typhoid fever, respectively, annually, resulting in 95,000 and

117,000 deaths from infection with cholera and typhoid fever, respectively (WHO, 2012). Nutrients and pathogens produced by human waste (Best, 2019) are also sources of pollution that primarily stress water bodies. Pollution of rivers and groundwater by wastewater is widespread worldwide (Parsa, 2021). Some of the recognized massive rivers such as Ganges, Amazon, Congo, Parana, Nile, Yenisey, Lena, Zambezi, and Niger are polluted by pathogens from wastewaters (Mianabadi et al., 2020). Discharging wastewater into rivers is a significant source of environmental pollution in developing countries (Okore et al., 2014). For instance, sewage and industrial waste are discharged into the Marimba River in Zimbabwe, resulting in heavy pollution of the river and numerous environmental hazards (Nhapi, I., & Tirivarombo, 2004). In Nigeria, more than 90% of hospital waste is directly discharged into the environment without any treatment (Lekwot et al., 2012). Consumption of raw and untreated water contaminated with viruses such as norovirus, rotavirus, astrovirus, and hepatitis A and B viruses by vulnerable individuals, particularly children, the elderly, and pregnant women, can lead to a high mortality rate (Nwadike et al., 2024). It was projected that one million people in developing countries could die due to contact with waterborne diseases every year (Bagordo et al., 2024). Certain countries such as Jordan, Lebanon, Qatar, Kuwait, UAE, Saudi Arabia, Nepal, Bangladesh, India, Sudan, Niger, Algeria, Egypt, Libya and Nigeria, which are home to almost 25% of the world's population have been facing tremendously high ranks of water stress currently (Reig, 2013). Meanwhile, these countries experience a high average daily solar irradiance and receive numerous hours of bright sunshine annually (Özturan & Seyhan, 2024). Since water is closely linked to daily human activities, providing safe drinking water is one of the primary public health priorities. Several water treatment techniques, including coagulation and precipitation, reverse osmosis, oxidation-reduction, membrane techniques, biological treatments, and electro dialysis, have been developed and examined so far. However, these methods require electricity and a skilled workforce in remote and rural areas that suffer from a lack of electricity (Jasrotia et al., 2013). Approximately 20 million cubic meters of treated water are produced daily by over 10,000 desalination plants worldwide,

which require significant amounts of electricity. Coal and fossil fuel combustion were used as input energy to supply electricity for these systems, which discharge huge amounts of hazardous greenhouse gas emissions into the atmosphere, increasing global temperature and climate change (Goosen et al., 2012; Mir & Bicer, 2021). Considering this issue, the applications of solar energy as thermal desalination methods to treat the unclean surface or groundwater and producing clean and safe water can be utilized as a cost-effective alternative to assist eliminating the water scarcity issues for the local rural and remote societies of the countries mentioned above who suffer from the water borne diseases and lack of the clean hygienic fresh water.

1.1 Definition of the conventional solar still (CSS)

According to the World Health Organization (WHO), a person requires 2-3 liters of daily water for survival (WHO, 2012). A CSS is a closed container that consists of a transparent cover, allowing solar irradiance to pass through under natural convection mode and heat the saline water in the basin (Fig. 1) (Riahi et al., 2016; Kumar et al., 2024). Solar distillation still as a thermal desalination technique is one of the most stated low-cost and sustainable water treatment practices using merely the energy from sun to provide high quality potable water from poor quality water resources for the remote, rural and coastal residents who lack access to other water treatment alternatives (Al-Qadami et al., 2020).

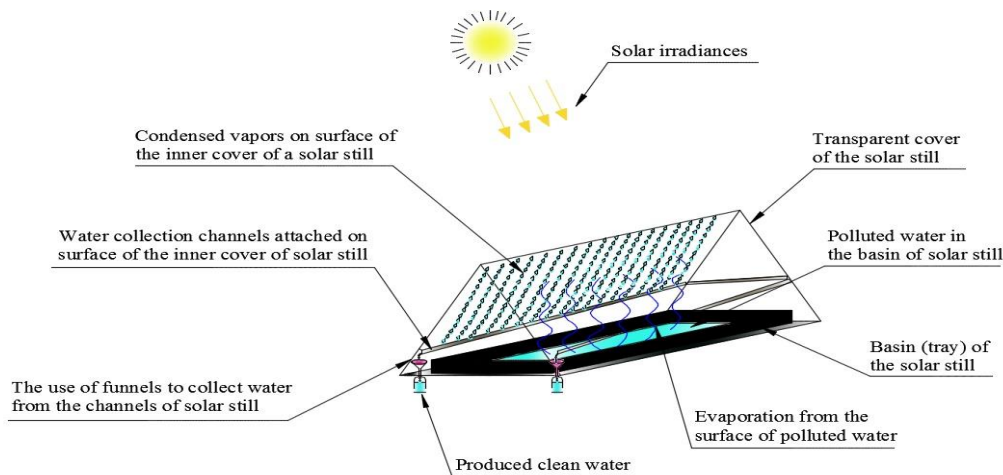


Figure 1. Sketch of a triangular-shaped CSS operating under natural convection mode, with basin water serving as the evaporation region and a condensing glass cover as the condensation region (adopted from Riahi et al., 2016).

It was reported by several related studies, Arunkumar et al. 2019; Bhargva et al. 2019; Nazari et al. 2019; Shoeibi et al. 2021; Shoeibi et al. 2021; Yusof et al. 2022, that the amount of CSSs freshwater production is generally affected by the temperatures differences between its basin water and glass cover in which the basin water temperature in CSS plays a vital role in increasing the evaporation rate of the CSS by undergoing into the phase change of water to vapors exposed to the Sun's rays that the vapors hit the inner cover of the CSS. Subsequently, the vapors undergo another phase change, transitioning from vapors back to liquid via condensation on the surface of the inner cover of the CSS, achieved by decreasing the condensing cover temperature in the solar still. The condensed vapors, in the form of clean water

droplets, fall to the collection channels attached to the bottom of the inner cover of the CSS (Fig. 1). The pollutants of heavy metals and chemicals were removed from the brackish groundwater, geothermal groundwater and diluted raw sewage using a trapezoidal-shaped single basin single slope solar still studied in Southern new Mexico (Hanson et al., 2004), from natural surface (lake and pond) waters using glass (GSS) and polythene film (PSS) cover solar stills (Riahi et al., 2018). GSS coupled with a solar power system (Al-Qadami et al., 2020) investigated in Malaysia, from arsenic-rich groundwater using a single slope single basin (SSSB) solar still studied in India (Jasrotia et al., 2013), from seawater using a triangular-shaped solar still (TrSS) tested in Malaysia (Ahsan et al., 2012) and from urban grey water using a double

slope solar still (PSSG1) in Malaysia (Yusof et al., 2022). All the water quality parameters tested after experiment using the above solar stills, PSS and GSS (Riahi et al., 2018), passive and active solat

stills (Al-Qadami et al., 2022), SSSB (Jasrotia et al., 2013), TrSS (Ahsan et al., 2012) and PSSG1 (Yusof et al., 2022) were in compliance with the standards of the WHO drinking water, WHO, 2012, (Table 1).

Table 1. The performances of some solar desalination stills after treating lake water, arsenic-rich groundwater, seawater, and urban grey water samples, as recommended for remote, rural, coastal, and urban community consumption.

Water quality parameters	PSS	GSS	Passive solar still	Active solar still	SSSB	TrSS	PSSG1	WHO standards for drinking water
pH	6.51	6.53	6.62	6.59	7.14	7.7	6.7	6.5-8.0
Total dissolved solids (TDS) (mg/l)	95	28	----	----	45	7.52	61.49	600
Total Arsenic (mg/l)	----	----	----	----	≤ 0.01	----	----	0.01
Salinity (mg/l)	0.1	0	----	----	Na	0.006	0.02	< 0.25
Nitrate (mg/l)	0.6	0.4	0.45	0.38	0.74	----	0.9	< 50
Nitrite (mg/l)	0.03	0.01	----	----	Na	----	0.03	< 0.05
Fluoride (mg/l)	----	----	----	----	0.02	----	----	1.5
Chloride (mg/l)	----	----	----	----	10.99	----	----	250
Hardness (mg/l)	----	----	----	----	33.81	----	----	200
Iron (mg/l)	0.03	0.02	0.1	0.07	0.00	----	----	0.3
Sulfate (mg/l)	----	----	0.2	0	0.72	----	----	250
Turbidity (NTU)	1.37	0.92	1.6	1.43	Na	----	2.0	< 5
Electrical Conductivity (EC) (µS/cm)	52.5	15.66	----	----	Na	11.6	41.2	< 250

Recently, another concern was also expressed by Parsa, (2021) and Yusof et al. (2022), Kumar et al. (2024) that various thermal resistance pathogens such as *E. coli*, *Klebsiella pneumoniae*, and *Enterococcus faecalis* which are the causes of some waterborne diseases such as diarrhea, cramps, nausea, bacteremia, endocarditis, meningitis, periodontitis and urinary and biliary tract infections were capable to transfer to the distillate through vapors of the passive and active solar stills studied by Riahi et al. (2018), Al-Qadami et al. (2020), Yusof et al. (2022), Winston et al. (2018) as these solar stills produced water at initial moments of their experiments when their working water temperatures were below 50°C. In water temperatures ranging from 30 to 35 °C, the transmission rate of *E. coli* was higher than that of *Enterococcus faecalis*. In comparison, the transmission rate of *Enterococcus faecalis* at the water temperature ranges of 40-45°C and 50-55°C was higher than the *E. coli* spreading rate (Ayoub et al., 2014). It was found that *Enterococcus faecalis*, a thermally resistant pathogen, can survive in water at temperatures up to 65°C. Exposing all parts of solar stills and the produced distillate water to sunlight with a high rate of radiation intensity during daily experiments was recommended by (Ayoub et al., 2014), (Ayoub et al., 2015), and (Malaeb et al., 2017) to prevent the growth of bacteria and pathogens in the produced water.

