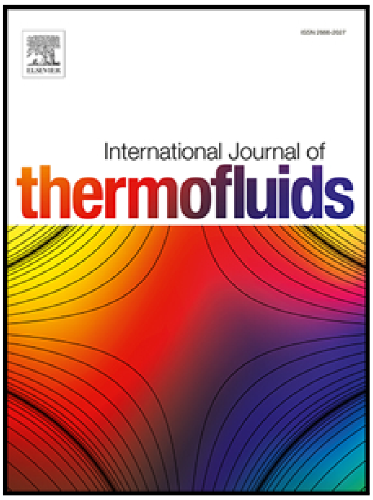

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Enhancement of Solar Distiller Performance by Photovoltaic Heating System

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Abstract

This study aims to improve the productivity of traditional multi-slope solar stills, which are still employed in isolated villages with no power and no clean drinking water. The conventional multi-slope solar still was equipped with a photovoltaic array system that heated the water through an electric heater submerged in the basin to increase the productivity of the conventional solar stills. This study analyzed and compared the productivity of a PV-coupled solar still (PVSS) with a solar still basin area of 0.64 m^2 to that of a conventional solar still (CSS). The results showed that the productivity of the PVSS improved more than triple times (9.39-10.9 L/m^2.day) during active mode compared to the CSS, which had a daytime solar still production without a PV system (passive mode) that varied between 2.2-2.34 L/m^2.day. The daily efficiency of the passive mode without any additional external energy input was around 27%, which resulted in a distilled water yield of 1.4 L. However, when operated in active mode with supplementary energy inputs, such as electrical heating elements that were powered by solar panels, the daily efficiency of the solar still was approximately 44.8%, resulting in a distilled water yield of 6 liters. The payback period for

PVSS was found to be two years. The main observation is that the PVSS has demonstrated its applicability for distillation improvement and a significant increase in production for the entire day when employing a clean energy source.

Keywords: Renewable energy, water distillation, solar energy, PV system, solar still

1. Introduction

There is an urgent need for an appropriate and reliable supply of drinking water in many countries. Brackish water from rivers, lakes, seas, and ponds contains dissolved salts and/or harmful microbes and hence cannot be consumed directly. Access to safe drinking water is becoming scarce worldwide. Most human diseases are caused by contaminated or non-purified water resources. Water shortages are a significant issue in developing countries due to unplanned processes and pollution caused by man-made activities. According to the World Health Organization (WHO), Jordan has one of the lowest levels of water resources in the world, and there is an increasing need to produce drinkable water from salty water. Jordan imports 97% of its total energy. However, Jordan has a solar potential of more than 320 sunny days per year in most regions [1,2].

Technology for water purification without harming the ecology is essential for a sustainable future. Because many nations have abundant solar energy resources, it is projected that technological and scientific capacities in the field of renewable energy will increase to 60% by 2030 [3]. Therefore, solar energy has an enormous potential worldwide. Its most potential uses include space heating and cooling, electricity production, and water desalination [4–6]. By 2045, potable water will no remain without purification. Therefore, water supply purification is more crucial. Incorporating renewable energy sources to convert unclean and salty water into fresh water is becoming a viable solution for providing clean water with inexpensive and environmentally friendly energy. Solar energy is the primary source of heat that can be delivered to dirty/saline water to evaporate it into clean and potable water [7]. It is worth noting that the development of novel low-grade systems for water desalination, cooling, and heating would save 5 MTon of fuel per year by 2030, resulting in a 9 million ton decrease in CO_2 emissions [8].

Different ways of providing fresh water to desert places are primarily examined using technologies [9–11]: water transportation from other sites, desalination of salty water, and water extracted from atmospheric air. However, it is expensive to transport water across these areas. The second approach, which uses desalination, is dependent on the existence of salty water supplies, which are often scarce in dry areas. However, the third approach is based mostly on atmospheric air, which provides massive and renewable water storage. The atmosphere contains 3100 cubic miles of water, 98% of which is vapor and 2% clouds. Water evaporates or seeps daily at 280 cubic miles. Furthermore, one cubic mile of water holds nearly one trillion gallons of water [12]. Owing to these factors, the method of extracting water from atmospheric air has various benefits over other methods. First, Air is a sustainable and pure water supply. Second, atmospheric air contains 14000 km^3 of water, compared to 1200 km^3 of fresh water.

