Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2019.23478

145 (2019) 36–45
March

Performance of embedded photovoltaic solar still for water purification system in the tropics

Noradira Abdul Latiff[a,*], Mohammad Effendy Ya'acob[a,b], Siti Mazlina Mustapa Kamal[a], Guangnam Chen[c]

[a]*Department of Process & Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, 43400, Selangor, Malaysia, email: noradira.latiff@gmail.com (N.A. Latiff), fendyupm@gmail.com (M.E. Ya'acob), smazlina@upm.edu.com (S.M.M. Kamal)*
[b]*Centre for Advanced Power and Energy Research (CAPER), Universiti Putra Malaysia, Serdang, 43400, Selangor, Malaysia,*
[c]*Faculty of Health, Engineering and Sciences, University of Queensland, Toowoomba, QLD, 4350, Australia, email: chengn@usq.edu.au (Chen.G)*

Received 14 March 2018; Accepted 16 November 2018

ABSTRACT

A massive amount of energy is needed to generate clean and safe potable drinking water. Malaysia, strategically located on the earth's equator, is turning to solar energy as a solution. This study focuses on the integration of a solar photo voltaic system with the existing solar still technology. It is designed by harvesting the heat energy directly from the Sun and partially combining it with the shaded section using PV modules together with the PV Water Purification System (PvWPS). The experiment was conducted for three days in November 2017, in Malaysia. A stainless steel basin of 1 m long and 0.54 m wide together with a clear glass cover of 0.33 m long and 0.54 m wide served as a new solar still. Results showed that the internal temperature of the still basin increased by more than 5% above the average temperature, accelerating the evaporation process in the purification system. The power efficiency increased by 0.325%, increasing the expected PV module efficiency to 14.15%. Water production using the PV Water Purification System (PvWPS) was expected to increase by 10%. This study also discusses the cooling mechanism justification, the water quality produced and the cost involved to observe the social and economic benefits of the system.

Keywords: Embedded photo voltaic; Shading effect; Solar still; Water purification; Tropical temperature; Heat storage; Cost analysis; Cooling mechanism; Greenhouse

1. Introduction

Solar photo voltaic is one of the more popular renewable energy resources that is adopted worldwide. It has a great potential if it is integrated with any currently available water purification system in the market. By definition, a water purification system refers to the movement and conversion of brackish water to freshwater, making it suitable for human consumption. The World Health Organization (WHO) has set the minimal guidelines for a safe drinking water and has continuously promoted water sustainability to cater to the increasing demand of the urban population [1,2].

An interesting case study by Ingyu [3] showed that the quality of river water in Kuantan, Malaysia is very poor due to the discharge of wastewater from the residential and industrial areas into the river without being properly treated. Malaysia, as a participant of the United Nations Framework Convention on Climate Change (UNFCCC), has pledged to reduce 45% of her greenhouse gas (GHG) emissions by 2030 during the Conference of Parties (COP) 21 in Paris [4]. This commitment has opened the door to new opportunities in technology integration as well as resolving the demand for freshwater. Alternative strategies and continuous support to promote renewable energy would be the best solution to mitigate negative impacts of climate change especially when harvesting the free abundant solar power. Annual reports from the Sustainable Energy Devel-

*Corresponding author.

opment Authority (SEDA) shows that the solar energy produced using Photo voltaic (PV) technology emerges as the most preferred renewable energy among the energy mix in Malaysia. A typical PV module can convert 6%–20% of solar radiation into electricity, depending entirely on the climatic condition. The rest of the solar energy is converted into dissipated heat, in which, the PV module's efficiency decreases significantly with respect to the increase in the surrounding temperature [5]. This statement is supported by Park et al. [6] where they explain the effect of temperature rise in PV module's thermal characteristics on its electrical generation performance Building Photo voltaic (BIPV) where approximately 0.5% reduction of energy is generated based on 1°C increase of the module temperature. Most of the water treatment technologies available in the market are largely dependent on the various types of contaminants to be treated or filtered. However, a consistent price hike of the fossil fuels an expensive treatment and a complicated design used in a water treatment plant is main factors the resulting emissions of GHGs have rendered them rather unsustainable [7] or indirect; combining conventional desalination techniques, such as multistage flash desalination (MSF).

Conventional solar desalination method for the production of potable drinking water from saline water and the solar still purification system have been applied for several years in many countries. Besides the additional features of the heating element, condensation and collection of freshwater droplets can occur due to gravity. The solar still technology has been proven to be capable of removing 96% of brackish content from polluted feed water [8], enabling freshwater production of around 2.383–2.549 kg/m^2-d per person [9,10]. Generally, the rate of condensation and evaporation influence solar still productivity because condensation occurs on the under of the glass cover and the evaporation (in water) come from ambient temperature but is significantly accelerated higher temperature because of the greenhouse effect occurring inside a solar still [11]. Sartori [12] presents a theoretical comparison between the thermal behavior of a basin type solar still and solar evaporator. This study showed evaporative in solar evaporator more than 50% of the corresponding total heat transfer rate than that in a solar still type (due to the greenhouse effect). Ninad and Kashinath also investigated greenhouse effect in a solar still and the result shown that the productivity of clean water with insulation and greenhouse effect have a drastic change in the efficiency of solar still [13].

Many researchers have investigated and proposed to upgrade the traditional method of solar still technology in an effort to produce a greater yield of clean drinking water. It has been found that a solar still with a bottom sand layer combined with a 50 W solar photo voltaic-DC heater could produce 33% to 43% higher productivity as compared to a conventional solar still [14]. It was also observed in an experiment performed in Oman, that a higher water temperature can be achieved by using an inverted absorber solar still (IASS) as compared to the single slope solar still (SS) at water depths of 0.01 m, 0.02 m, and 0.03 m [15]. The temperature increase led to a higher daily yield of IASS which were 6.302, 5.576, and 4.299 kg/m^2-d as compared to the solar still which were 2.152, 1.931, and 0.826 kg/m^2-d, respectively. Al-Garni demonstrated that the performance of a solar still immersed with a 500 W water heater and an external fan can drastically increase by 370 % [16]. In another view, ST technology basically implies the same concept of harvesting the energy from the sun for energy conversion. However, the main difference between ST and solar still is the use of photo voltaic materials for electricity generation via photonic effects. Heat energy is also produced from both systems but generally, ST utilizes this dissipated heat for energy conversion as compared to PV material where this energy is dissipated as heat waste.