However, this recommendation is not completely practical due to some parts of the solar stills studied (Hanson et al., 2004; Riahi et al., 2016; Riahi et al., 2018; Al-Qadami et al., 2020) may not receive the solar radiation irradiances in initial experimental hours in the morning, and the existence of pathogens in the produced water of solar stills seems to be predictable (Parsa et al., 2021).

Moreover, another challenge of CSS was generating a low amount of fresh water—i.e., less than 5 L/m²—due to the failure to reach a high basin water temperature, which resulted in low rates of evaporation and thus, low water production.

Thus, employing the external heat sources integrated with a CSS to increase the initial working temperature of the CSS above 65°C instantaneously and maintain this temperature throughout the experiment seems crucial in eliminating the thermal resistance pathogens (*Enterococcus faecalis*, *E.coli* and *Klebsiella pneumoniae*) from the basin water of CSS and enhancing the amount of CSS water production. Recently, integrating low voltage direct current (DC) machines powered by photovoltaic modules with the CSSs to increase the CSS yield received much attention in some countries having plenty of sunny days and shortage of fresh water annually, thus, the main aim of this work is to review the impacts of the DC machines such as DC fans, DC heaters, DC motor rotating shaft, DC stirrers, DC rubber scrapers and DC Thermo-

Electric Cooling (TEC) units employed in different types of CSSs on increasing the basin water temperatures of CSSs, the CSSs' rates of evaporation, condensation and hence, enhancing the amount of fresh water production and possible eliminating the pathogenic organisms from the basin water in order to produce safe clean water. Thereafter, based on the above conducted review, a recommended design of the combination of few aforementioned DC machines powered by PV modules integrated with a CSS as a direction for the future work to increase the initial and average basin water temperatures of the CSS to eliminate the waterborne pathogens and microorganisms from the contaminated basin water of the CSS and improve the daily freshwater production of the CSS will be elucidated.

1.2 Definition of low voltage Direct Current (DC) power

Electrical power can be classified as AC or DC power, depending on the direction of the energy flow (Bakır et al., 2023). AC stands for alternating current, and DC stands for direct current. The current flowing in alternating direction is termed as AC, and the current flowing in only one direction is called DC Power. DC Power refers to the

unidirectional flow of electrons (electric charge) and is the form of power that is most commonly produced by sources such as solar cells and batteries. All solar panels nowadays produce DC power. One of the most significant advantages of DC power is its suitability for specialized applications. When AC power transmission is not practically feasible or possible over long distances, DC power can be used in remote and rural areas without access to electricity, relying on solar photovoltaic modules (Bakır et al., 2023). A stand-alone PV system is independent of the electricity grid, with the energy produced usually stored in batteries (Kalogirou et al., 2023). A typical stand-alone system would consist of a PV module or modules, batteries, and a charge controller. An inverter may also be included in the system to convert the DC generated by the PV modules into the alternating current (AC) form required by standard appliances (Kalogirou et al., 2023). DC power is widely used in low-voltage applications, including charging batteries, automotive and aircraft applications, and other low-voltage machines. A schematic diagram of a stand-alone PV system is shown in Fig. 2. As can be seen, the system can simultaneously satisfy both DC and AC loads.

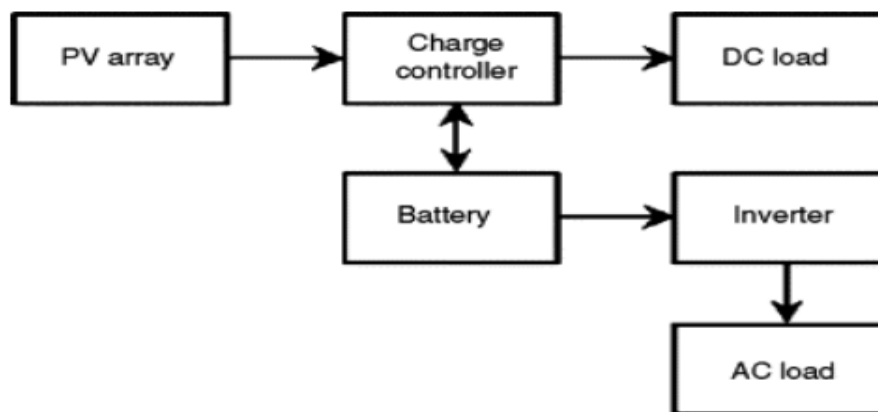


Figure 2. Diagram of solar photovoltaic modules, charge controller, batteries, DC and AC loads.

Thus, solar photovoltaic modules can be employed to convert the solar energy to the electricity in the rural and remote communities of the countries having more than 3000 sunshine hours annually to supply power for the AC and DC machines to be integrated with the CSS for increasing the water production of the CSS. Some researchers have integrated the low voltage DC apparatuses such as DC fans (Taamneh & Taamneh,

2012), DC heaters (Riahi et al., 2019), DC motor rotating shaft (Abdel-Rehim & Lasheen, 2005), DC stirrers (Rajaseenivasan et al., 2017), DC rubber scrapers (Al-Sulttani et al., 2017) with the CSSs to increase the temperature of basin water of CSSs and enhance the CSSs evaporation rate, while, some incorporated the DC TEC units (Rahbar & Esfahani, 2012; Rahbar et al., 2016) with the CSSs to decrease the temperature of the condensing covers of the

CSSs and rise the condensation rate of CSSs which enhancements in both evaporation and condensation rates resulted in increasing the amount of CSSs water production. The aforementioned DC machines received power from solar PV modules regulated by a charge controller (Fig. 2) to operate in the CSS.

As stated by Herrando et al. (2014), the output powers of PV modules ($P_{\text{output,PV}}$) exposing to the sun greatly depend on the rates of varied fluctuations of radiation intensities receiving from the sun (I_s), the number of PV modules (n), the efficiency (η_{pv}) and the surface area of each PV module (A_{PV}) which is shown in the following Eq. (1) as follow:

$$P_{\text{output,PV}} (W) = n \times \eta_{\text{pv}} \times I_s \times A_{\text{PV}} \quad (1)$$

where the units of I_s and A_{PV} are W/m^2 and m^2 , respectively.

The output powers of DC devices operating under direct climatic conditions depend heavily on variations in solar radiation intensity and the output power of photovoltaic modules (Riahi et al., 2019).

1.3 Effects of forced convection DC devices on the performance of the CSSs for water vaporization and production augmentation

According to Tamneh & Tamneh (2012), Jordan experiences more than 300 sunny days annually in most regions. However, it has the lowest levels of water resource availability globally. Thus, they studied the effect of a forced convection, low-power consumption DC fan powered by a photovoltaic module that functioned as a vapor motion device in a pyramid-shaped CSS, mounted on one side of the CSS glass cover in Tafila City, Jordan (Fig. 3a). The DC fan with the output power capacity of 10W, powered by solar photovoltaic panels, employed in that CSS, circulate the air and creates a turbulent air-vapor mixture motion inside the solar still in order to take away the vapors from the basin water surface and increase the evaporation rate of the still (Tamneh & Tamnen, 2012). The performance of the

CSS with a DC fan (Fig. 3a) was compared with that of another CSS having similar dimensions and fabricated materials, but without a fan (Fig. 3 b). Saline water samples with a volume of 57 litres were fed into the basin of each CSS. The basin water temperature increased from approximately 25°C at 7:00 am to a maximum value of 60°C at 2:00 pm (Fig. 4). Experimental hourly and daily yields of the CSS using the DC fan were obtained and compared with those of the free convection solar still without the fan. Maximum hourly distillates of 0.464 and 0.372 liter under maximum value of solar intensity of about 1000 W/m^2 were found for the forced and natural convection solar stills, respectively (Fig. 5) indicated that the low power DC fan was capable to take the water vapour away from the saline water surface, move it to the inner cover of the solar still, caused higher evaporation rate above the basin surface water and hence the higher water production rates which had a significant impact on the distillate production compared to those of the natural convection solar still without using fan. Accordingly, the cumulative daily distillate yield of the solar still, utilizing forced convection from a low-power DC fan, was 2.99 litres, 25% higher than that of the CSS. Employing a low power consumption DC fan integrated with a solar photovoltaic panel was stated by Tamneh & Tamneh (2012), as a cost-effective, viable, and sustainable system in improving the evaporation and productivity rates of the CSS for being used by the communities in the remote and rural areas of Jordan, which lack electricity and fresh water resources. However, it can be seen from Fig. 4 and Table 2 that the solar still using a DC fan produced 0.07 L/m^2 of fresh water at the initial working temperature of 25°C during starting moment of the experiment in the morning which is below 65°C in which that the water borne thermal resistance pathogens and viruses can be likely transferred to the produced water distillate of the CSS through vapors.

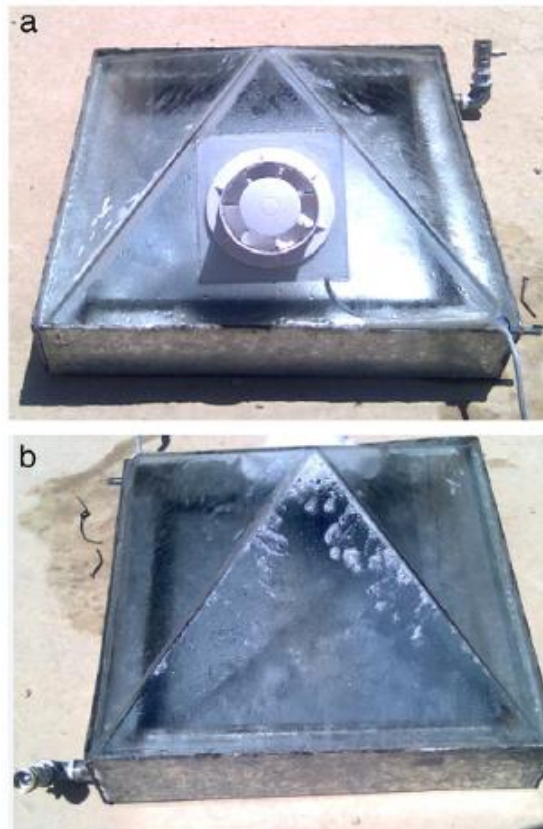


Figure 3. (a) Pyramid solar distiller with DC fan (b) without fan (Tamneh & Tamneh, 2012)

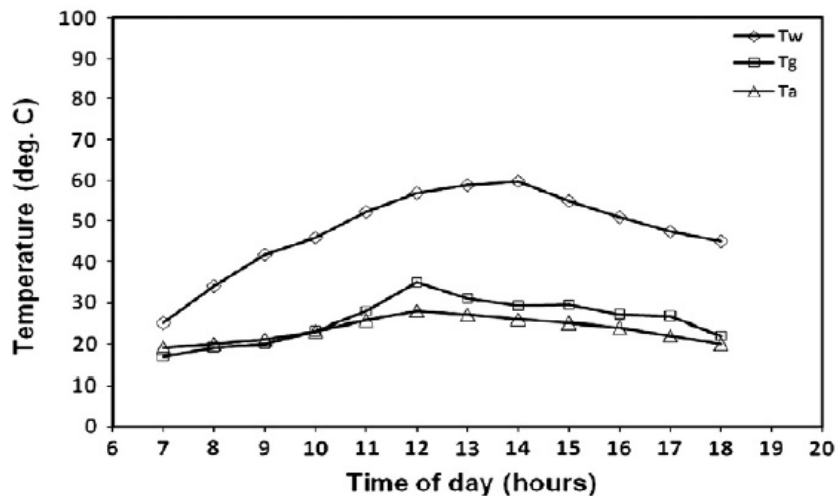


Figure 4. Hourly variations of basin water temperature, glass cover temperature and ambient temperature during day 1 of solar still testing.