Eltawil and Omara [13] emphasized the significance of water in socio-economic development. However, access to water that satisfies conventional water quality requirements is limited, particularly in the African. Solar desalination can enhance the quality of saline/brackish waters. Distillation systems are divided into two types: passive and active systems. Murugavel et al. [14] reviewed the studies on passive solar distillation and concluded that the use of various materials in the basin considerably increased production. Sampathkumar et al. [15] reviewed active solar distillation, which requires external energy to increase the system performance. Tiwari et al. [16] investigated passive and active solar distillation systems. They recommended that only passive solar stills be used to supply drinkable water. Commercially, active solar distillation systems are cost-effective. External sources, such as a flat plate collector, concentrated collector, a hybrid PV/T system, heat exchanger, and solar pond, are used in active-type basin stills to increase the temperature of the water in the basin. The solar still, coupled with a flat plate collector, can operate in either forced or natural circulation mode. Riffata et al. [17] analyzed the performance of a solar still and a flat plate collector. In terms of simplicity, reliability, and cost-effectiveness, they observed that the solar thermal device in the thermosiphon mode (natural circulation mode) outperformed the forced circulation mode. Zaki et al. [18] evaluated the combination of active single-sloped solar stills with flat plate collectors and found a maximum production improvement of up to 33%. Badran and Al-Tahaineh [19] revealed that combining a solar collector with a still enhanced production by 36%. Furthermore, the increase in the depth has reduced production, while solar still productivity is shown to be proportional to the intensity of solar radiation. Sampathkumar et al. [4] determined that several parameters influence the performance of the solar still, including water depth in the basin, basin material, wind velocity, solar radiation, ambient temperature, and inclination angle. The temperature difference between the water in the basin and the inner surface glass cover affects the productivity of any type of solar still. Solar radiation is received directly by basin water in a passive solar still and is the only source of energy for increasing the water temperature and, as a result, evaporation, resulting in lower production. This is the main drawback of the passive solar stills. Subsequently, various active solar stills were developed to address this issue. Extra thermal energy was supplied to the basin through an external mode to promote the evaporation rate and improve its productivity. Some uncontrolled characteristics, such as solar radiation intensity, ambient temperature, and wind velocity, cannot predict or enhance solar performance. However, several characteristics, such as water depth, glass cover angle, construction materials, water temperature in the basin, and insulation thickness, impact the performance of the solar still and can be modified to improve performance [20–23]. Al-Marahleh and Badran [24] demonstrated that coupling vacuum tubes with a single solar still enhanced the yield by 50% compared to an uncoupled system. Abdullah et al. [25] found that the temperature difference between the water in the basin and condensing glass cover had a direct influence on the performance of the solar still. The temperature difference between the evaporating and condensing surfaces increased as the amount of water in the basin increased. To improve the evaporation and condensation rates, the temperature of the water in the basin can be boosted by introducing thermal energy from outside sources. Abdallah et al. [26] improved the thermal performance of a solar still by using a super heat conduction metal vacuum tube (SHCMV). The SHCMV method achieved continuous operation using a flat plat photovoltaic system. They found that the SHCMV generated 12 L/m^2/day of distilled water, whereas the traditional solar still produced approximately 1 L/m^2/day. The SHCMV enhanced the yield by approximately 90%. During daylight, the SHCMV provided more than 60% efficiency for more than 5 hours. Abdullah et al. [27] improved the performance of tray solar stills by increasing the absorber surface area and rate of heat transfer. Three solar stills were tested: a flat tray solar still, a corrugated tray solar still, and a conventional solar still. The corrugated tray solar still was improved with the use of a wick material and a phase change material mixed with CuO nanoparticles, and the basin. Moustafa et al. [28] improved the water yield and thermal efficiency of a tubular solar still through the use of an electrical heater powered by a photovoltaic panel. A fine-tuned artificial intelligence model was also developed to predict the thermal efficiency and water yield of the solar still. The results showed that the modified tubular solar still had an improved water yield of 3.41 L/m^2/day and a higher energy efficiency of 38.61%. Kabeel and Abdelgaied [29] developed a hybrid system combining a photovoltaic (PV) panel with reflectors and cooling integrated with the solar still with air injection. The results showed that the electrical power of the PV panel improved by up to 39.69% with reflectors and cooling. The freshwater production improved by up to 40.98% with the use of air injection. Taamneh et al. [30] evaluated the performance of the modified solar stills n both passive (PISS) and active (AISS) modes in producing fresh water from brackish water. The AISS had a Spiral Tube Collector integrated for fresh water extraction. The highest production of distilled water was 4.4 kg/day for the PISS and 8.3 kg/day for the AISS. Ghandourah et al. [31] designed a Pyramid Solar Still (PSS) for producing drinking water from brackish or saline water. The authors added a corrugated plate to increase the evaporation area, leading to a higher yield compared to a conventional solar still (CSS). The results showed that the proposed designed produced 4.5 L/day compared to 2.95 L/day for the CSS and had a 52.54% higher yield with a 45.5% average thermal efficiency. Nagaraju et al. [32] proposed a new method to enhance the performance of a single slope solar still by incorporating sand troughs. Experiments were conducted with different water levels in the basin and the maximum yield was obtained for 1 cm water level at 2 PM. The solar still with sand troughs had a 71.4% higher daily productivity compared to the still without sand troughs and was more efficient with an efficiency of 65.08%. Al-Ahmadi et al. [33] investigated the performance of a double slope solar still (DSSS) incorporated with a flat plate collector (FPC) or parabolic trough concentrator (PTC), as well as the coupling of both. The devices were connected in series and the results indicated that coupling the solar still with both FPC and PTC led to a substantial improvement in productivity, with a 170% increase in yield compared to the standalone still. Furthermore, the temperature of the water increased by approximately 27% for the solar still integrated with both collectors, relative to the standalone solar still under similar climatic conditions. Tiwari [16] classified solar distillation systems into passive and active solar stills based on the various modifications and modes of operation implemented in conventional solar stills. In the case of active solar stills, extra-thermal energy from the external mode is fed into the basin of passive solar stills for faster evaporation. The external mode may be a collector/concentrator panel and waste thermal energy from any chemical/industrial plant. If no such external mode is used, then that type of solar still is known as a passive solar still. Parikh and Patdiwala [34] investigated the impact of nanofluid on productivity. They found that this had a beneficial influence on the production of distilled water. Extra-thermal energy from the external mode is delivered into the basin of the passive solar stills for faster evaporation in the case of active solar stills. A collector/concentrator panel and waste thermal energy from any chemical/industrial facility can be employed as external modes. If no external mode is utilized, the solar still is referred to as a passive solar still. Bari and Randhawa [35] stated that waste heat from internal combustion engines can be captured and used to generate freshwater from seawater or brackish water. Alrabai [36] utilized solar power for humidification-dehumidification desalination (HDD) process to provide fresh water.

It can be concluded that solar distillation is both cost-effective and environmentally safe, particularly in rural regions. Although numerous studies have been conducted on active distillation devices aimed at overcoming the issue of low distillate yield in passive solar stills [37,38], an effective solution for providing a reliable source of fresh water to communities in remote locations, such as deserts, where water scarcity is a daily issue and water tanker supply is costly, has yet to be found. The objectives of this study were to determine how to increase the yield of conventional multi-slope solar stills by coupling them with photovoltaic arrays, to improve the heat transfer of the still basin and increase evaporation. The aim is to provide a large amount of fresh water to people living in remote areas and address the issue of daily water scarcity.

The novelty of this work is based on the integration of various distillation enhancers, including electrical heaters supplied by PV panels and direct distillation from the sun onto a black surface, within a single compact system designed to maximize productivity. Furthermore, A night heating system has been developed that utilizes battery backup to supply electricity to the electrical heater, thus resulting in an improvement in the low productivity that is traditionally associated with solar stills. To our knowledge, this approach has not been attempted globally, nor within our region, specifically with regard to the pyramid multi-slope single basin solar still, as demonstrated by our literature survey. In addition, this study offers a comprehensive analysis of the impact of photovoltaic enhancers on the productivity of solar stills, and specifically examines the influence of these enhancers on productivity. This approach offers a cost-effective and environmentally friendly solution for providing access to clean water in remote areas. The thermal modeling of various types of active single-slope solar distillation systems provides insight into the scope of future research and suggestions for improving active solar distillation systems.

