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Research Article

Solar Stills Productivity with Different Arrangements of PV-DC Heater and Sand Layer in Still Basin: A Comparative Investigation

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Abstract: Solar energy as a sustainable and accessible energy source can be harnessed and converted to electrical energy using photovoltaic modules. Solar Photovoltaic (PV) systems show tremendous promise as sustainable, environmentally friendly and low-cost electricity sources. Solar energy can also be applied to produce potable water using solar distillation still. In this study, water production performance of four low-cost solar stills with different arrangements of PV module-DC heater and sea sand layer in the solar still basin was evaluated. Four types of double slope single basin solar distillation stills with similar shapes were fabricated. A stainless steel basin with length 50 cm, width 30 cm and depth 8 cm was used in each solar still. The still configurations differed based on inclusion of 2 cm depth of sea sand layer in the basin and use of a 50 Watts PV-DC heater. A comparison of the cumulative water production among these solar stills showed that the integrated system that included sea sand in the solar still basin and also used PV-DC heater was the most effective; producing two times the water produced by a conventional solar still. The integrated solar still can be employed in coastal and rural areas with lack of clean water and electricity supply.

Keywords: Direct Current (DC) power, energy conversion, photovoltaic module, solar energy, solar still, water distillation

INTRODUCTION

The availability of clean drinking water is fundamental to human existence. Yet, the supply of clean fresh water to everyone remains a challenge in many parts of the world. Some States in Malaysia, for example, are facing difficulties in supplying fresh water that complies with the Malaysian Department of Environment (DOE) as well as World Health Organization (WHO) standards. These standards for drinking water supply require removal of chemicals and heavy metals from natural water resources (Jasrotia *et al*., 2012). One of the reasons for water supply shortages in Malaysia is the pollution of rivers by toxic and chemicaldischarges. The use of brackish and saline water as feed water to water treatment plants requiresapplication of expensive desalination processes such as reverse osmosis and distillation. As Malaysia receives enough sunshine throughout the year, solar energy can be tapped to provide an economical means of treating water for potable use (Ahsan *et al*., 2014; Syuhada *et al*., 2013).

In recent years, various studies have been conducted on different configurations of solar stills to enhance the water production. A Triangular Solar Still (TrSS) with a tilt angle of 60° was fabricated in Malaysia (Ahsan *et al*., 2014) using black painted Perspex sheet basin and transparent polythene film cover which resulted in a water yield of 1.55 L/m².day. Another experimental study was conducted in Jordan (Akash *et al*., 2000) to determine the optimum tilt angle of a basin type solar still. The optimum tilt angle of 35° was found to enhance the water production by 226% (productivity of 6.2 L/m².day). A comparison between single and double basin solar stills was made in Bahrain (Al-Karaghouli and Alnaser, 2004) to improve water production. The double basin solar still produced 3.91 L/m².day of water; an enhancement of 37% over the single basin solar still. A transportable hemispherical solar still in Dhahran (Ismail, 2009) showed water production of 5.7 L/m².day.

The use of external heat energy source was employed in some works to improve the basin water temperature and solar still productivity. Two electrically powered 500 W AC heaters were used to

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increase the basin water evaporation of a double slope solar still in Saudi Arabia (Al-Garni, 2012). The productivity was enhanced by 370% to 11.8 L/m².day compared to 2.5 L/m².day obtained for the conventional still (without heater). A comparative study of the performance of an Inverted Absorber Solar Still (IASS) and a single slope Solar Still (SS) conducted in Muscat, Oman (Dev *et al*., 2011) found that the (IASS) enhanced the water production by 192% with a maximum productivity of 6.3 L/m².day. A solar still using aparabolic-trough concentrator with thermal insulation and wind protection in Cocayalta, Peru (Saettone, 2012) produced 6.36 L/m².day compared to 3.25 L/m².day for the simplest model.