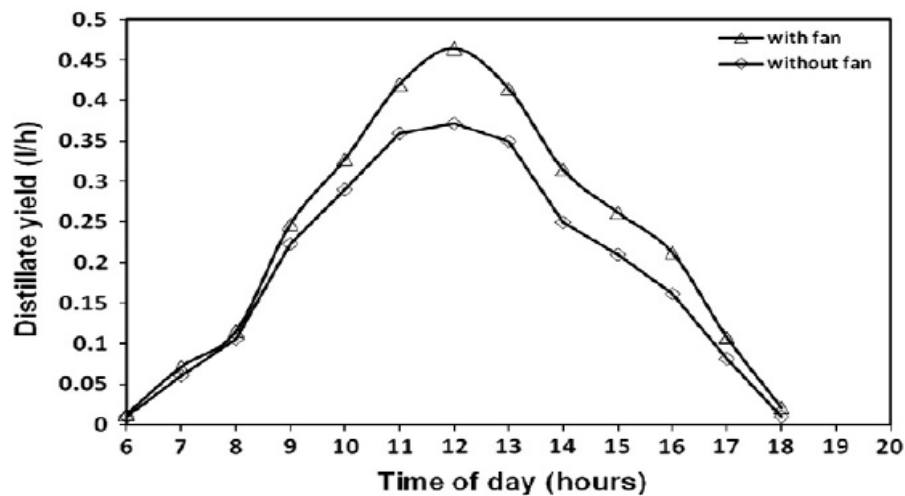


Figure 5. Hourly variation of freshwater production for a solar still with and without a fan (Tamneh & Tamneh, 2012).

In another study conducted by Riahi et al. (2019) in Malaysia, the effect of a low-voltage DC heater powered by a photovoltaic module placed in the basin of a conventional passive solar still (PSS) was investigated. As reported by Azhari et al. (2008), Malaysia is known as a tropical country that enjoys a high annual average daily solar irradiation of 4.96 kWh/m², with maximum and minimum rates of 5.56 and 4.21 kWh/m², respectively. The country receives more than 3,000 hours of bright sunshine annually. Thus, utilizing solar energy in Malaysia is an effective way to treat surface waters, such as lakes, and produce freshwater using solar distillation systems. The PSS, incorporated with the DC heater and PV module, known as the ACSS, featured a black-painted stainless steel basin and a transparent polythene film layer as a condensing cover. The performance of the ACSS was compared with that of PSS, which had a similar shape, dimensions, and fabricated materials as ACSS, but without utilizing the DC heater (Figs. 6 and 7) (Riahi et al., 2019). The 12V DC heater had a maximum output power of 50W powered by a DC solar polycrystalline photovoltaic panel with the peak output power capacity (P_{max}) of 45.9 W, length of 1.0 m and the width of 0.45 m, regulated using a 10A solar charge controller during the daily experimental hours (Fig. 6 and 7). Lake water samples with the volume of 4.50 litre was fed into each basin of PSS and ACSS (Fig. 7). Results interpreted that the maximum and average basin water temperatures (T_w) and hourly (M_{hexp}) and

cumulative water yields (M_{cexp}) of ACSS were always higher than those of the PSS exposed to the similar values of solar radiation intensities (I_s), ambient temperature (T_a) and wind speed (V) in 7 experimental days in different months under Malaysia tropical climate. The basin water temperatures and hourly water production of PSS and ACSS increased from about 28°C and 0 L/m² at 8.0 am to the the highest values of 53 and 56°C recorded at 2.0 pm and 0.83 and 0.61 L/m² recorded at 3.0 pm, respectively (Figs 8a and b) on 1st February 2015 in which the rate of average solar radiation intensity was reported the highest compared with the rates of average solar intensities for the other six experimental days. Riahi et al. (2019) stated that the use of a low-power consumption and low-voltage DC heater, coupled with a solar panel, increased the maximum productivity of a solar still by 36% to 4.36 L/m²/day, indicating the effectiveness of the DC heater in enhancing water evaporation inside the solar still. However, the cost per litre of ACSS was USD 0.030 higher than that of PSS.

However, it can be seen from Figs 8-a and -b and Table 2 that the CSS using a DC heater produced 0.32 L/m² of water at its initial working temperature of 49°C in the morning that is below the temperature of 65°C and it can indicated that likely the existing water borne thermal resistance pathogens and viruses can be readily transferred to the produced distillate of the solar still through vapors at the early moments of the experiment.

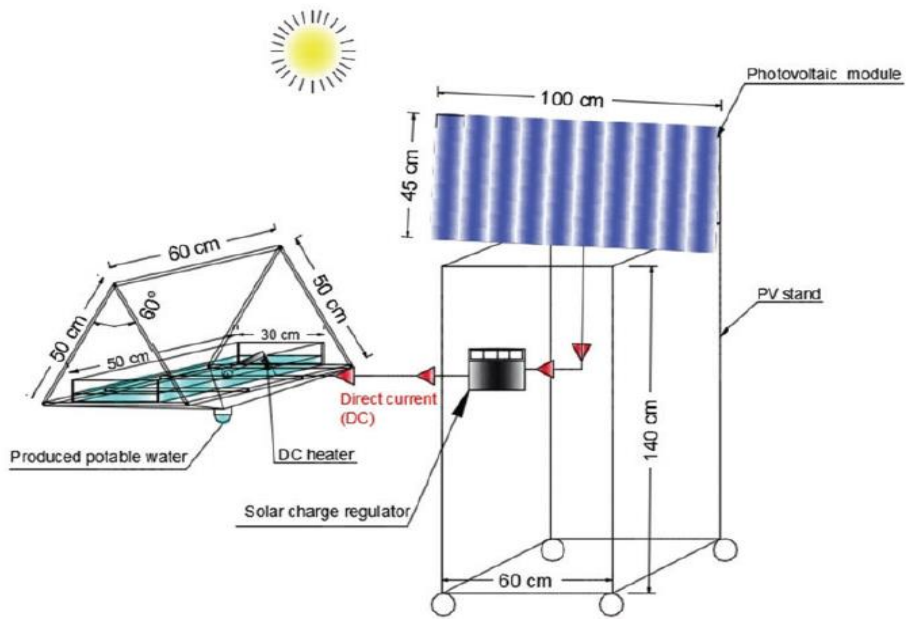


Figure 6. sketch of active solar still integrated with PV module-DC heater (ACSS) (Riahi et al., 2019)



Figure 7. Photograph of experimental setup of ACSS and PSS (Riahi et al., 2019)

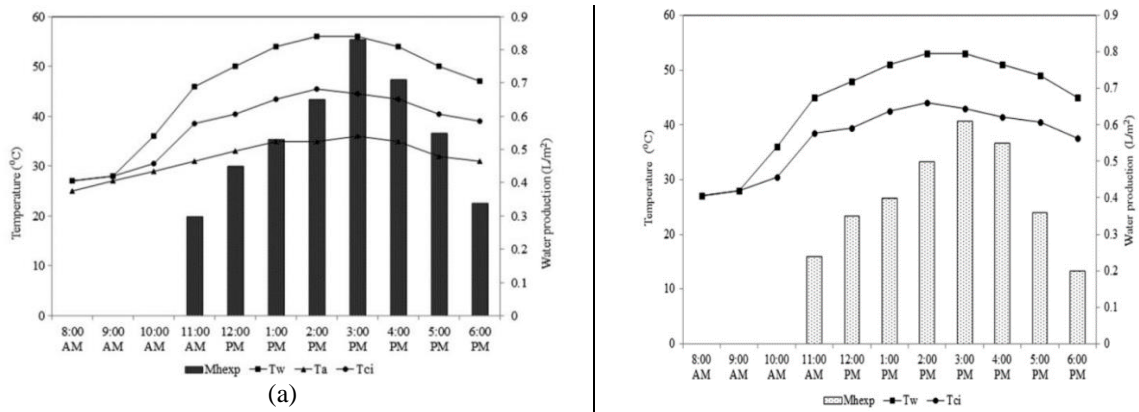


Figure 8. Hourly variations of experimental productivities, water and inner cover temperatures of solar stills, ACSS (a) and PSS (b) versus their basin water and inner cover temperatures (Riahi et al., 2019)

In a study, Abdel-Rahim and Lasheen (2005) designed, fabricated and tested three single-slope single-basin solar stills with similar shapes, dimensions, and materials under Cairo climatic conditions during three consecutive days in May, June, and July 2003. The basin area of each solar still was 1.0 m². The first solar still was performed as a conventional type (CSS). The second solar still was the CSS modified with the installation of a packed layer formed from glass balls as heat storage

materials in the bottom of its surface (CSS with a packed layer of glass balls). The third solar still was the CSS improved by employing a rotating shaft DC motor as a forced convection mode (CSS with DC motor rotating shaft) to enhance the CSS's water evaporation and production rates. The DC motor's rotating shaft was utilized in the solar still (CSS) to move the basin's water surface and break its boundary layer, thereby increasing the vaporization rate inside the solar still (Fig. 9).