2. Solar Still Operation

The raw water was poured into the still to create a few centimeters-high water layer in the basin. The glass cover allows solar radiation to enter the still, where the blackened base primarily absorbs it. This interior surface employs a blackened material to improve sunlight absorption and heat transfer to the basin's water. As the water warms, the moisture content of the air trapped between the water surface and glass cover increases. When the air became saturated, heated water evaporated from the basin and condensed inside the inclined glass cover. The condensed water flowed down the inclined glass top into an inner collecting trough and out into a storage bottle. Each day, feed water that approximately surpasses the distillate output should be provided to ensure thorough flushing of the basin water and to remove surplus salts left behind during the evaporation process. The solar radiation and ambient temperature variation on a typical day is displayed in Fig. 1.

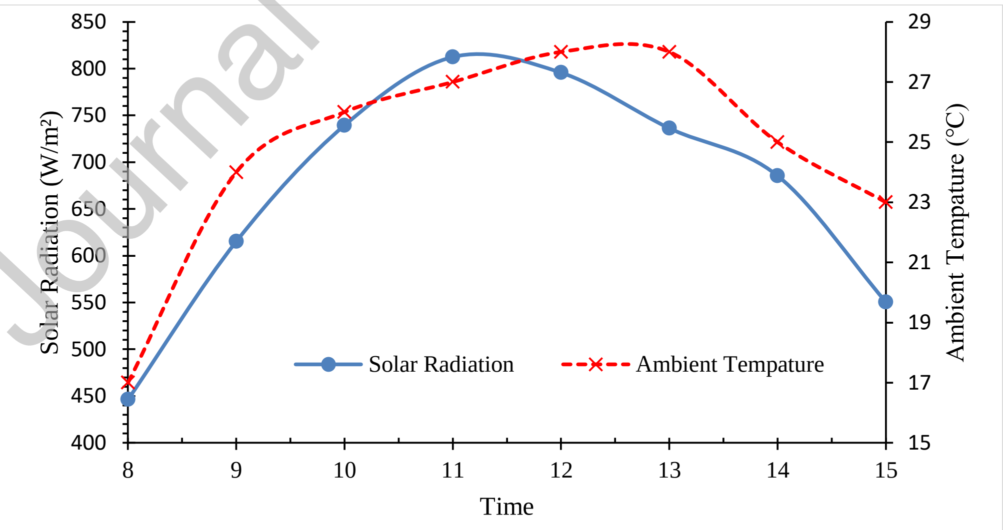

Fig. 1 Solar radiation (W/m^2) and ambient temperature variation with time

3. Experimental Setup and Methods

3.1. Water Distillation System with PV Array

The solar radiation was measured using a solar power meter (Mini Pocket Solar Radiation Power Meter Tester Range 4000 W/m^2 and model no. TM-750), with an accuracy of ±5% and an additional temperature-induced error of 0.38 W/m^2 / °C. It can be observed that the maximum solar radiation occurred around midday, with a value of 800 W/m^2.

Data were gathered during the autumn season in November. The average measured wind velocity was 2-3 m/s. It can also be observed that high solar radiation corresponds to the peak sun hour (PSH), which is 6 hours in Jordan [39]. Cloudy days are avoided. The experimental setups were installed on the roof of the Faculty of Engineering Technology (FET) at Al-Balqa Applied University, Marka, Amman. Marka experiences more than 320 days of sunlight each year, with an annual sunshine length of approximately 3360 hours. It is a city with annual global radiation exceeding (2620) kWh/m^2, daily direct normal irradiation (DNI) of approximately 7.1 kWh/m^2, and yearly DNI of approximately (2100) kWh/m^2. Therefore, Marka is one of the best locations for conducting solar energy experiments. Before each experiment, the glass cover was cleaned to prevent dust accumulation on the top glass cover of the still basin. The following variables were examined in this experiment: basin water temperature (Tw), inner glass cover temperature (Tg), vapor temperature (Tv), ambient temperature (Ta), solar radiation (I), and distillate production (L).

Fig. 2 displays a schematic diagram of the hybrid water distillation system that employs a photovoltaic (PV) array. The PV system provides electrical power to a battery, which is then used to power a heater that heats the basin water during nighttime hours when there is no sunlight. The diagram includes the following components:

1. PV array - the source of electrical power
2. Batteries - store the electrical power generated by the PV array

3. Controller - regulates the flow of power from the batteries to the heater
4. Inverter - converts the DC power from the batteries to AC power for the heater
5. Water distiller - the device that performs the actual distillation process using the heated water.

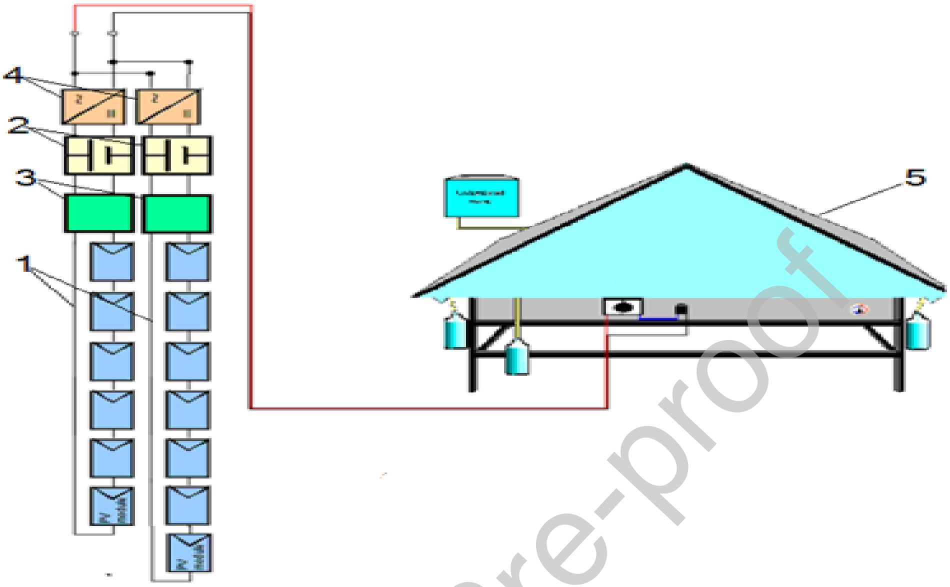

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Fig. 2 Water distillation system using PV array

Fig. 3 depicts the main components of pyramid multi-slope single basin solar still. In addition to passive heating, the current hybrid distiller includes an electrical heater to heat water in the basin. The inverter was coupled to the heater through batteries charged by the PV array during the day. The use of PV arrays in combination with batteries is intended to prolong the operation of a solar still for night distillation to boost the total output of a conventional still by using a renewable and clean power source.