A comprehensive review of the literature shows that an active solar still improves the efficiency of generated electricity and productivity of fresh water. However, this paper presents an altogether different approach in harvesting the dissipated heat energy from photo voltaic to enhance productivity by modifying and transforming the solar still into a photo voltaic water purification system. The aim of this research work is to embed the solar still in an existing solar photo voltaic farm for purification and evaluate the performance of solar still in providing maximum freshwater yield.

2. Methodology

2.1. Design setup

In this study, two different configurations were designed, fabricated and tested under the actual outdoor condition in order to review and compare the effectiveness of their operation and production. The first design was a simple single basin (SSB) and the second design was a photo voltaic water purification system (PvWPS). Both stills were constructed to face 160° south. The SSB consisted of a wall frame, clear glass, distilled collection trough and feed water supply as shown in Fig. 1a.

The PvWPS was designed by adding a photo voltaic array (no. 10) at the bottom of the SSB structure (no. 1 to no. 9) as shown in Fig. 1b.

This section will discuss in detail the fabrication of a photo voltaic water purification system as shown in Fig. 2.

The sides and bottom of the external wall frame were constructed from a rectangular hollow aluminum of 1.6 mm thickness, having dimensions of 0.54 m × 1 m × 0.0318 m; the basin was made from stainless steel with 1.5 mm thickness and placed inside the wall frame. The partitions were for holding feed water in the internal basin with a 0.1 m gap. The overall area of the PvWPS was 0.54 m^2 as shown in Fig. 2a. The center of the PvWPS is distilled collection as pointed by arrow no. 1. The clear glass of 0.54 m × 0.33 m with 4 mm thickness functions as an outlet of fresh water produced shown in Fig. 2b.Fig. 2c shows the bottom of the solar still embedded with PV array as pointed by arrow no. 2. Besides that, the structure and materials in the aging junction box were in good shape. Furthermore, the junction box had a warranty from the manufacturer. Based on Lu [17], there were some cases of good operations even after 17 years of operation in a harsh environment. Some aspects of careful installation and storage (on supply side) are important to maintain the quality of PV materials [18] fast depletion of fossil fuels, along with environmental concerns throughout the world has led to the requirement of commissioning Solar PV plants in large scale. Solar photo voltaic (PV. The long-term evaluation of the seal between PV panel and stainless-steel

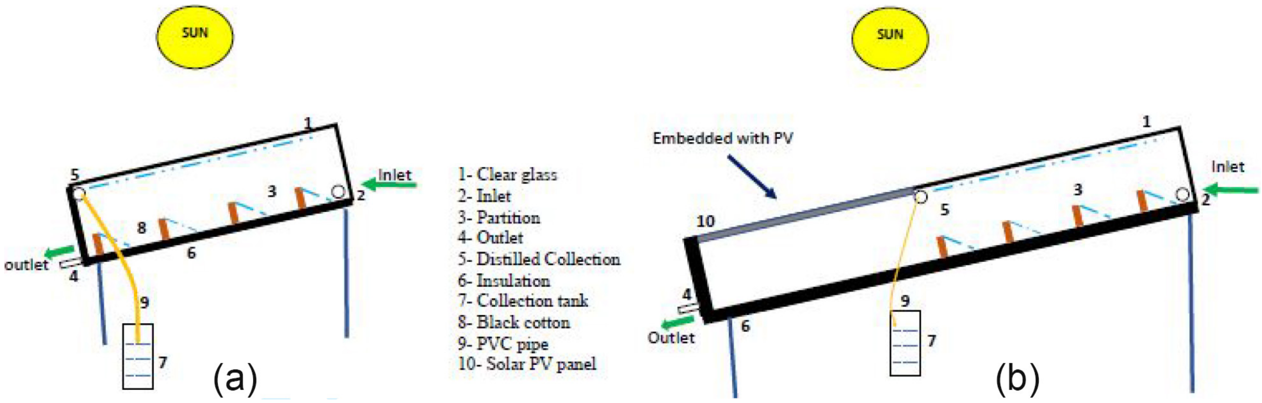

Fig. 1. Cross section diagram for SSB (a) and PvWPS (b).

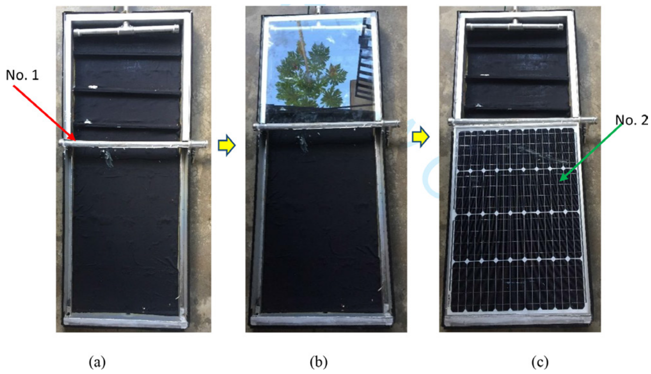

Fig. 2. The basic frame of PvWPS (a), top of PvWPS is glass area (b) and The space for photo voltaic (c).

frame as based on the manufacturer's warranty, whereby the panels, steel frames, cablings and other in-tack parts are all IEC certified for long-term operation. Moreover, the warranty is a strong document for the end-user in order to rectify any faults or insufficient power generation to the manufacturer/ installer (despite the normal yearly degradation).

The system consisted of a source tank of rainwater that acted as brackish water. The entire external surfaces of the wall frame were insulated from the ambient air using rubber foam air conditioner. The basin surface facing the Sun was covered with a black cotton cloth to increase solar radiation absorption [19]. The water temperature increased because of the heat transferred through conduction from the internal structure to the water. A silicone PVC hose was connected to the source tank to supply the two solar stills with rainwater.