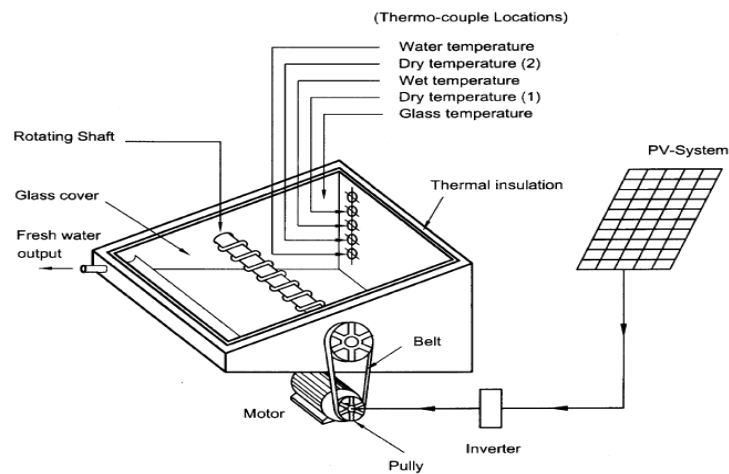


Figure 9. Schematic diagram of the modified CSS using DC motor rotating shaft (Abdel-Rahim & Lasheen, 2005)

The rotating shaft connected to a DC motor with current (I_m), Voltage (V_m), output power (P_m), and motor angular speed (ω_m) of 10 A, 38 V, 0.35 kW, and 958 rpm, respectively, powered directly by a PV module (one solar cell) from 10 am to 5 pm during the 3 days. The performance of the DC motor greatly depended on the direct power received from the PV module and the available solar insolation rates throughout the experimental days (Fig. 9). It was reported by Abdel-Rahim and Lasheen (2005) that the DC motor was performed with the maximum power of 0.35 kW directly when the PV module absorbed highest rates of the solar insolation at noon and afternoon generally from 12 to 2 pm. It was stated by Abdel-Rahim and Lasheen (2005) that the water evaporation and condensation increased since the rotating shaft moved the surface water in the basin of the second still from 10 am to

6 pm, resulting in a higher hourly water temperature and distiller freshwater productivity compared to the CSS without modification (Figs 10 and 11). However, using glass balls as heat-storing materials increased the hourly water temperature and production of the third solar still, which was higher than the other two stills throughout the experimental work (Figs. 10 and 11). It was reported that the solar still modified with a rotating shaft DC motor had a higher cumulative yield compared to the CSS due to generating constant motion of basin surface water that increased the evaporation rate of the still while using a packed layer of the glass balls as heat storage materials in the basin of solar still obtained the highest water temperature and hence, productivity throughout the experiment among the other two solar stills (Fig. 11).

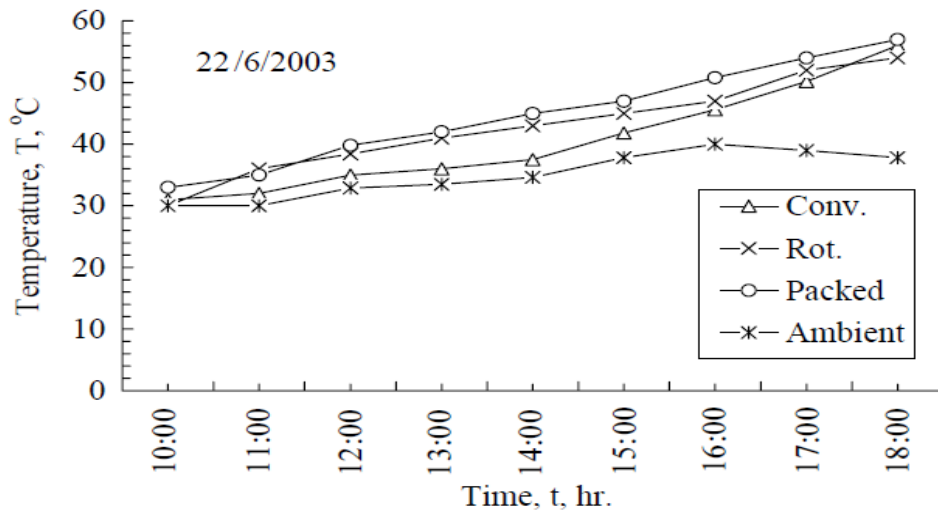


Figure 10. Diurnal variations of ambient temperature and the hourly water temperatures of CSS, CSS integrated with a packed glass balls layer, and CSS with a DC rotating shaft motor (Abdel-Rahim & Lasheen, 2005).

Alteration of the conventional solar still configuration using a rotating shaft DC motor powered by a PV module system increased the productivity of the solar still by 2.5, 5, and 5.5% in May, June, and July, respectively. However, it can be seen from Fig. 10 and Table 2 that the basin water temperatures of the solar still using a rotating shaft DC motor increased from 30°C at 10 am to the peak

of 50°C at 5 pm, which was below 65°C throughout the experiment and the CSS produced 0.11 L/m² freshwater at the initial working temperature of 30°C in beginning of the experiment resulting in transferring the existing waterborne thermal resistance pathogens and viruses into the produced distillate of the solar still through vapors.

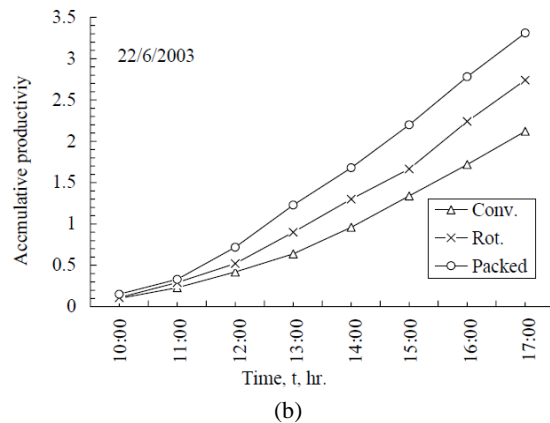
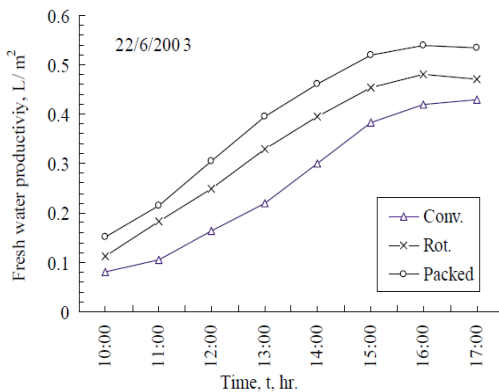


Figure 11. Values of (a) hourly and (b) cumulative water production of the CSS, CSS with DC rotating shaft motor, and CSS with packed layer of glass balls in a typical day (Abdel-Rahim & Lasheen, 2005).

In another study, Rajaseenivasan et al. (2017) considered the effects of four DC stirrers in the basin of a conventional single-slope single-basin solar distiller with and without heat-storing materials, including charcoal and paraffin wax (Fig. 12). The performance of the modified solar still using DC stirrers was compared with that of the CSS without modification. A wooden box with an area of 1.21 m² and a thickness of 0.025 m was used

as the frame of the CSS, which had vertical distances of 0.6 m at one end and 0.4 m at the other end, covered by glasses with tilt angles of 10° (Fig. 13-a). A galvanized iron sheet with an area of 0.64 m² was used as the basin of each CSS. A saline water depth of 1 cm (corresponding to a volume of 0.121 liters) was maintained in the basin of the solar stills throughout the experiments. Four DC stirring motors, each with a capacity of 2 W, were employed

and installed inside the basin of the modified solar still to induce the stirrers' mechanisms, powered by a solar photovoltaic module with a capacity of 40 W (Fig. 12). Initially the influence of basin height variations from 0.15 to 0.45 m on the CSS

performance was evaluated which increased the basin saline water temperature (Fig. 13) and the yield of solar still corresponded to the reduction of the basin heights (Rajaseenivasan et al., 2017).

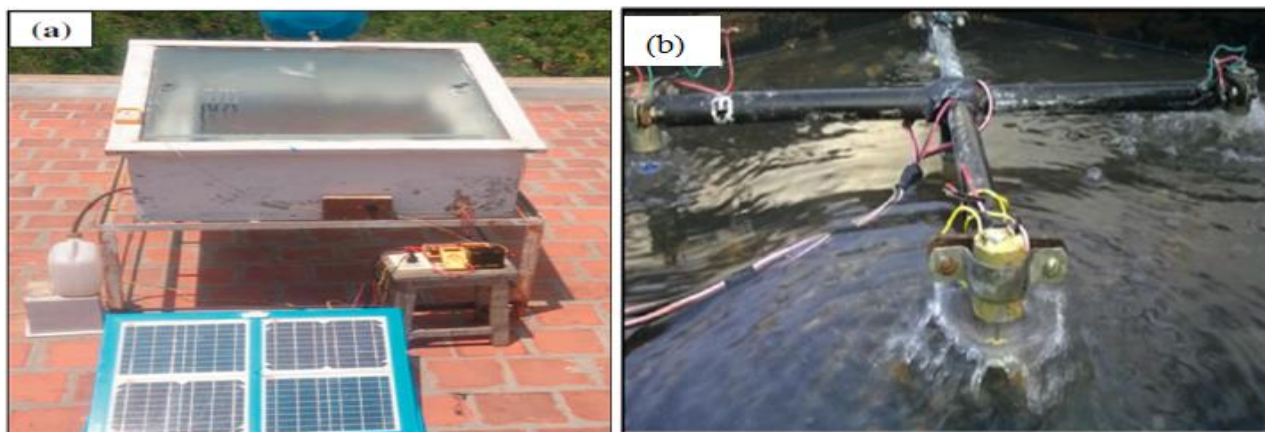


Figure 12. Photographs of (a) the experimental setup of the CSS and PV modules and measuring equipment, and (b) four DC stirrers were stirring saline water in the CSS basin (Rajaseenivasan et al., 2017).