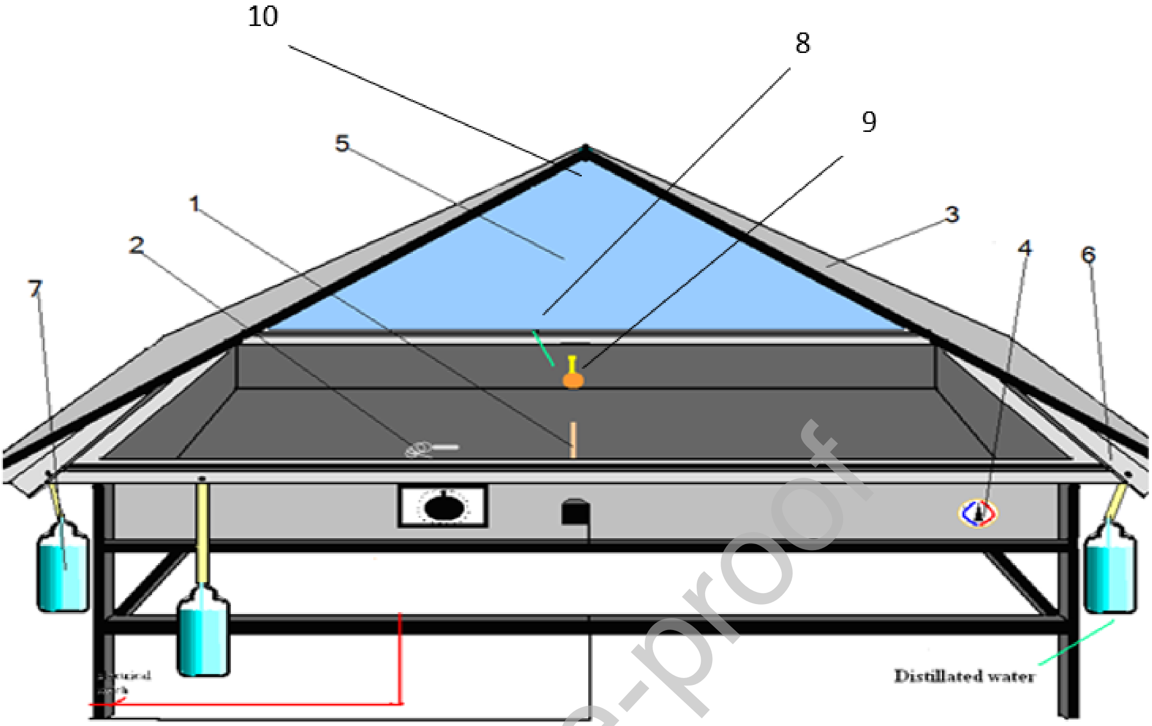


Fig. 3 Schematic diagram of water distiller components. (1) electrical heater, (2) Thermostat, (3) steel sheet, (4) basin thermocouple, (5) glass surface, (6) distilled water channel, (7) distilled water bottle, (8) vapor thermocouple, (9) water thermocouple, and (10) glass thermocouple

The solar irradiation on the PV array during the day supplies DC power that can be stored in a battery bank via a charge controller, thereby extending the life of the batteries. The DC power is inverted to AC power using an inverter to supply electricity to the heater during the night to improve the productivity of the solar still because of the low ambient temperature. Solar radiation was employed throughout the day to generate vapors, which condensed on the inner glass cover and flowed down to the distilled water channel owing to gravity, allowing them to be collected in a distilled water bottle, as illustrated in Fig. 3. During the daytime test, large droplets formed on the glass surface and returned to the basin. This behavior resulted in a significant loss of distillation.

The PV panel array on the roof of the Faculty of Engineering Technology, Al-Balqa Applied University in Amman was designed and built. The PV panels used were of poly crystalline silicon type. Thirteen PV panels are connected in series. The rated power of each panel was 75 W, and the total power was approximately 975 W. This is adequate for power heaters ranging from 100 W to 500 W.

The charge controller is an essential component of battery-powered systems. The primary role of the controller is to regulate the charging of the battery bank and the proper supply of electrical power to the electrical appliances if coupled with a battery bank. It prevents overcharging of the battery bank and manages the rate of the current and voltage at which it charges. Furthermore, some charge controllers have load controls. The current controller had a rated voltage of 12-24-48 V DC. The rated output voltage of the inverter was 220 V AC, and the frequency was 60 Hz. The current inverter transforms the stored electrical energy in the battery to alternating current (AC) to power the heater submerged in the basin during night operation of the solar still.

Fig. 4 depicts the experimental setup installed at the top of the Faculty of Engineering Technology. A 4 cm thick rock wool insulator was installed at the bottom and sides of the still basin to prevent heat loss. The thermal conductivity of the rock wool insulator utilized is (0.035 W/m. K) at 24 °C, and its density was 70 kg/m^3. Evaporated water inside the basin was condensed on toughened glass with a thickness of 4 mm fixed on the east and west slope sides of the still. This allowed solar radiation to pass through the water basin for evaporation. Stainless steel sheets with a thickness of 2 mm were mounted on the northern and southern slopes of the still to act as condensers to improve the distillation process. A measuring bottle was used to collect condensed water from the basin, as presented in Fig. 3. A silicone sealant was supplied to keep the toughened glass and stainless-steel sheets in contact with the solar still trough. K-Type Temperature Probe Sensor Mini-Connector Thermocouples (Temperature Range: -50~250°C) with ± 0.1 ^{0}C accuracy were used for temperature measurements.