In this experiment, a 50W photo voltaic module with dimensions of 0.54 m × 0.67 m × 0.03 m was embedded at the bottom of a clear glass and served to increase water temperature. The PV module was not to generate electricity. The machine was sealed using aluminum plaster on the collar of the still to prevent any vapor leakage. Freshwater was collected using a 15 mm long stainless-steel pipe and the excess feed water was drained at the end part of the still. A high rear wall using stainless steel pipe with silicone tubes was designed as the inlet brackish water and a valve was used to control water flow.

A 15 L brackish water tank was used as a feeder with the sample water flowing hourly and maintained throughout the experiment by constantly refilling feed water into the still. Freshwater collected in the stainless-steel pipe was taken through silicon tubes into the bottle with the whole unit being mounted on an angle iron stand.

2.2. Experimental setup

The PvWPS was constructed to evaluate the performance of temperature. Thus, the temperature inside and outside the still was measured at 1-min intervals using a 1-wire digital thermometer DS18B20 with an accuracy of ± 0.5°C. A pyranometer (model PMA-2144) was used to measure solar radiation intensity at a time interval of 1 minute, placed outside the still. The experimental solar radiation intensity accuracy value by the pyranometer is ± 1.0 W/m². An electronic scale was employed to measure the hourly fresh water production. The DS18B20 thermometer was placed in different locations; for basin temperature (T_b), glass temperature (T_g), bottom photo voltaic temperature (T_{pvb}), photo voltaic temperature (T_p), and ambient temperature (T_a) of the surrounding environment. The thermocouple was linked with a data logger (Raspberry PI) to capture the temperature every 1 min. Fig. 3 shows the position of the sensor inside and outside of the solar still and the experiment was conducted on the 17th, 18th, and 19th November 2017.

The setup was built at the PV Pilot Plant in University Putra Malaysia as shown in Fig. 4.The experiments started

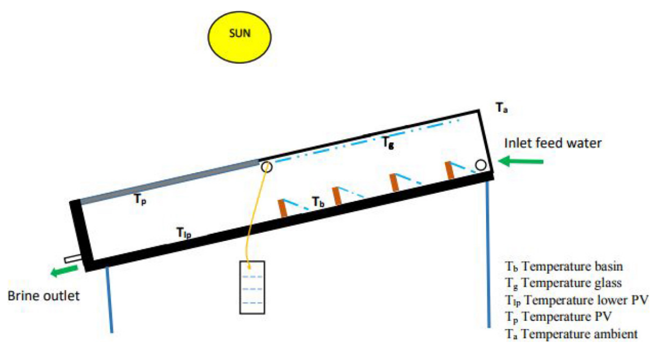

Fig. 3. The position of sensor at PvWPS.

Fig. 4. Photographs of experimental setup (a) and location of the still (b).

from 9 a.m. to 7 p.m. local time in the month of November 2017. The experiment procedure began by cleaning dust from the external glass cover of the still.

3. Results and discussion

The experiment was conducted to evaluate the performance of each solar still due to the effects of solar radiation. Thus, the experiment was carried out during the sunny and rainy days of the year (November 17, 18, 19 of 2017). The basin and glass cover temperature were the two most influential parameters in the performance of the solar still. Therefore, only the heat transferred between the basin temperature and the glass cover temperature will be discussed here.

3.1. Atmospheric condition

The fluctuating pattern of the daily average and maximum recorded data for radiation and ambient temperature for tropical climate condition at the site for a year is shown in Fig. 5. Fig. 5 is taken from [20] Tracking Flat (TF).

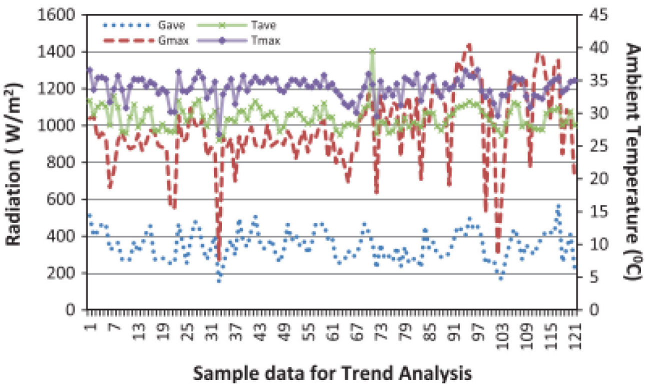

Fig. 5. Trend analysis for radiation and ambient temperature recorded.

The surrounding condition at the test site is shown in Fig. 5 and the experiment was carried out in the month of November 2017. Fig. 6a shows the hourly variation of solar intensity with respect to time. The maximum solar intensity during the experiment was recorded at 845.55 W/m^2 on November 19, 2017. The average solar intensity per day during the experiment was recorded to represent an average of 305.72 W/m^2 to 572.70 W/m^2. The results showed that during the experiment there was low solar intensity due to the shading caused by clouds. This is because Malaysia typically experiences the northeast monsoon between October to March, bringing in more rainfall and heavy winds compared to the other months in a year.

Fig. 6b shows the ambient temperature during the three days of experiment and the maximum recorded ambient temperature was 35.43°C on November 19, 2017, while the average ambient temperature during the experiment was 30°C to 31°C. The average wind velocity is plotted in Fig. 6c. It is recorded that the wind velocity was lower in the morning and increased in the evening. The maximum wind velocity recorded on November 19, 2017 was 3.639 m/s. The average wind velocity during the three days of experiment was recorded at 0.6–1 m/s.