In order to increase solar still productivity, several researchers have used heat storage materials in solar still basin as internal heat energy source. Asymmetrical solar still using dry sawdust as thermal insulation basin material was studied in Egypt (Mohamad *et al*., 1995). It increased the productivity by 35%. Quartzite rock used in the basin of a double slope solar still in India (Murugavel *et al*., 2010) enhanced water production by 17.6% to reach 3.66 L/m².day. Application of sand as heat absorption material in the basin liner was investigated in Iran (Tabrizi and Sharak, 2010). It was found that the sandy heat reservoir also acted as a compensative heat source during low solar radiation intensity periods which aided in enhancement of productivity up to 75% with a production of 3.00 L/m².day. A modified single slope solar still using fin, sand and sponge in the basin also increased the water production by 75% to 2.77 L/m².day (Velmurugan *et al*., 2008). An improvement of 61% water production to 3.703 L/m².day was obtained using aluminum floating plates as heat storage material in a solar still basin (Panchal and Shah, 2012).

Some researchers have enhanced the condensation process by cooling the outer or inner surface areas of solar still covers. An experimental investigation was carried out in Algeria to compare the condensation augmentation (Zeroual *et al*., 2011). The authors used shading screen and water flow to cool the covers of the double slope solar still. A productivity improvement of 11.82% was achieved using shading screen compared to water flow usage. In another work, a solar fan powered by a PV was installed in the cover of a pyramid shape solar still in Jordan (Taamneh and Taamneh, 2012). The aim of fan usage was to circulate and remove humid air above the basin water to increase the amount of evaporation and cool the inner cover's area. The productivity reached up to 2.99 L/m².day; 25% increase compared to the conventional type.

A survey of the literature shows that, the use of an integrated system comprising PV-DC heater and sea sand layer in basin, as external and internal heat energy sources respectively, to improve solar still productivity has not been reported. From the above discussion, it is evident that there is ample room for further improvement of solar still performance through innovative designs and configurations. The present work is a comparative study on the productivity of four solar stills with different arrangements of PV-DC heater and sea sand layer to convert lake water into clean water.