Fig. 4 Photograph of the solar distillation system integrated with photovoltaic (PV) panels

3.2. Error Analysis

To assess errors in the experimental measurements, various instruments were utilized, such as solar power meter, thermocouple, graduated flash, power supply, and a multimeter. The solar radiation power meter used in this study was estimated to have an accuracy of ±1 W/m^2. Temperature measurements were performed using ten channels, which were logged using two Pico Technology USB TC-08 temperature data acquisition boards and Omega Engineering logging software. The thermocouples used were K-type and were calibrated prior to use, with a temperature range of 0°C to 150°C and an accuracy of ±1°C. The collected water yield was measured using a flask with a range of 0 to 1000 mL and an accuracy of ±10 mL. The depth of water inside the still was measured with an accuracy of ±0.1 cm. The accuracy of the instruments used in the experiments is shown in Table 1. The percentage error was determined using the equation [40]

(1)

Table 1 Uncertainty error measurements for various measuring instruments

Equipment	Accuracy	range	% Error
Solar power meter model no. TM-750	±1 W/m^2	0-4000	2.5%
Thermocouples K-Type	± 0.1 ^{0}C	0-150 °C	0.7%
Graduated flash	±10 mL	0-1000 mL	10%
Data Logger (Digital TC-8)	±0.5 ° C (< 0.1 C resolution)	0-100 °C	3.3%
Anemometer	±0.1 m/s	0-15 m/s	10%
Multimeter/ Current	±0.1 A	0-10 A	10%
Multimeter/ Voltage	±1 V	0-1000 V	0.5%

4. Results and Discussion

A thermostat was used to control the electrical heater of 500 W placed in the basin of the solar still to boost condensate production from the conventional solar still. Furthermore, it was utilized to control the temperature of the basin water to 65 °C to minimize excessive evaporation rates, which caused droplets of condensed vapor to separate from the glass surface and fall into the basin, reducing the condensate flow to the condensate collecting channel. It is worth noting that the initial amount of water tested throughout the daily operation was 32 liters (5 cm x 80 cm x 80 cm). The utilization of such a large volume of water (5 cm height) resulted in a very poor condensate yield because most of the input heat from solar radiation was utilized for sensible heating of water before evaporation started. According to numerous studies [15,19,20,22,25], the height of the water in the basin was decreased to 2.5 cm with a water volume of 16 L employed to minimize the necessary sensible heating and boost the output yield.

However, because there is no solar radiation accessible at night, a heater is required. The heating input from the heater was relatively high, so the capacity of the water basin was extended to 32 L owing to the high evaporation process and minimization of droplet dropping in the basin. Accordingly, the height of the water depth in the still basin increased from 2.5 to 5 cm during night operation.

A 500 W heater was utilized for all afternoon tests (i.e., after 3.00 pm) and was supplied by a battery bank attached to the PV array to collect a suitable quantity of condensate from the system. Experiments were performed at various heater powers (100 – 500 W) to determine the optimal yield. It was found that a heater power of 500 W was optimal for achieving high productivity and optimum conditions. Hence, all significant tests were performed using 500 W heating powers. Table 2 exhibit the data gathered over two days.

Fig. 5 shows that during the daylight testing period (9.00-15.00) for two days of trials, low distilled water was generated (i.e., 1.4 L and 1.5 L, respectively). However, the most distilled water is collected throughout the night, from 17:00 to 8:00. The system was improved by 313% (6-7 L) during night time operation when the battery bank powered the water heater, as indicated in Table 2. Following preliminary tests, the whole experimental system was modified to the final stage for the maximum productivity of the still coupled with the PV array. The following improvements were made to boost the system's yield:

1. The interior walls of the distiller are painted black to absorb scattered solar radiation from the water basin and surrounding.
2. During the daylight tests, the water height in the distiller is reduced to 2.5 cm rather than 5cm. This indicated that the water capacity was reduced to 16 L.
3. The energy input of heater was increased from 100 to 500 W for the maximum distillation output without droplets.

The effects of reducing the water height and employing a larger heating capacity in the still basin using an electrical heater were investigated for optimal production at this stage. Data were collected for the following two days.