3.2. Effects of Photo voltaic on basin and glass temperature of PvWPS solar still

Fig. 7 and Fig. 8 represent the variation of the basin, glass and ambient temperature for SSB by adding two temperature sensors at bottom PV (T_{pvb}), PV (T_{pv}) for PvWPS. Fig. 6 shows that temperatures of solar still basin (T_b), glass (T_g), PV (T_{pv}) and bottom PV (T_{pvb}) for PvWPS reached the maximum value of 51.81°C, 45.56°C, 52.63°C, and 46.72°C, respectively at 1 p.m. However, the temperature of PV was higher than the other temperatures due to the direct PV material heating effect [21]. The second highest temperature was the basin temperature which received and absorbed solar radiation directly from the Sun and the heat dissipated from the embedded photo voltaic array. However, the bottom PV only produced 5% of heat that

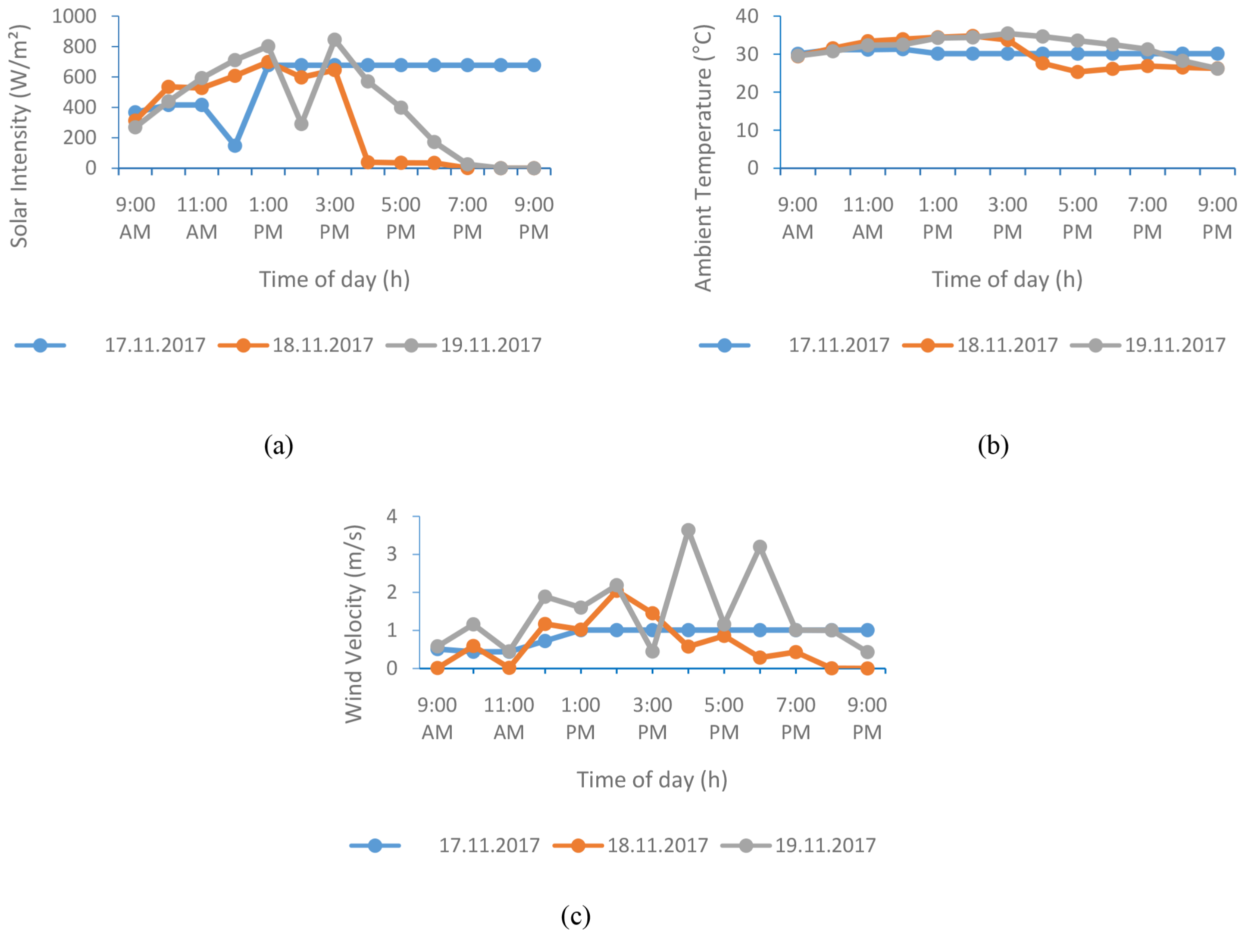

Fig. 6. Typical measurement of (a) solar intensity radiation history curves during the experiment, (b) ambient temperature with respect to time for experiment, and (c) wind velocity.

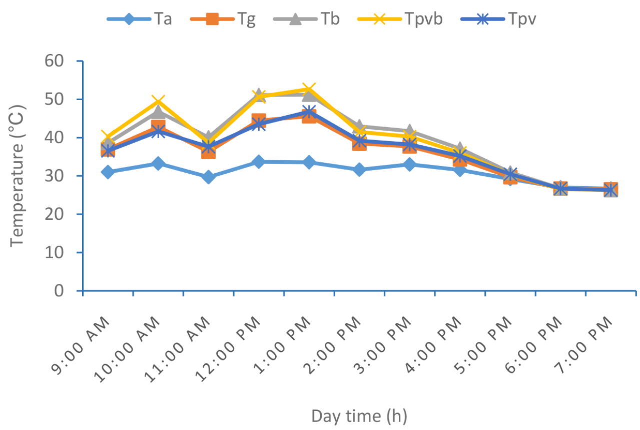

Fig. 7. Variation of hourly basin, glass, basin PV, bottom PV, and ambient temperature during experiment for PvWPS.

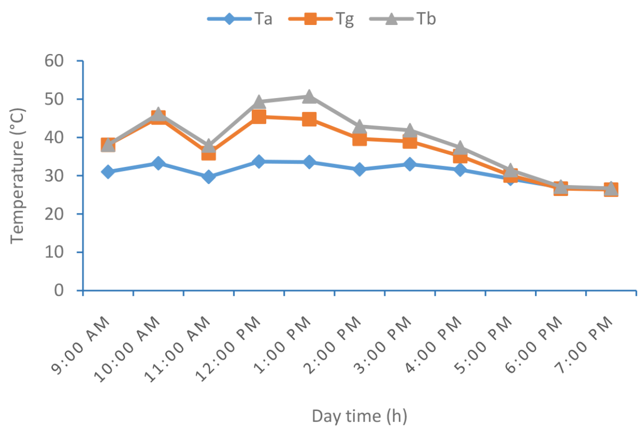

Fig. 8. Variation of hourly basin, glass, and ambient temperature during experiment for SSB.

was transferred to the basin temperature. The lowest temperature was the glass temperature which was around 30°C to 35°C and it was a positive response. In order to gain a greater productivity of fresh water, the temperature at the bottom of the glass cover needed to be reduced [22]. The freshwater dropped due to the gravity towards the collecting channel and it was measured using the electronic scale.