The highest productivity of 3.19 kg/day was achieved using an average height of 0.15 m between the surface of the saline water and the glass cover of the CSS, which increased the productivity of the still by 184.8%. The highest basin water temperatures, ranging from 65°C to 70°C, were obtained when the solar intensity reached its peak of 900 W/m², and the heights between the surface of the saline water and the glass cover of the CSS varied from 0.30 to 0.15 m. However, it was reported that the water temperature values were below 65°C from morning to noon, while the solar intensity rates were below 900 W/m².

Subsequently, the effects of using four stirrers coupled with the energy storage materials of charcoal and paraffin wax (PCM) on the yield of conventional solar still were perceived and concluded that the solar still productivity climbed by 31.03, 48.59 and 63.95% to 4.18, 4.47 and 5.23 kg in 24 hours experimental work using the stirrers only, stirrers with charcoal and stirrers with PCM, respectively (Fig. 14) compared to the CSS with the yield of 3.19 kg without using PCM, charcoal and stirrers in the basin. It was illustrated an increase in basin water evaporation using the stirrers as they breached the boundary layer of the basin surface water (Figs. 13 and 14). However, it can be seen from Fig. 13 and Table 2 that the solar still working temperatures at the initial moments of the experiment using DC stirrers under the low rates of solar intensities (about 400 W/m²) was 40°C which

was below 65°C and the CSS also produced 0.065 L/m² water in that initial temperature which likely the water borne thermal resistance pathogens and viruses can easily be transferred to the distillate of the solar still through vapors during that period.

Al-Sulttani et al. (2017) designed two double slope conventional solar stills and mounted two rubber scrapers performed as condensed vapours collectors on the inclined inner glass covers of one of the solar stills named DSSSHS which worked using two 12 V DC motors powered by 2× 12V, 150 Ah DC batteries (Fig. 15). A 12V, 200W DC solar photovoltaic module was used to absorb and convert sunlight into direct current, powering the batteries, which a charge controller regulated. DSSSHS had an aluminum rectangular basin with a length and width of 1 m (an area of 1.0 m²), a height of 0.03 m, and was covered by glass with an inclination of 3° to the horizontal plane. Saline water with a volume of 19 litres (depth of 19 mm) was fed and maintained in the basin of the solar stills using an aluminium head water tank (Fig. 15). The performance of DSSSHS, which employed two rubber scrapers, was compared with that of a double slope conventional solar still named DSSS, which had the same shape, dimensions, and specifications as the DSSSHS without using the rubber scrapers (Fig. 15). Each scraper had a length of 954 mm and was mounted on a hollow iron post that could rotate 360 degrees in a horizontal plane at 15-minute intervals, with a speed of 0.2 m/s, controlled by an

electrical control board. These boards consist of DC 12 V delay dispatch timers, a micro basin switch with a rotary roller hinge lever, resistors, and a

wiring system. Aluminium water guides were installed under each scraper to prevent losses of collected condensed water by the scrapers.

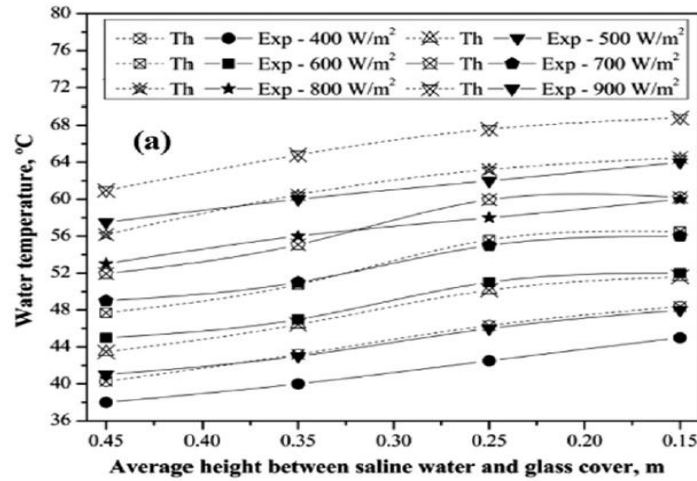


Figure 13. Influence of basin height variations and solar radiation intensities on basin water temperatures in the CSS (Rajaseenivasan et al., 2017).

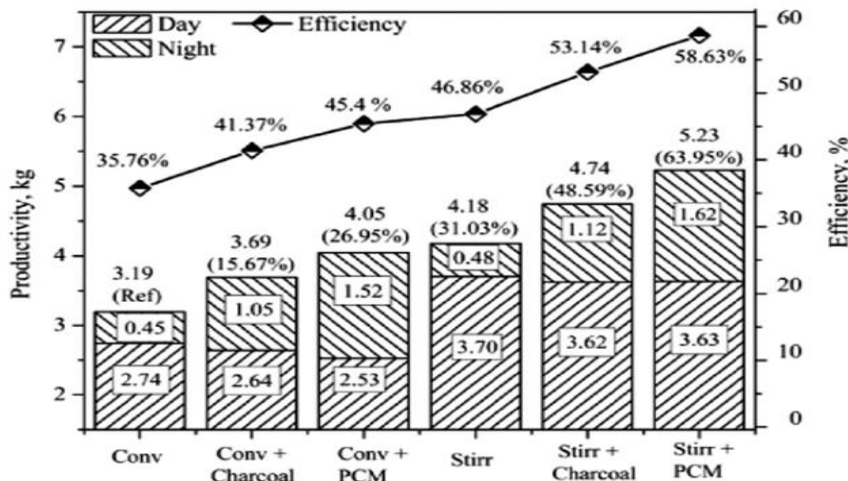


Figure 14. Production rates of the CSS, CSS + charcoal, CSS + PCM, CSS with stirrers, CSS with stirrers + charcoal and CSS with stirrers + PCM (Rajaseenivasan et al., 2017).

The application of DC rubber scrapers caused an increase in the temperature of the saline water in the DSSSHS basin from 15°C at 8 am to a peak of 76.67°C at 4 pm (Fig. 16). The differences between the maximum temperatures of still basin, basin water, air inside the still and glass of DSSSHS and DSSS were 8.91, 5.72, 0.83, and -2.83 °C (Figs 16 and 17) which represented that the performances of rubber scrapers were advantageous made the glass condensing cover more transparent, allowed more sun's rays to penetrate through it, hit the basin surface water and increase the evaporation rate of DSSSHS. The difference in temperature between

the basin water and the glass cover of DSSSHS was higher than that of DSSS, resulting in higher evaporation rates and, consequently, higher water production rates during the daytime experiment for DSSSHS (Figs. 16, 17, and 18). DSSSHS utilized rubber scrapers to achieve a cumulative water production rate of 4.24 L/m², compared to DSSS, which had a productivity of 2.6 L/m² (Fig. 18). Thus, the use of DC rubber scrapers in the solar still resulted in a 63% increase in cumulative water production. However, it can be seen from Fig. 16 and Table 2 that the solar still working temperatures at the initial moments of the experiment using DC

rubber scrapers was 47°C and generated 0.20 l/m² water under that temperature which was below 65°C that indicated the possibility of transferring the

microorganisms, pathogens and viruses into the produced water of the CSS.

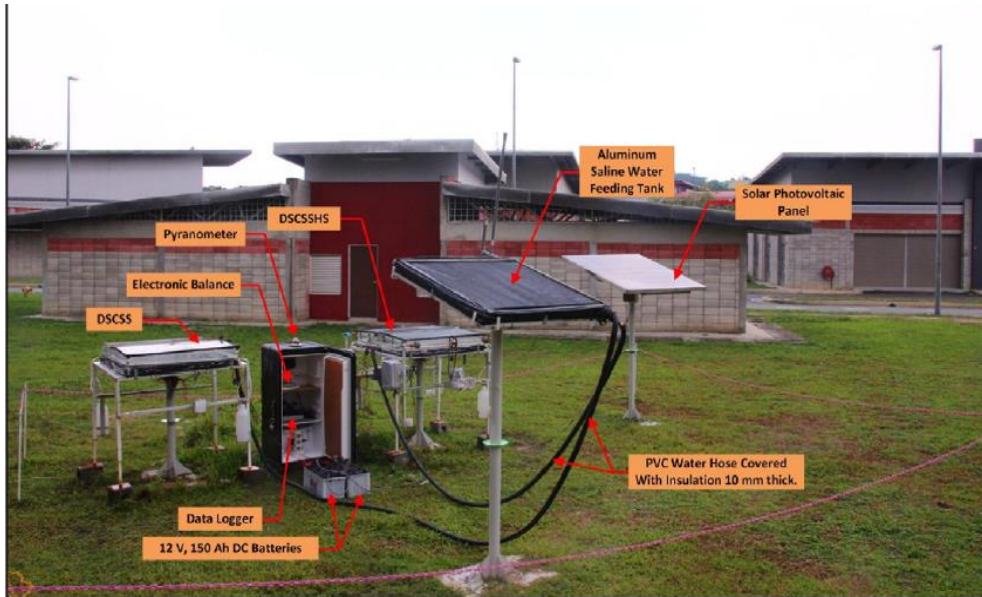


Figure 15. photograph of the experimental setup of DSSS and DSSSHS (Al-Sulttani et al., 2017).

1.4 Effects of forced convection DC devices on the performance of the CSSs for water vapour condensation and water production augmentation

Some researchers, Rahbar & Esfahani, (2012) and Rahbar et al. (2016), studied the cooling effects of the commercial DC TEC units on the condensing cover of the solar still and reported the increase of

temperature difference between the basin water (evaporation region) and the condensing glass cover (condensation region) of the solar stills occurred and this resulted in obtaining higher condensation and productivity rates. A typical DC TEC unit comprises a Peltier module, internal and external finned aluminium heat sinks, and a DC cooling fan (Fig. 19).