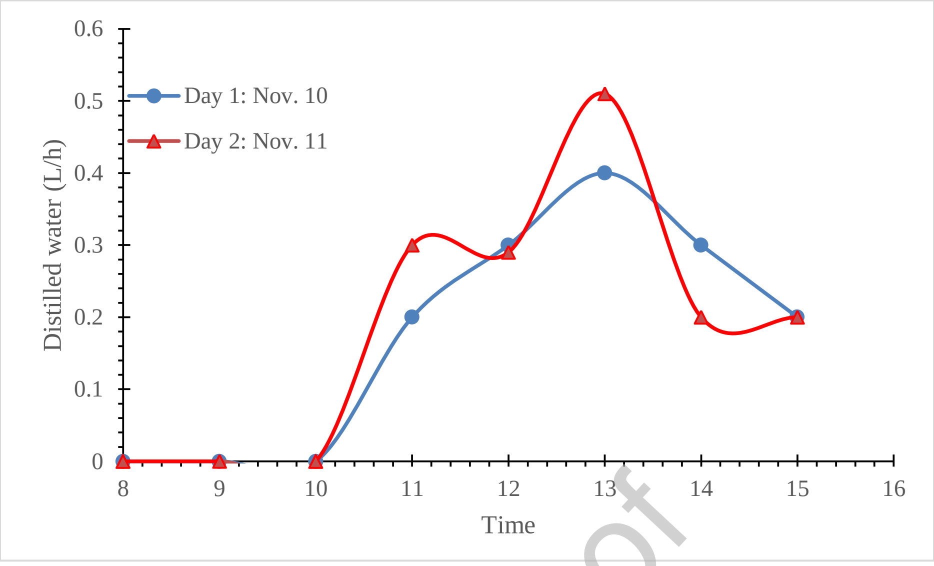


Fig. 5 Distilled water varies with time during the day

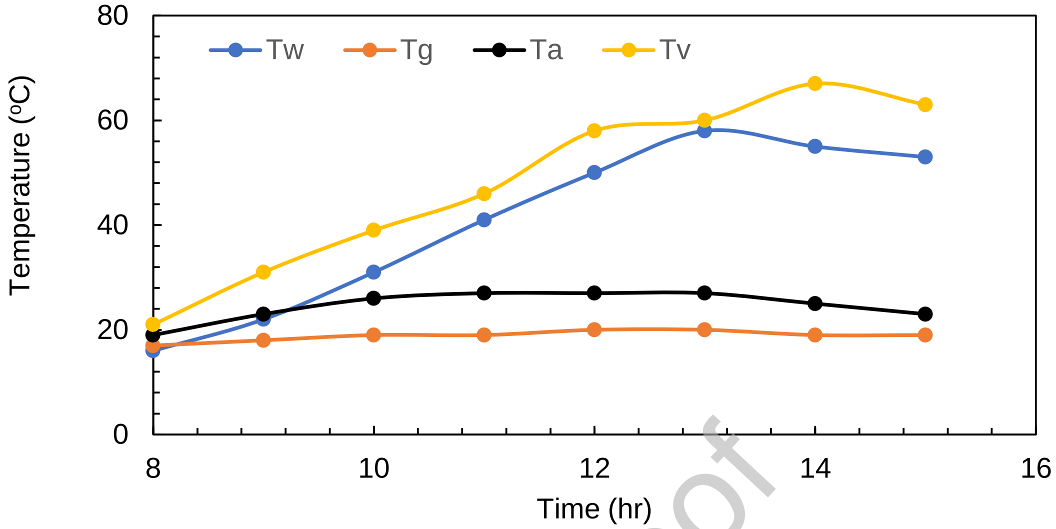
Time	Solar radiation (W/m^2)		Water temp. (°C)		Glass cover temp. (°C)		Air temp. (°C)		Vapor temp. (°C)		Distilled water (L)	
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
08:00	450.3	446.3	16	15	17	17	19	17	21	23	-----	-----
09:00	610.2	615.2	22	24	18	17	23	24	31	32	-----	-----
10:00	737.4	739.4	31	32	19	18	26	26	39	42	-----	-----
11:00	810.4	812.4	41	43	19	19	27	27	46	49	0.20	0.30
12:00	790.7	795.7	50	52	20	19	27	28	58	57	0.30	0.29
13:00	731.3	736.3	58	59	20	20	27	28	60	61	0.40	0.51
14:00	683.5	685.5	55	57	19	20	25	25	67	68	0.30	0.20
15:00	549.6	550.6	53	54	19	19	23	23	63	64	0.20	0.20
Day 1 Day yield Total = 1.4 L Night reading (from 15:00 to 7:00) = 4.6 L using heater Total condensate for 24 hours = 6 L						**Day 2** Total Day yield = 1.5 L Night reading (from 15:00 to 7:00) = 4.7 L using heater Total condensate for 24 hours = 6.2 L						

According to the information presented in Fig. 5 and Table 2, the daily yield during the hours of 8:00-15:00 for day 1 was 1.4 liters, while for day 2 it was 1.5 liters. The nighttime yield using a heater, during the hours of 15:00-7:00, for day 1 was 4.6 liters, and for day 2 it was 4.7 liters. This results in a total yield of 6 liters for day 1 and 6.2 liters for day 2. The slight variations in total yield, around 4%, can be attributed to the following factors, including the changes in ambient temperature, heat capacity of the basin water, height of water in the basin, the use of an electrical heater, the power of the heater, and the utilization of a renewable energy source such as a PV system. On the second day, the ambient temperature was higher which improved the basin water temperature, heat capacity, and vapor temperature resulting in an increase in total yield by 5% both during the day and night production. Furthermore, table 2 indicates that employing the heater in the basin of the solar still during the night, from 17:00 to 8:00, increases the distillate production by 350%. This demonstrates that nighttime distillation at a low ambient temperature of approximately 16 ℃ could be used for high condensation. It produced results similar to those of natural occurrences, such as a dew point appearing on plants when the ambient temperature (which varies depending on pressure and humidity) falls below the dew point when water droplets begin to condense.

The total production of distilled water for each experiment was around 6.2 L. This demonstrates that using a renewable energy source, such as a PV system, can significantly improve the clean water output of traditional solar stills. As a result, the appropriate use of renewable energy technology can augment freshwater production to offer quantitative and qualitative clean water. Therefore, the future global issues of delivering low-polluting drinking water should be reduced.

Figs. 6 (a) and (b) depict the hourly temperature fluctuations measured by thermocouples at several locations on a multi-slope solar still. The figures show the impact of increasing the heat capacity of the basin water, represented by Tw, at several temperatures, such as vapor and inner glass temperatures, which are the main parameters determining still production. The figures indicate that the second-day ambient temperature Ta (Fig.6 (b)) was slightly higher (≅>1 ^{0}C) than that of the first-day test. This improved the basin water temperature Tw, as well as the heat capacity and vapor temperature, resulting in an increase in total yield of 1.4 L to 1.5 L during the day and 4.6 to 4.7 L at night, respectively. This means improving productivity by 5% during day and night production.