Although SSB shows the same trend as PvWPS, the basin and glass temperatures recorded were lower in SSB than in PvWPS. The maximum basin and glass temperatures reached by SSB were 50.69°C and 44.75°C, respectively, as shown in Fig. 8. In the morning, the ambient temperature increased and reached its peak value at 1 pm. The temperature then began to decrease slowly until it reached its minimum when there was no more sunlight. From the observation of the three-day experiment, the glass temperature of SSB increased slightly compared to the glass temperature of PvWPS.

Variation in the cumulative productivity of fresh water with respect to time is shown in Fig. 8. The maximum fresh water productions from PvWPS were higher than that in SSB. Both stills started the experiment with an hourly inlet feed water into the stills. Fig. 9 shows that PvWPS produced a higher yield at 2.67 L/m^2 per day as compared to the cumulative productivity of fresh water for SSB at 2.12 L/ m^2 per day.

The adaptation of PV modules embedded in the solar still enhanced the productivity of the fresh water by 10% optimization due to the heat evaporation which led to a gain in the quantity of fresh water produced, a key parameter in any purification device. The increase was, however, only 10%. This is because the condensed water dropped back into the basin which reduced the effect on the productivity of fresh water. Hence, it can be suggested that the productivity of fresh water did not record a great increase due to the internal circulation in the solar still. The low solar radiation also contributed to the low productivity by the PvWPS.

3.3. Effect of embedded photo voltaic on heat transfer coefficient

To evaluate the performances of PvWPS, careful and meticulous calculations of heat transfer must be computed. Generally, heat transfer is classified into two groups; internal and external heat transfer. Radiation, convection and evaporation are grouped as internal heat transfer. On the other hand, the external heat transfer consists of radiation, conduction, and convection. In this study, the observation and calculation contributing to the internal heat transfer is from the basin temperature to the glass cover still.

Convection heat transfer coefficient from basin to the glass is given by [2] and [23],

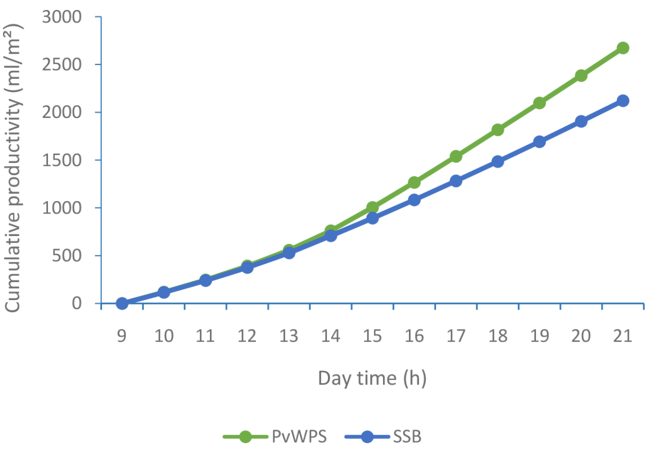

Fig. 9. Variation of cumulative productivity of fresh water during experiment.

$$h_{cbg} = 0.884\left[\left(T_b - T_g\right) + \frac{\left(P_b - P_g\right)\left(T_b + 273\right)}{\left(268.9\times10^{-3} - P_b\right)}\right]^{1/8} \quad (1)$$

The partial vapor pressure at basin temperature is given by,

$$\boldsymbol{P_b} = \boldsymbol{exp}\left(25.317 - \frac{5144}{273 + \boldsymbol{T_b}}\right) \quad (2)$$

The partial vapor pressure at bottom glass temperature is given by,

$$\boldsymbol{P_g} = \boldsymbol{exp}\left(25.317 - \frac{5144}{273 + \boldsymbol{T_b}}\right) \quad (3)$$

Radiation heat transfer between basin and glass can be expressed by,

$$h_{rbg} = \sigma\times\frac{\left(T_b + 273\right)^2 - \left(T_g + 273\right)^2}{\left(\frac{1}{\varepsilon_b} + \frac{1}{\varepsilon_g} - 1\right)}\times\left(T_b + T_g + 546\right) \quad (4)$$

where ε_b and ε_w are basin and glass emissivity with the values of 0.90 and 0.96, respectively; T_g and T_b are the temperatures of glass and basin (°C), and; σ is Stefan-Boltzmann constant value 5.6697 × W/m^2 K^4.

The evaporation heat transfer coefficient between basin and glass is given by [24]

$$h_{ebg} = \left(16.273\times10^{-3}\right)\times h_{cbg}\times\frac{\left(P_w - P_g\right)}{\left(T_w - T_g\right)} \quad (5)$$

The method of linear regression analysis, R^2 is used to determine the relationship between dependent and independent variables; between basin temperature and glass temperature. The coefficient of R^2 is 0.913. The R^2 regression analysis shows that the relationship between dependent variables and independent variables is very strong. The heat transfer coefficients, h_{cbg}, h_{rbg}, and h_{ebg} are calculated using Eqs. (1), (4), and (5), respectively.

Table 1 shows the result of convection, radiation, and evaporation heat transfer coefficients from basin temperature to glass cover of PvWPS. The highest values of convective, radiative and evaporative heat transfer coefficients from PvWPS are 3.313, 6.540, and 29.010 W/m^2 °C, respectively. The standard deviation value was found to be large due to the environmental parameters such as solar radiation intensity, ambient temperature, and wind velocity. The evaporative and radiative heat transfer coefficients reached their peak value at 12 and 1 p.m. respectively and then slightly reduced to lower values at the end of the sunlight period.