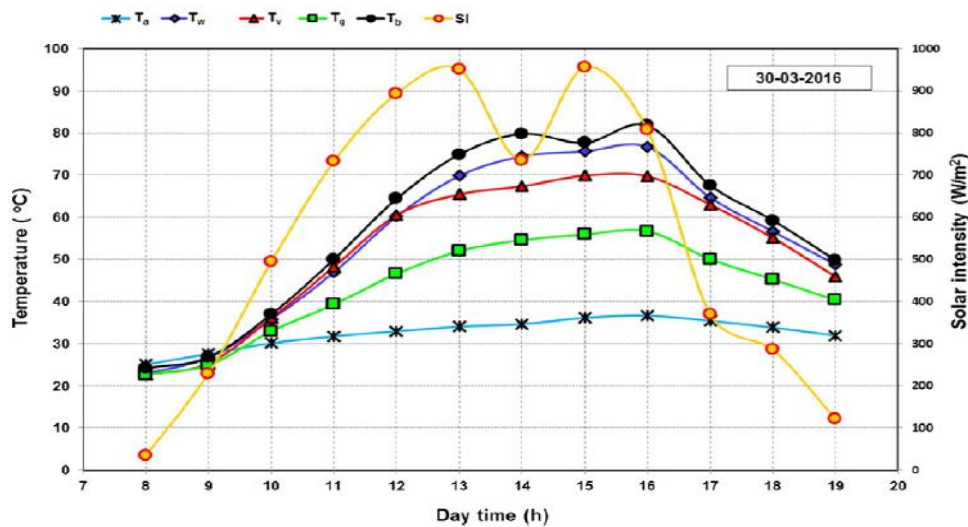


Figure 16. Variations in hourly basin, water, air inside the still, glass, and ambient temperatures, as well as solar intensity during daytime, for DSSSHS (Al-Sulttani et al., 2017).

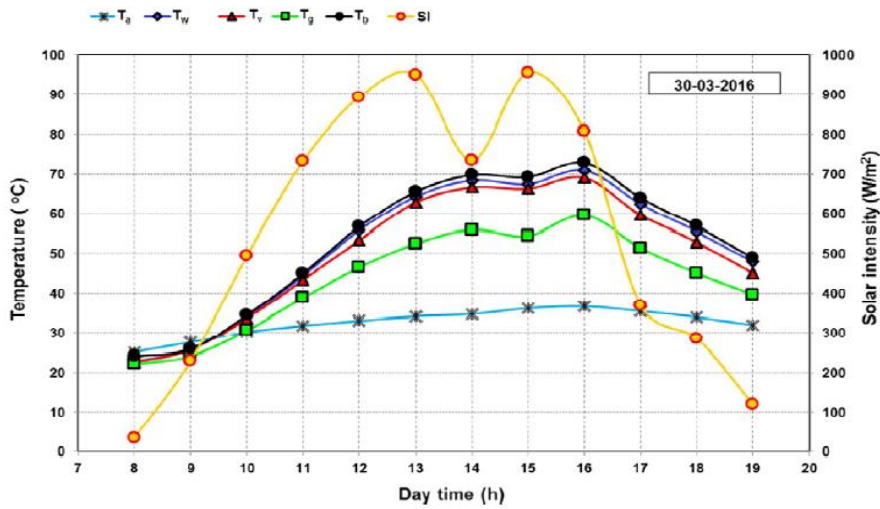


Figure 17. Variations in hourly basin, water, air inside the still, glass, and ambient temperatures, as well as solar intensity during the daytime, for DSSS (Al-Sulttani et al., 2017).

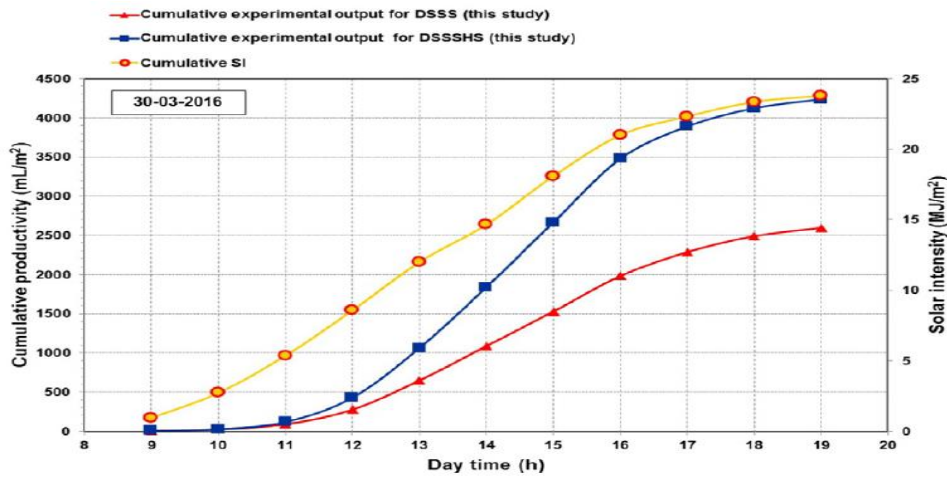


Figure 18. Comparison between the cumulative hourly experimental productivities for DSSS and DSSSHS with cumulative solar intensity (Al-Sulttani et al., 2017).

The Peltier module in the TEC unit comprises P-type and N-type blocks of semiconductor thermoelements (Fig. 20) (Esfahani et al., 2011). When electrons pass through a P-type to an N-type semiconductor, one side of the Peltier module becomes cooler. In contrast, the other side becomes hotter (Fig. 19-a), a phenomenon known as the Peltier effect. It was also stated by Rahbar & Esfahani, (2012), Rahbar et al. (2016), Riahi et al. (2021), Esfahani et al. (2013) that the lowest temperature on the cold side of the Peltier module occurs when heat removal from the hot side of the Peltier module increases.

Rahbar et al. (2016) considered the effects of three DC thermoelectric cooler (TEC) units (TEC-12708) mounted on an aluminium plate used as a wall of the condensing cover of an asymmetrical

solar still and its water production rate was compared with the productivity of a glass mounted on another side of the similar solar still without using TEC units (Figs 21 and 22). The solar still has been tested over six summer days under the climatic conditions of Semnan, Iran. Three DC fans with power of 2W were used to dissipate the excess heat from the hot side of the Peltier modules (Fig. 22). The basin of the solar still was made of black painted Plexiglas to absorb highest rates of solar radiation and the volume of 15 litre (width of 30 cm, length of 100 cm and depth of 5 cm) was fed into the still basin. Furthermore, the bottom part of the solar still was divided into two collecting sections to collect freshwater dropped down from the plate attached to the TEC units and the glass, independently (Figs 21 and 22). The solar still was

exposed to the sun from 8.00 am to 10 pm, which caused an increase in temperature of the basin saline water of the still from 22°C at 8 am to the peak of 58 °C at 2 pm, corresponding to the highest value of ambient temperature (Fig. 23). Rahbar et al. (2016) reported that the temperature of the aluminum plate attached to the TEC units was always much lower

than that of the glass throughout the six experimental days from 8 am to 10 pm which resulted in higher condensation rate of on the plate inner surface that produced higher cumulative water compared to the glass inner surface as it was noticed that the maximum yield of plate was eightfold than the glass yield (Figs 23 and 24).

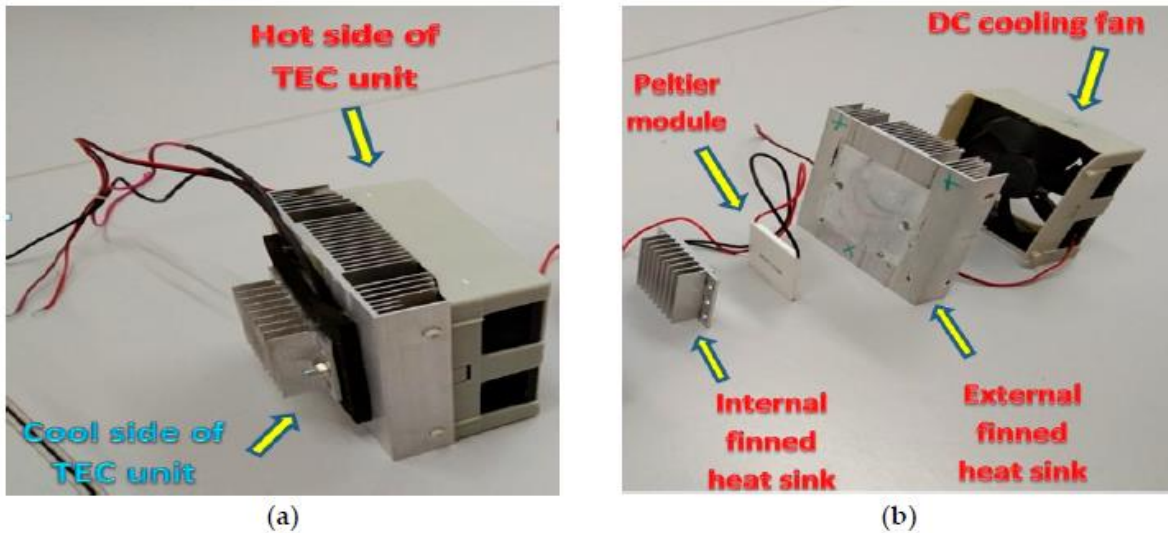


Figure 19. Photographs of (a) an assembled set of a thermoelectric cooling (TEC) unit; (b) the main components of a thermoelectric cooling (TEC) unit included the internal and external finned aluminum heats sinks, the direct current (DC) cooling fan, and the Peltier module used in MSAWG (Riahi et al., 2021).