(a) Day 1: November 10



(b) Day 2: November 11

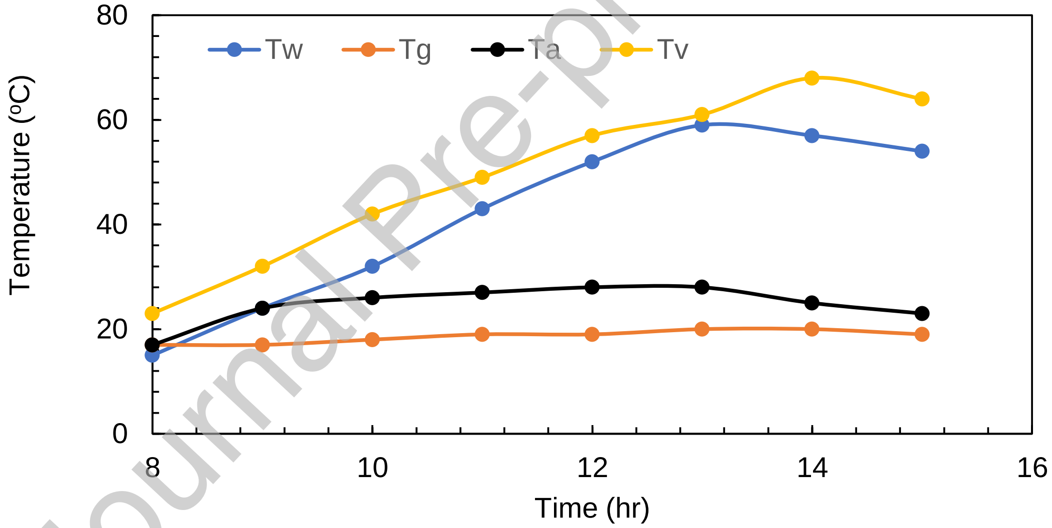


Fig. 6 Different measuring temperatures in solar still for two tests

4.1. Daily Efficiency of Solar Still

When evaluating the efficiency of a solar still, it is necessary to consider various factors that can impact its performance. These can include the total solar radiation incident on the still, the latent heat of water vaporization, and the yield of distilled water produced. The latent heat of water vaporization, also known as the heat of vaporization, refers to the amount of heat energy required to convert a substance from a liquid to a gas at a constant temperature. In this case, it is the amount of heat energy required to vaporize water. The total solar radiation incident on the still refers to the total amount of solar energy that reaches the still. The yield of distilled water produced is the amount of water produced by the solar still in a given period of time, and this can be impacted by various factors such as the size and shape of the still, the angle and orientation of the still with respect to the sun, and the temperature and humidity of the surrounding air. The efficiency of a solar still at a given moment, denoted as ηi, is the ratio of the energy utilized for producing water to the total amount of solar radiation received, expressed as:

(2)

$$(\text{—}) \qquad (\text{—})$$

(3)

The efficiency of a daily solar still (η_d) is defined as the ratio of the heat of vaporization of the daily condensate yield to the total solar irradiation received during the day. In other words, the daily efficiency of the solar still can be calculated by dividing the volume of distilled water produced by the total solar radiation incident on the system. This can give a good indication of the performance of the still and can be used to identify areas for improvement if necessary. The following equation can be used to compute the efficiency [41–43]:

(4)

$$\frac{\sum}{\sum}$$

$$[\qquad]$$

(5)

Where; is the distilled yield in kg, is the heat of vaporization for water in J/kg, H is the total amount of daily solar radiation in W/m^2 falls on the projected area Ab of the still surface, and represents the average temperature of basin water, and the amount of power consumed by the distiller system during night time is referred to as "P_{heater}," and it is provided by the heater through the PV. It is worth noting that, on average, the heater operated for about 15 hours at night with an average power consumption of 300 W per hour and for 9 hours during the day with an average power consumption of 100 W per hour. It is important to mention that on November 11th, the total solar radiation in Marka City was recorded as 5363.4 W/m^2, still base area 0.64 m^2, and the latent heat of water vaporization was calculated using Eq. 5 and found to be 2.37587×10^6 J/kg at an average temperature of = 49.5 °C. It was found that the passive mode of operation, which solely relies on solar energy to heat the basin and produce water vapor without any additional external energy input, such as PV, resulted in a daily efficiency of approximately 27% and a distilled water yield of 1.4 L. Utilizing the inclined panel to concentrate more solar radiation onto the basin can further increase the productivity of a passive inclined solar panel basin solar still. In contrast, when operated in active mode, the solar still was engineered to include supplementary energy inputs, such as electrical heating elements that were powered by solar panels. The daily efficiency of the solar still was found to be around 44.8%, which resulted in a distilled water yield of 6 liters. By utilizing both the inclined panel to concentrate more solar radiation onto the basin and the electrical heating elements powered by PV, an active inclined solar panel basin solar still would thus be able to significantly boost the productivity of the still. Table 2 illustrates that the yield in the active mode (6 L) was more than triple that of the passive mode (1.4 L), representing an increase of approximately 313%.

Fig. 7 depicts the percentage of yield collected throughout the day and night for the two consecutive days of the tests. It can be observed that the accumulation of the night time utilization of PV heating is significant and has increased production by 76%.

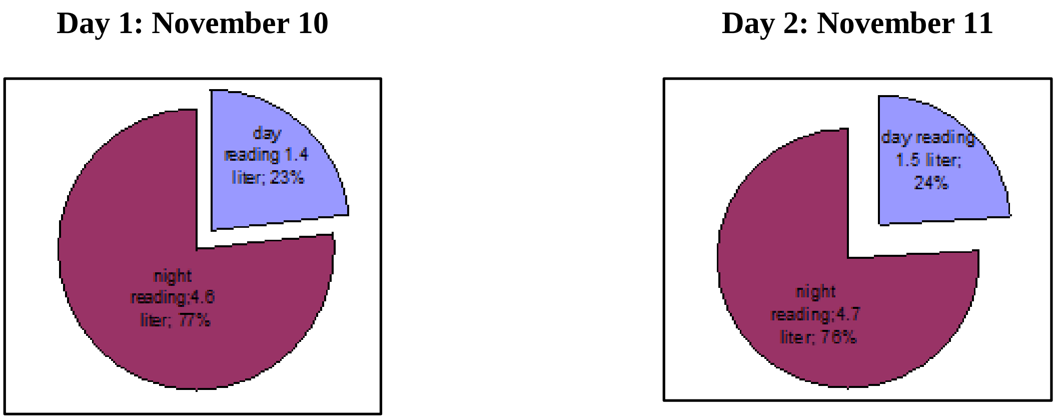


Fig. 7 Total distilled water in two days

4.2. Economic Analysis: Payback period

An economic study was performed to determine the payback period for the PV-still system cost. The payback period of a solar still combined with a PV heating system is determined by different variables such as the whole system cost, assembly cost, operating cost, maintenance cost, feed water cost, and government financial incentive. The economic analysis of the PV- solar still system and key details regarding the cost and production of distilled water in the Jordan market are presented in Table 3. The cost of manufacturing and construction of multi-slope solar stills is approximately $ 400, and the cost of a whole PV system is approximately $ 1300. Therefore, the total cost of producing distilled water, including both the multi-slope solar stills and the photovoltaic system, is 1700 $. However, the government provides a 30% reduction in the system cost through incentives, bringing the cost down to $ 1,190. On average, the production rate is 2,190 L per year, which equates to 6 L per day, and the price of distilled water is 0.6 $/L according to the current market pricing of distilled water bottles in Jordan. The estimated net revenue for producing distilled water is 1,095 $, calculated by multiplying the price per liter by the annual production rate. The payback period is the duration required for the entire photovoltaic-solar still system to recover its costs for manufacture, operation, maintenance, and feed water, after which the system generates profits. The equation for the payback period is typically calculated as follows:

Payback Period = Initial Investment / Annual Cash Flow

where: Initial Investment is the total cost of the investment, including any upfront costs for manufacturing, operation, maintenance, and feed water. Annual cash flow is the net annual revenue generated by the investment, after taking into account any costs for operating and maintaining the system, as well as the price of raw materials. It is worth nothing that the annual cash flow can be positive (generating a profit) or negative (incurring a loss) depending on the net revenue generated by the investment. The payback period represents the point at which the cumulative cash flow equals the initial investment, at which point the investment is considered to have "broken even".