Fig. 10 shows the variation in the evaporation heat transfer coefficient for PvWPS and SSB during sunlight according to this study (h_{ebg}). The result shows a considerable difference in the coefficients between PvWPS and SSB. The highest coefficient recorded value of 29.010 W/m^2 °C by PvWPS was at 12 p.m. and continued to decrease

Table 1
The convective, radiative and evaporative heat transfer coefficients from basin to glass cover for PvWPS

Time	hcbg (W/m² °C)	hrbg (W/m² °C)	hebg (W/m² °C)
09.00	0.699	5.914	3.883
10.00	1.863	6.321	14.244
11.00	1.565	5.937	8.867
12.00	3.312	6.504	29.010
13.00	2.815	6.540	25.278
14.00	1.955	6.081	12.439
15.00	1.709	6.023	10.383
16.00	1.132	5.797	5.707
17.00	0.446	5.496	1.726
18.00	0.022	5.305	0.074
19.00	0.068	5.288	0.216

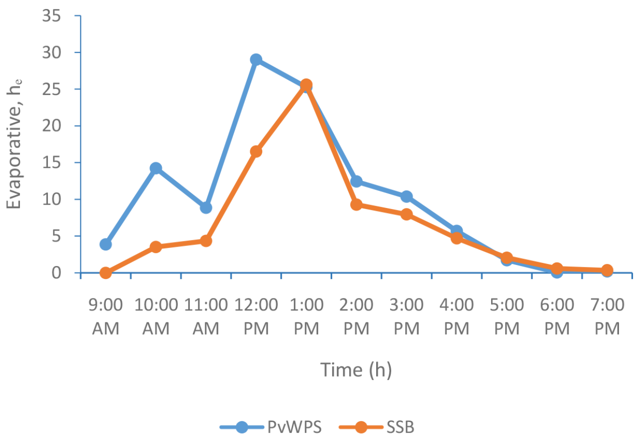

Fig. 10. Variation of evaporative heat transfer coefficient with respect to time.

until 7 p.m. However, the highest value of evaporation rate coefficient of SSB which occurred at 1 p.m. was only 25.606 W/ m² °C. The difference between two heat transfers is 3.404 W/m² °C.

3.4. Effect on the performance of PV panel

The highlights of this work concern more on the temperature values where the PV material has proven to enhance the system configuration for water purification. The heat dissipated under the PV array is a crucial aspect to be examined with respect to the continuous clean water produced for the water purification system underneath. The values are measured using DS18B20 digital temperature sensor and the result is shown in Fig. 11. The temperature bottom PV (T_{pvb}) versus ambient temperature (T_a) shows a linearly correlated pattern with the maximum value, T_{pvb} = 83°C and T_{amax}= 45°C which is the heat dissipated under PV array can help to increase the temperature inside the still.

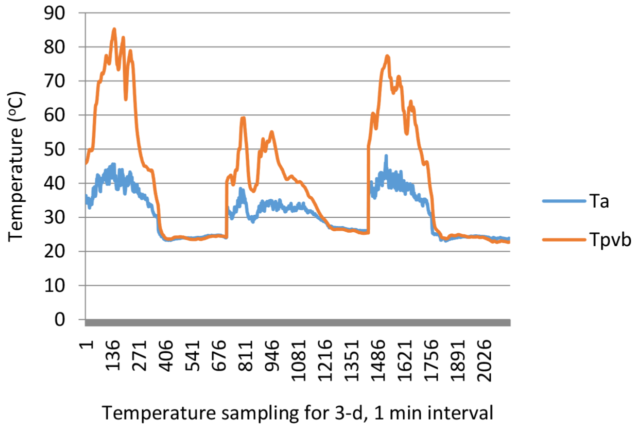

Fig. 11. Temperature effect bottom PV array in tropical weather.

$$\textit{Efficiency difference}, E_d = \textit{Temperature difference}, \Delta T \times 0.5\% \quad (6)$$

Thus;

$$\textit{PvWPS estimated efficiency}, \% = E_m + E_d \quad (7)$$

3 d monitoring with one minute interval (sampling 2161 unit) as shown in Fig. 10.

Normal PV module Efficiency, E_m: 13.82%

Temperature reduction on the PV bottom surface, ΔT: 0.65°C

PvWPS estimated efficiency: 14.15%

Efficiency difference, E_d: 0.325%

The PV efficiency enhancement is calculated based on the temperature reduction of 0.65°C (on the PV bottom surface) of the water flow mechanism. This temperature reduction process has a direct impact on the ability of the basin in absorbing heat discharged from the solar PV arrays which is considered as a good cooling mechanism at a minimal cost. The solar PV power efficiency increases to 0.325% which further increases the expected PV module efficiency to 14.15%. If the water purification system under solar PV array can be properly attached, this setup would create a low cost cooling mechanism with the projected savings as follow. For more details, Table 2 shows the calculation in estimating the value of cooling mechanism with highlights on the additional energy expected from the cooling mechanism during in 5 years onward.

3.5. Water quality analysis

Table 3 shows the water quality parameters as outlined by the World Health Organization (WHO) and Drinking Water Quality (DWQ) to determine the suitability of purified rainwater as drinking water. The purified water has a slightly acidic value with a much lower TDS of only 16 mg/L. However, the Turbidity value is double as compared to before purification due to an insufficient filtering process. Nevertheless, it is still within the acceptable range of drinking water standards.

Table 2
The calculation in estimating the cooling mechanism

	2017	2022
Revised PV power efficiency (add 0.325%)	14.15%	14.15%
Expected energy output (kWh/year)	117,436	81,694
Expected energy output with cooling mechanism (kWh/year)	3,257.91	2,226.49
% Additional energy increase (% kWh/year)	0.06% (3,029.85 kWh)	0.06% (3,029.85 kWh)

*This value is calculated for 8 hours of PV operation with reference to [25].