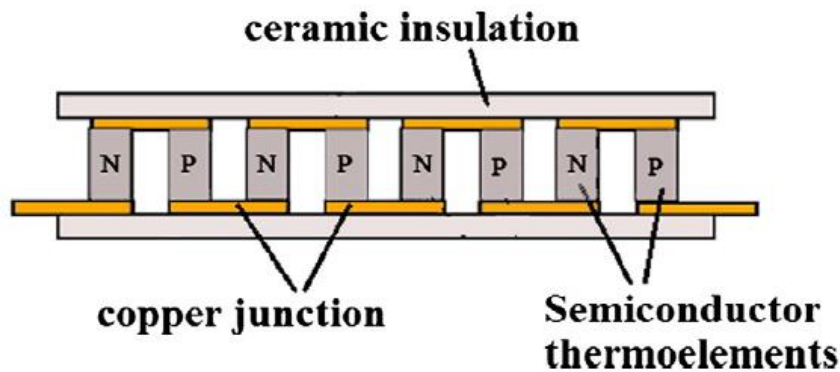


Figure 20. A Peltier module comprises P-type and N-type blocks of semiconductor thermoelements (Esfahani et al., 2013)

Variations of the temperatures of the aluminum plate connected to the TECs, glass, ambient and basin water for a typical experimental day was shown in Fig. 23. The maximum temperature for TECs aluminum plate, glass and basin water of solar still occurred at 2.30 pm when the ambient temperature was at the highest point (Fig. 23). At this time, the difference between the temperature of the glass-water and the aluminum plate (TECs)-

water was approximately 3 and 18 °C, respectively, which caused the higher production rate to occur on the inner surface of the aluminum plate compared to the glass inner surface (Fig. 23). It has been concluded that the total volume of freshwater produced by the aluminum plate connected to the three TEC units was nearly 3.2 times larger than that of the glass, despite the surface area of the plate being 2.8 times more minor (Figs. 23 and 24).

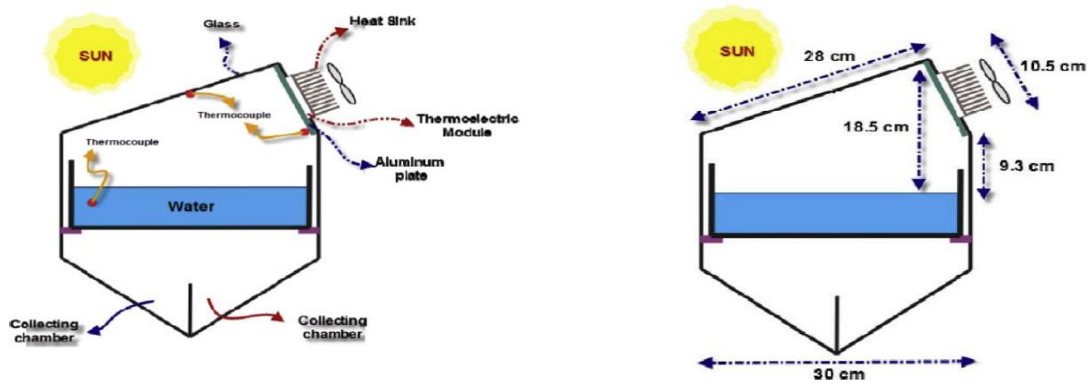


Figure 21. Schematic views of the asymmetrical solar still with thermoelectric modules studied in Iran (Rahbar et al., 2016).



Figure 22. Photograph of the portable asymmetrical solar still (Rahbar et al., 2016).

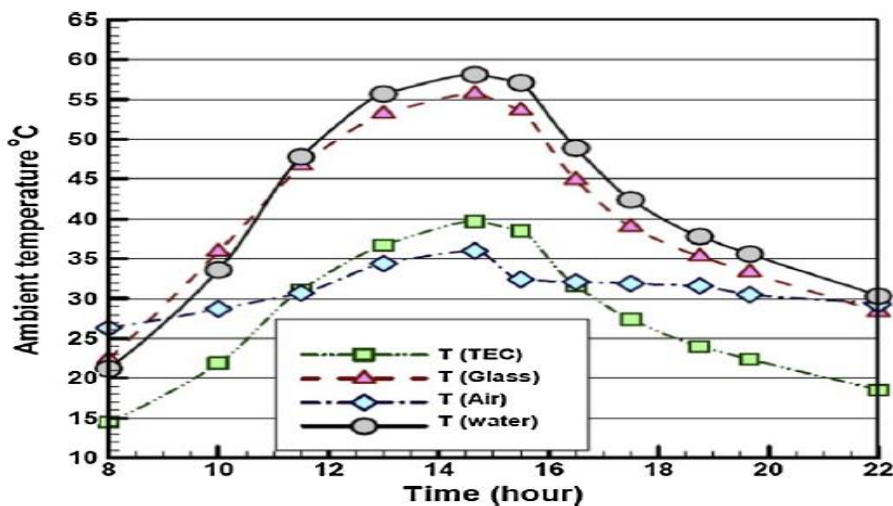


Figure 23. Hourly variations in the temperatures of basin water, glass, ambient air, and TEC aluminium plate (Rahbar et al., 2016).

Thus, it was reported by Rahbar et al. (2016) that the leading cause of enhancing condensation and water production rates was the use of TEC units mounted on the solar still condensing cover, which was due to the increase in the temperature difference between the basin water and the aluminium plate attached to the TEC units.

The lowest and highest amounts of water produced by the above solar still, using TEC units

on one side of its condensing cover, were obtained at 225 and 500 ml, respectively, when the solar still was exposed to the minimum and maximum solar intensity rates of 20,500 and 25,500 J/m², respectively. However, it can be seen from Fig. 23 and Table 2 that the solar still produced 0.20 L/m² water under an initial working temperature of 40°C, through which waterborne thermal resistance pathogens and viruses can be transferred to the

produced water distillate of the solar still via vapors.

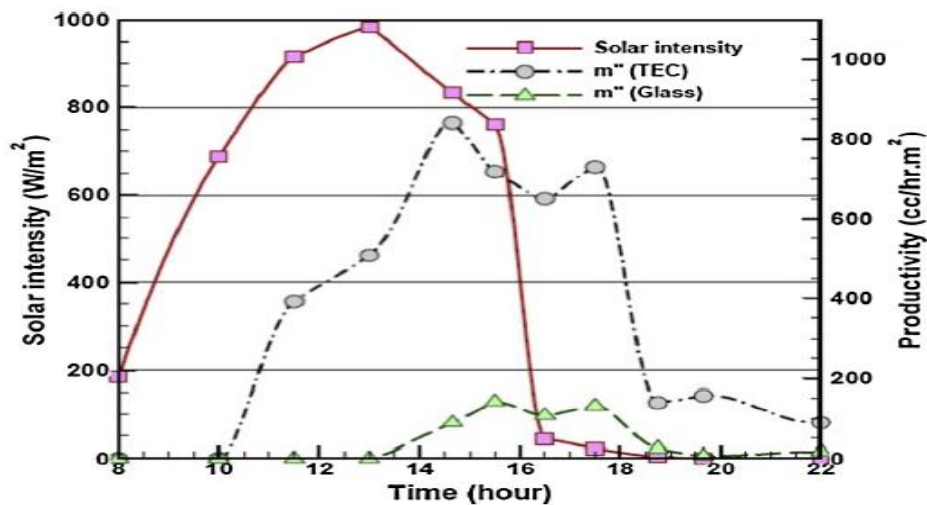


Figure 24. Hourly variations of solar radiation intensities and water production of TEC plate and glass (Rahbar et al., 2016).

2. Discussion

One of the leading public health concerns for the remote and rural communities was a lack of access to safe water, free from waterborne pathogens and microorganisms. The use of passive and active solar stills as thermal desalination techniques to treat the impure water and produce fresh water was of interest to the above communities. However, possible transferring the various water borne pathogens such as *E. coli*, *Klebsiella pneumoniae*, and *Enterococcus faecalis* into the distillate of some passive and active solar stills through vapors was reported by Parsa, (2021) and Yusof et al. (2022) which indicated as a vast public health concern as the above solar stills were able to produce water at their initial working temperature between 20 and 50°C. Nevertheless, the above waterborne pathogens were able to resist the heat in the basin water of the CSS until 65°C. Such a condition is a crucial factor in the viability and survival of waterborne pathogens and viruses in the basin water and distillates of the CSSs. The effects of the DC systems such as using a DC fan (Taamneh & Taamneh, 2012), a DC heater (Riahi et al., 2019), a DC rotating shaft motor (Abdel-Rehim; & Lasheen, 2005), four DC stirrers (Rajaseenivasan et al., 2017), two DC rubber scrapers (Al-Sulttani et al., 2017) and three DC thermoelectric cooling units (Rahbar et al., 2016) integrated with CSSs reviewed in this work and revealed that they were able to enhance the evaporation and condensation rates in the solar stills and hence increase the productivities

of the CSS by 25, 36, 5.0, 63.95, 63 and 320 %, respectively. However, the above DC machines were unable to increase the initial working temperatures of the CSS's basin waters to 65°C. Thus, it was concluded that the above CSSs, when integrated with the DC apparatuses, were unable to eliminate or prevent the transfer of the aforementioned thermal resistance pathogens into the solar stills' distillates. Furthermore, in a review study reported by Yusof et al.

Table 2. 12V direct current (DC) apparatuses as forced convection integrated with the conventional solar stills (CSSs)

Country, Reference	Type of the 12V DC devices integrated with the CSS	Area of the CSS basin (m ²)	Volume of water in the basin (liter)	The initial basin water temperature from which the solar still produced distillate (°C)	Productivity rate of the solar still at initial water temperature (L/m ²)	Maximum daily yield of the CSS integrated with DC machines (L/m ²)	Percentage rate of CSS yield increase (%)
Jordan, Taamneh and Taamneh, (2012)	A DC fan	0.95	57.0	25°C	0.07 L/m ²	2.99	25
Malaysia, Riahi et al. (2019)	A DC water heater	0.15	4.50	49°C	0.32 L/m ²	4.36	36
Egypt, Abdel-Rehi and Lasheen, (2005)	A DC rotating shaft motor	1.0	150.0	30°C	0.11 L/m ²	2.70	5.0
India, Rajaseenivasan et al. (2017)	Four DC stirrers	1.21	121.0	40°C	0.065 L/m ²	5.23	63.95
Malaysia, Al-Sulttani et al. (2017)	Two rubber scrapers	1.0	19.0	47°C	0.20 L/m ²	4.24	63
Iran, Rahbar et al. (2016)	Three DC thermoelectric cooling (TEC) units	0.30	15.0	40°C	0.20 L/m ²	3.0	320

(2022) and the findings of the studies, regarding examining the performances of the small-scale solar distillers called absorbers/ boilers with low capacity ranged from 100 to 250 ml integrated with the solar dish concentrators (SDCs) and solar tracking systems (STSc), the initial operating water temperatures of the solar distillers during the early hours of their experiments reached above 65°C, thus, it was indicated that using small-scale solar stills or absorbers with low capacity is advantageous to increase the initial basin water temperatures of the solar still immediately that incorporated with the external heat sources such as solar dish concentrators (SDCs). According to the above discussion and as it can be seen in Table 2 that the capacities of the basins of each CSS integrated with the DC systems were 57, 4.50, 150, 121, 19.0 and 15 liters, respectively which were much higher than the capacities of the absorbers (100 to 250 ml) studied in (Omara & Eltawil, 2013; Gorjian et al., 2014; Prado et al., 2016), hence, it could be a reason of obtaining low rates of initial working temperatures of the aforementioned CSSs incorporated with the DC systems that showed that the solar stills incorporated with DC apparatuses require more energy input to escalate their initial basin water temperatures up to 65°C in order to prevent transferring the water-borne pathogens and microorganisms through the vapors to their produced distillates. Therefore, employing small-scale CSSs and feeding them with lower capacities of brackish water, while integrating them with DC machines, is essential to achieve higher operating temperatures of the CSSs during their initial periods of operation.