Fig. 8 displays the cash flow based on the data presented in Table 3. To account for the increase in operating costs and raw material prices, a 2% increase over the previous year's cost was applied. As shown in Fig. 8, the payback period for this system is two years.

Table 3. Economic analysis of PV-solar still system

Item	Key Details	Note
Distilled water price in Jordan market	0.6 $/L	
Production rate	2,190 L/Year	On average, 6 L/Day
System cost	1,700 $	The cost includes the multi-slope solar stills and the PV system
Operating cost	146 $/year	It includes all the cost to produce the 6 L per day (0.4 $ /day) multiply by 365 days
Maintenance cost	109 $/year	Maintenance Daily cost estimated 0.3 $/day
Increase production cost annually	2% /year	The production costs will increase annually
Cost of feed water	219 $/year	Cost of 0.1 $/L
Raw material price increase	2%	The raw material price will increase annually
Subsidized cost given by government	30% reduction of the system cost	Government incentives is 510 $, therefore the system cost becomes 1,190 $
Net Revenues	1,095 $	Price of 1 L * Production rate

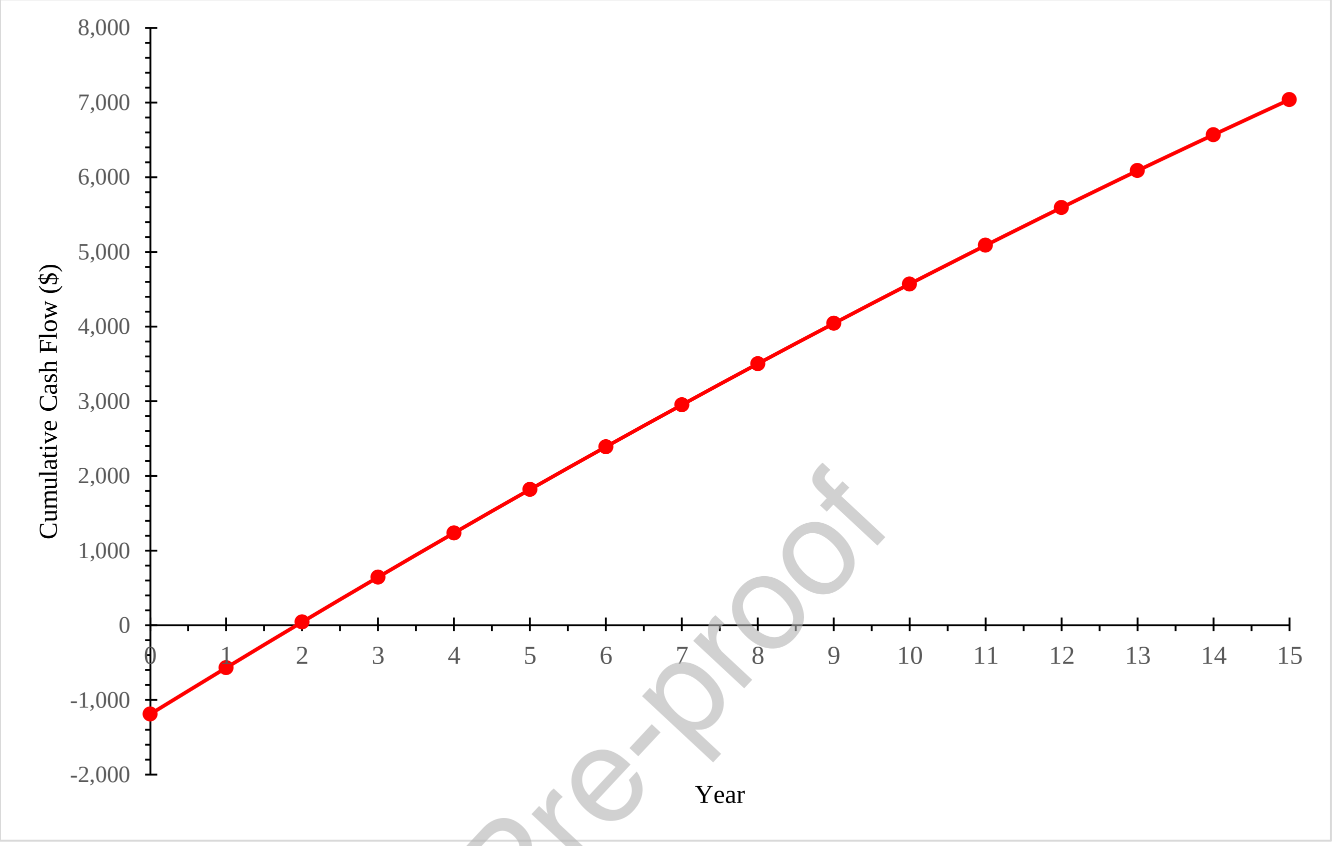


Fig. 8 Cumulative cash flow ($) with period in years

5. Conclusion

In summary, this study aimed to improve the productivity of traditional solar stills and investigated the efficiency and economics of a PV-solar still system. The results showed that the daily efficiency of the PV-heating solar still in active mode (44.8%) was higher than that of traditional solar stills in passive mode (27%). The yield in active mode (6 L) was more than triple that of the passive mode (1.4 L), representing an increase of approximately 313%. This can be attributed to the increased heating power provided by the PV-supplied electrical heater and the cooling impact of the ambient air during night operation compared to daily operation. The payback period for daily operation was found to be approximately two years, indicating the reliability of distilled water production. This study showed that clean water production from renewable sources would be one of the best options in the near future to satisfy the requirement for freshwater owing to the growth of the global population, which would place a strain on the global supply of clean water.

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Conflict of Interests

☓ Conflicts of Interest: The authors declare no conflict of 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.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Authors