Table 3
Quality of water from rainwater source purified using PvWPS

Water quality parameter	Rain water	Distilled water	WHO standards	DWQ standards
pH (μ mhos/cm)	6.82	6.32	6.5–8.0	6.5–9.0
Total dissolved solids (mg/L)	29	16	<600	<1000
Turbidity (NTU)	0.98	1.45	<5	<5
Nitrate (mg/L)	1.31	0.27	<50	<10
Chloride (mg/L)	1.20	0.5	250	250
Iron (mg/L)	1.10	0.3	250	250

Source: [26,27]

3.6. Cost analysis

The cost estimation details for the entire system are provided in Table 4. The overall fabrication cost for a PvWPS is 157.10 United States dollars (USD). The cost of the photo voltaic monocrystalline is not included in the calculation since the system uses the existing PV farm. The utilization of the solar still as a source of fresh water for commercial purposes should also consider the economic factor. The economic analysis of a water purification unit is given by [28–31].

The annual salvage value (sa), annual maintenance cost (ma), and annual first cost (fa) are factors to be identified in estimating the annual cost of the system.

Table 4
Cost estimation of the PvWPS components

No	Unit materials and components	Per unit cost
1	Steel structure Glass cover	RM 120 (US$ 29.92)
2	Glass	RM 60 (US$ 14.96)
3	Stand, bucket, Inlet and outlet collecting etc.	RM 350 (US$ 87.27)
4	Labor cost	RM 100 (US$ 24.93)
	Total	RM 630 (US$ 157.10)

Note: 1U$ = RM 4.01

The annual cost can be obtained as:

$$\textit{Annual cost} = \textit{annual maintenance cost} + \textit{annual first cost} \\ - \textit{annual salvage} \tag{8}$$

Assuming the useful life, u of the PvWPS as 10 years and considering the maintenance cost at 15% of the annual first cost; and taking the interest rate, r as at 12% per annum; P is the total cost of the still.

The annual first cost (fa) of the still is calculated as:

$$\text{fa} = \frac{r(1+r)^u}{(1+r)^u - 1} \times P \tag{9}$$

The annual salvage value (sa) of the system is taken as:

$$sa = \frac{r}{(1+r)^u - 1} \times s \tag{10}$$

Salvage value, s is the usable material of the still system, such as glass cover, frame, insulation etc. The salvage value is half of the initial cost.

The average daily productivity of fresh water of the still is determined to be at 2.67 L/m^2. The total operation duration of the still is expected to be 335 d in a year as the sunlight duration in the region of Serdang, Malaysia. The economic analysis for the PvWPS is explained in Table 5. The analysis clearly shows that the annual cost of the fresh water is 0.03 US$/kg and the total annual cost is 27.91 US$/m^2.

4.Conclusion

A solar still embedded with photo voltaic has been fabricated and tested with the daily fluctuation of a tropical field condition. It has been proven that solar energy can be effectively harnessed not only for electricity generation but also for utilizing the heat energy dissipated as a medium in clean water production. A field test was carried out on both simple single basin (SSB) and photo voltaic water purification system (PvWPS) in the month of November 2017 to assess their performances. It has been found that the temperature of the PvPWS increased up to 5% above the average temperature that may expedite the evaporation process internally. The directly embedded solar PV module successfully enhanced the heat

Table 5
Economic analysis of the PvWPS

Cost-type	Value	Unit
Total cost	157.10	US$
Annual cost (ac)	27.91	US$/m^2
Annual first cost (fa)	127.79	US$/m^2
Annual maintenance cost (ma)	4.168	US$/m^2
Annual salvage cost (sa)	14.044	US$/m^2
Annual yield (y)	894.45	liter
Annual cost of yield (yc)	0.03	US$/kg

Note: y = productivity/year operation, yc = ac/y.

absorbing capacity in the basin section. At the same time, the embedded cooling mechanism via solar still under the PV array reflected the heat absorption capabilities as shown by the reduction of 0.65°C. Thus, it effectively reduced the PV module temperature. The experimental results show that the treated water fulfilled the requirements of drinking water standards and is expected to be effective in the removal of microbial cells. Other benefits of the system are health improvement of the community, low-cost process and the flexibility of the system to be applied in any solar PV farm. The concept of PV Embedded solar still has numerous advantages as compared to the conventional solar still. This is due to the elements of the new technological approach which grooms a green and clean concept in producing purified water with special features of in-situ power generator. This machine can be further up scaled or modulated based on industrial requirements.

Acknowledgement

The authors delegate their special thanks to the Research Management Centre (RMC) of University Putra Malaysia for the approval of research funding under the IPB Putra Grants Scheme (Vote no: 9515303)

Symbols

A_c	—	Annual cost (US$)
A_b	—	Basin area
A_g	—	Glass area
d_w	—	Depth of water in still (m)
E_m	—	Normal PV module Efficiency
E_d	—	Efficiency difference
Fa	—	Annual first cost (US$/m^2)
GHG	—	Greenhouse gas
h_{cbg}	—	Convective heat transfer from basin to glass (W)
h_{ebg}	—	Evaporation heat transfer between basin and glass (W)
h_{rbg}	—	Radiation heat transfer between water and glass cover (W)
Ma	—	Annual maintenance cost (US$/m^2)
P_b	—	Partial vapor pressure basin
P_g	—	Partial vapor pressure glass
Sa	—	Annual salvage value (US$/m^2)
T_a	—	Ambient temperature (°C)
T_b	—	Basin surface temperature (°C)
T	—	Glass surface temperature (°C)
Y	—	Annual yield (liter)
Y_c	—	Annual cost over yield (US$/kg)
ε_g	—	Emissivity of glass cover
ε_b	—	Emissivity of basin
ΔT	—	Temperature reduction on the PV bottom surface