3. Conclusions and Directions for Future Research

Based on the above reviews and discussions, DC apparatuses such as a DC fan, a DC heater, a DC rotating shaft motor, four DC stirrers, and two DC rubber scrapers integrated with different designs of the CSSs were effective in increasing the basin water temperatures, evaporation rates and hence, the CSSs' freshwater production. Meanwhile, incorporating three DC TEC units with the CSS increased the condensation rate and the CSS's productivity. However, it seemed that the above CSSs were unable to produce safe (pathogen-free) freshwater for the remote and rural communities as the pathogens and viruses, particularly thermal resistance pathogens, were likely being transferred into the CSSs' distillate through vapors as the CSSs were unable to obtain the initial working water

temperatures above 65°C integrating with the DC appliances. The cause of the deficiency of the CSSs in obtaining high initial working temperatures was the basins of the CSSs that were constructed on a large scale and carried high capacities of water. Thus, there would be a need to supply more energy to heat the basin water of the CSSs. Therefore, it was concluded that designing and constructing a CSS with a smaller-scale basin or absorber and having a low water capacity in its basin while integrating with DC machines is vital to achieve higher working temperatures and prevent the transfer of pathogens and viruses to the CSS's distillates. This matter will also assist the CSSs in increasing the rates of safe water production.

From the literature reviewed in the present work, it can be observed that a combination of some aforementioned DC apparatuses, such as a DC heater and a TEC unit powered by PV modules and batteries, as a conceptual future hybrid DC system integrating with a small-scale pyramid/cone-shaped solar distiller with the capacity from 150 to 250 ml experimenting under sunny days is recommended to likely enhance the initial basin water temperature of the CSS above 65°C, the CSS' productivity, eliminating the microorganisms and thermal resistance pathogens from the basin water of the CSS and producing safe clean water. For this purpose, a cone-shaped absorber for a solar distiller, with a diameter of 0.15 m and a height of approximately 0.07 to 0.10 m, shall be designed and constructed. An aluminum or copper pipe will be connected to the top opening of the solar distiller to transfer the vapors out from the distiller (Figs. 25 and 26). Water with a volume of approximately 250 ml shall be fed into the distiller absorber. A DC heater with a power of 50W is suggested for placement inside the absorber to heat the CSS's absorber water. Thereafter, the produced water vapors shall be condensed instantly using a DC thermoelectric cooler (TEC) unit with the maximum output power of 60W (consisting of the total output powers of a Peltier and a DC fan), which should be placed at the end point of the copper pipe to cool down the water vapors. Assuming 8 hours of high solar radiation intensity on a sunny day, the proposed DC heater and DC TEC unit will consume approximately 400 Wh (8 hours × 50 W) and 480 Wh (8 hours × 60 W) per day, respectively. To avoid receiving power with frequent fluctuations due to existing clouds during the day from a photovoltaic module., it is suggested that a 12V battery power the DC heater and TEC unit, and then the battery be recharged and supported by a photovoltaic module and a charge controller. Thus, referring to calculations of the required 12V batteries and

photovoltaic modules for powering the DC appliances, it is estimated that a 12V 100Ah battery recharging by a 250W monocrystalline photovoltaic module with access to the direct sun's rays can

power a 50W DC heater and a 60W TEC unit in the periods of 8 hours daily.

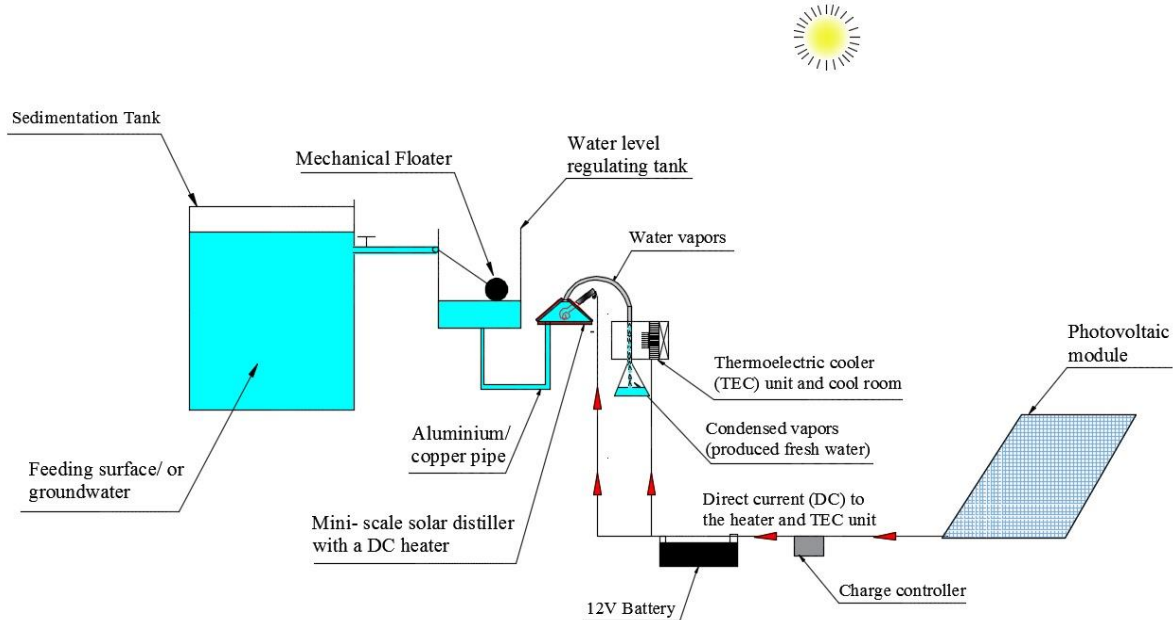


Figure 25. Schematic diagram of a recommended small-scale solar distiller (CSS) integrated with a DC heater and a DC thermoelectric cooling (TEC) unit powered by a 12V direct current (DC) battery recharging by a DC photovoltaic module

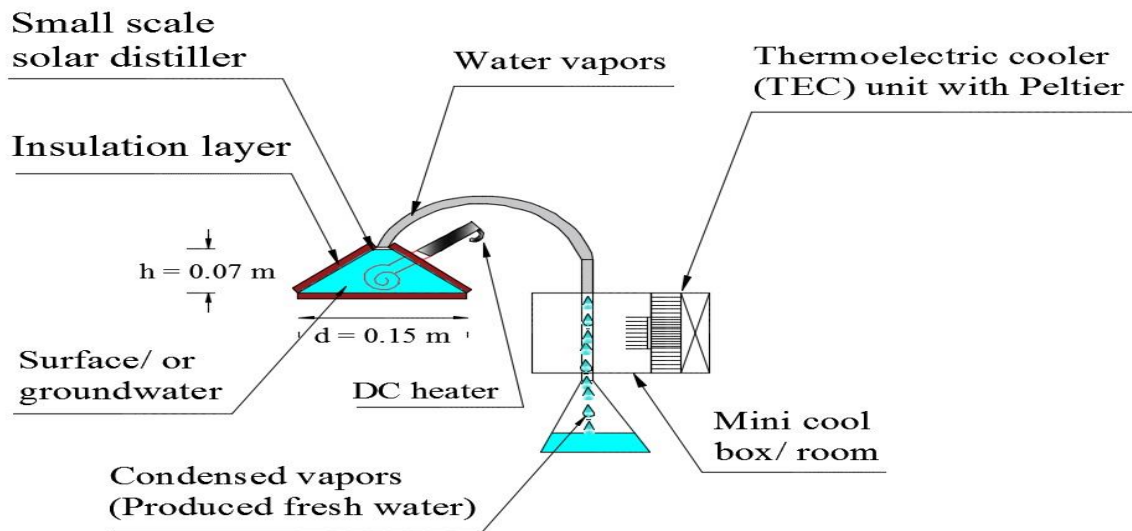


Figure 26. Sketch of a suggested small-scale distiller with its dimensions heating by a DC heater and cooling its vapor by a DC thermoelectric cooling (TEC) unit

Furthermore, a sedimentation tank, a headwater tank, or a water level tank with a mechanical floater shall feed the CSS's absorber and maintain the volume of water at approximately 250 ml inside the

absorber (Fig. 25) during the experimental day. Optimistically, the suggested conceptual design is expected to be advantageous for heating the absorber water and promptly achieving a working

temperature above 65°C after the experiment. Therefore, this recommended hybrid solar thermal desalination system may serve as a decentralized, sustainable water treatment alternative for producing safe water in remote and rural communities that lack electricity and clean water but receive more than 3,000 hours of bright sunshine annually.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Ali Riahi wrote the manuscript, collected some parts of the corresponding literature review, and revised it accordingly. Mohd Fazly Yusof collected some literature review of the manuscript and also revised the introduction section. Mohd Hazwan Hisyam Bin Abu Hassan collected some literature review of the manuscript. Mohd Remy Rozainy Mohd Arif Zainol cooperated in writing the manuscript and also revised it.

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