Greek

σ	—	Stefan-Boltzmann constant (W/m^2-K^4)
ε	—	Emissivity

References

[1] B. Gordon, P. Callan, C. Vickers, WHO guidelines for drinking-water quality, WHO Chron., 38 (2008) 564.
[2] H. Sharon, K.S. Reddy, D. Krithika, L. Philip, Experimental performance investigation of tilted solar still with basin and wick for distillate quality and enviro-economic aspects, Desalination, 410 (2017) 30–54.
[3] I. Lee, H. Hwang, J. Lee, N. Yu, J. Yun, H. Kim, Modeling approach to evaluation of environmental impacts on river water quality: A case study with Galing River, Kuantan, Pahang, Malaysia, Ecol. Modell., (2017) 1–7.
[4] The Government of Malaysia, Intended nationally determined contribution of the Government of Malaysia, United Nations Framew. Conv. Clim. Chang., (2015) 6.
[5] S. Dubey, J.N. Sarvaiya, B. Seshadri, Temperature dependent photo voltaic (PV) efficiency and its effect on PV production in the world: A review, Energy Procedia., 33 (2013) 311–321.
[6] K.E. Park, G.H. Kang, H.I. Kim, G.J. Yu, J.T. Kim, Analysis of thermal and electrical performance of semi-transparent photo voltaic (PV) module, Energy, 35 (2010) 2681–2687.
[7] H.M. Qiblawey, F. Banat, Solar thermal desalination technologies, Desalination, 220 (2008) 633–644.
[8] B.B. Sahoo, N. Sahoo, P. Mahanta, L. Borbora, P. Kalita, U.K. Saha, Performance assessment of a solar still using blackened surface and thermocol insulation, Renew. Energy, 33 (2008) 1703–1708.
[9] R. Bhardwaj, M.V. ten Kortenaar, R.F. Mudde, Inflatable plastic solar still with passive condenser for single family use, Desalination, 398 (2016) 151–156.
[10] S. Parekh, M.M. Farid, J.R. Selman, S. Al-Hallaj, Solar desalination with a humidification-dehumidification technique—A comprehensive technical review, Desalination, 160 (2004) 167–186.
[11] K. Voropoulos, E. Mathioulakis, V. Belessiotis, A hybrid solar desalination and water heating system, Desalination, 164 (2004) 189–195.
[12] E. Sartori, Solar still versus solar evaporator: a comparative study between their thermal behaviors, Solar Energy, 56 (1996) 199–206.
[13] N. Mahadeshhwar, K. Patil, A green house effect in solar still, Int. J. Adv. Sci. Eng. Technol., 5 (2017) 69–71.
[14] A. Riahi, K.W. Yusof, N. Sapari, B.S. Singh, A.M. Hashim, Novel configurations of solar distillation system for potable water production, IOP Conf. Ser. Earth Environ. Sci., 16 (2013) 012135.
[15] R. Dev, S.A. Abdul-Wahab, G.N. Tiwari, Performance study of the inverted absorber solar still with water depth and total dissolved solid, Appl. Energy, 88 (2011) 252–264.
[16] A.Z. Al-Garni, Productivity enhancement of solar still using water heater and cooling fan, Sol. Energy Eng., 134 (2012) 1–8.
[17] H. Lu, Long-term reliability study of photo voltaic (PV) system installation on islands, APEC Energy Working Group, 2017, Singapore, Accessed at: https://www.apec.org/Publications/2017/07/LongTerm-Reliability-Study-of-Photovoltaic-PV-System-Installation-on-Islands.
[18] A. Sahu, N. Yadav, K. Sudhakar, Floating photo voltaic power plant: A review, Renew. Sustain. Energy Rev., 66 (2016) 815–824.
[19] C. Tenthani, A. Madhlopa, C.Z. Kimambo, Improved solar still for water purification, Sustain. Energy Environ., 3 (2015) 111–113.
[20] M.E. Ya'Acob, H. Hizam, M.T. Htay, M.A.M. Radzi, T. Khatib, M. Bakri A, Calculating electrical and thermal characteristics of multiple PV array configurations installed in the tropics, Energy Convers. Manag., 78 (2013) 8–13.
[21] M.E. Ya, H. Hizam, Y. Hashimoto, B. Adam, N.F. Othman, Field evaluation of five-level heat dissipation models under PV array structure installed in the tropics, Appl. Mech. Mater., 789–709 (2015) 416–421.
[22] D. Bechki, H. Bouguettaia, J. Blanco-Galvez, S. Babay, B. Bouchekima, S. Boughali, H. Mahcene, Effect of partial intermittent shading on the performance of a simple basin solar still in south Algeria, Desalination, 260 (2010) 65–69.

[23] Y.H. Zurigat, M.K. Abu-Arabi, Modelling and performance analysis of a regenerative solar desalination unit, Appl. Therm. Eng., 24 (2004) 1061–1072.

[24] A. Alaudeen, K. Johnson, P. Ganasundar, A.S. Abuthahir, K. Srithar, Study on stepped type basin in a solar still, J. King Saud Univ. Eng. Sci., 26 (2014) 176–183.

[25] N.F. Othman, M.E. Ya'acob, A.S. Abdul-Rahim, M.S. Othman, M.A.M. Radzi, H. Hizam, Y.D. Wang, A.M. Ya'acob, H.Z.E. Jaafar, Embracing new agriculture commodity through integration of java tea as high value herbal crops in solar PV farms, J. Clean. Prod., 91 (2015) 71–77.

[26] N.S. Rashid, S.M. Praveena, A.Z. Aris, Drinking water assessment on ammonia exposure through tap water in Kampung Sungai Sekamat, Kajang, Procedia Environ. Sci., 30 (2015) 354–357.

[27] World Health Organization, Guidelines for drinking-water quality, World Health Organization, fourth ed., vol. 1, 2011, pp. 104–108, Accessed at:https://apublica.org/wp-content/uploads/2014/03/Guidelines-OMS-2011.pdf.

[28] Govind, G.N. Tiwari, Economic analysis of some solar energy systems, Energy Convers. Manag., 24 (1984) 131–135.

[29] S. Kumar, G.N. Tiwari, Life cycle cost analysis of single slope hybrid (PV/T) active solar still, Appl. Energy, 86 (2009) 1995–2004.

[30] A.E. Kabeel, A.M. Hamed, S.A. El-Agouz, Cost analysis of different solar still configurations, Energy, 35 (2010) 2901–2908.

[31] T. Arunkumar, R. Velraj, D.C. Denkenberger, R. Sathyamurthy, Influence of crescent shaped absorber in water desalting system, Desalination, 398 (2016) 208–213.