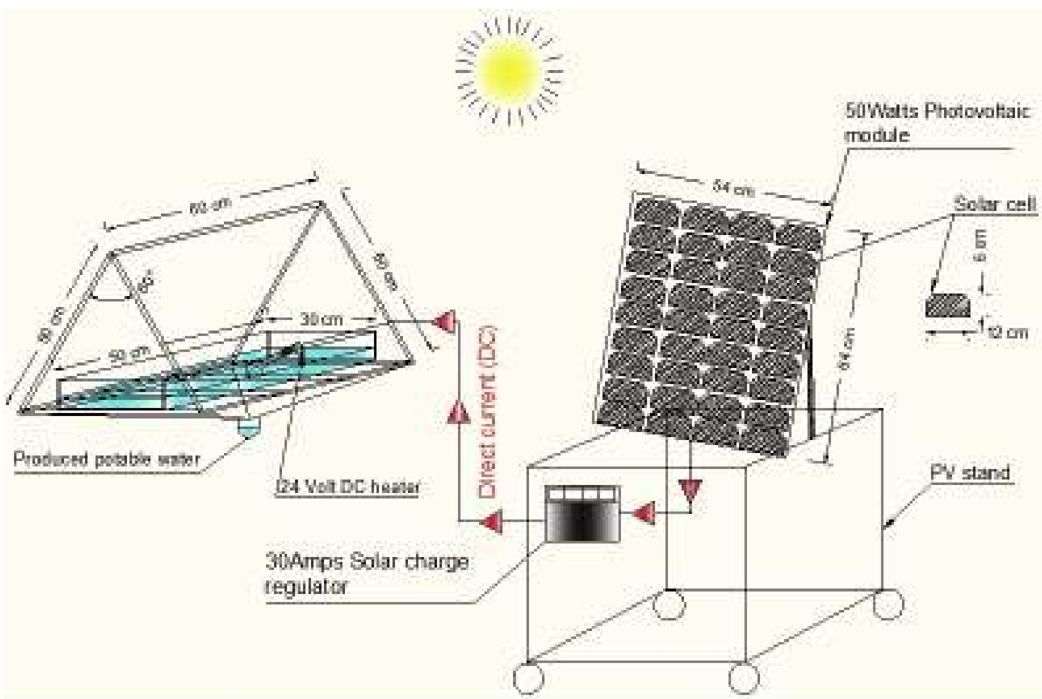

Fig. 1: Schematic diagram of solar still integrated with 50 watts photovoltaic module and 24 volt DC heater

EXPERIMENTAL SET-UP

Figure 1 and 2 show the schematic diagram of solar still integrated with 50 Watts photovoltaic module and 24 Volt DC heaters and a photograph of the experimental set up in this study respectively. Four types of single basin double slope solar stills were constructed with similar shapes. Each of them had a stainless steel trough as basin with a length of 50 cm, a width of 30 cm (area 0.15 m²) and a depth of 8 cm (volume 12 L). A tilt angle of 60° was selected for each solar still to fabricate a triangular solar still with similar side length of 50 cm (Riahi *et al*., 2013; Ahsan *et al*., 2014). The double slope frame, cover and trough (basin) of all solar stills were made of PVC pipe (15 mm diameter), transparent polythene film (0.15 mm thickness) and stainless steel, respectively. The solar stills were light and hence, portable. The total fabrication cost of this solar still was roughly RM 332 or US$ 102 (Table 1). The use of durable, cheap and locally available materials solar stills fabrication ensured low operation and maintenance costs. The cover of a basin-type solar still is usually made of heavy glass; this can make fabrication difficult especially in coastal and rural areas. PVC pipes and polythene films have longer durability of 3 to 5 years (Ahsan *et al*., 2013) compared to 2 years for vinyl chloride sheets (Ahsan *et al*., 2012). Thus, polythene film was selected as cover material for solar stills in this study (Fig. 3).

The four types of solar stills studied were:

- Solar still 1 (S1): Conventional solar still
- Solar still 2 (S2): Conventional solar still with sea sand layer in basin
- Solar still 3 (S3): Conventional solar still connected to PV-DC heater
- Solar still 4 (S4): Conventional solar still with sea sand layer in basin and connected to PV-DC heater

Fig. 2: Photograph of experimental set-up

(a) (b) (c)

Fig. 3: Photographs of (a) 24 volt DC water heater, (b) digital multimeter (thermocouple), (c) solarimeter (SL200)

A 2 cm sea sand layer as heat reservoir was included in the solar still basins as indicated above. Solar energy was harnessed as sustainable energy and converted to electrical energy (Direct current) using a Monocrystalline Photovoltaic (PV) module with an area of 0.64×0.54 cm (0.3456 m²) with a maximum capacity of 50 Watts and 15% efficiency to power a 50 Watts DC water heater with 24 Volt rating. A 30 Amps Solar charge regulator was used to control the Direct Current (DC) from PV module and conduct it to DC water heater (Fig. 1). A 24 Volt DC water heater was used to heat water inside the basin. The specifications of photovoltaic module, solar charge regulator and DC water heater are shown in Table 2. The output power of PV module as external heat energy source was calculated using Eq. (1) (María *et al*., 2014):

$$P_{pv} = I_s \times \eta_{pv} \times A_{pv} \tag{1}$$

Table 1: Fabrication cost of a double slope single basin solar still with 50 watts photovoltaic-DC heater

Items	Quantity	Unit cost (RM)	Cost (RM)
Polythene film cover (0.15 mm thickness)	1.2 m²	RM 1.80/m²	2.20
PVC pipe frame (15 mm diameter)	4.8 m	RM 6.00/m	28.20
Stainless steel tray	1	40.00	40.00
50 watts monocrystalline solar panel	1	210.00	210.00
30 amps charge regulator	1	40.00	40.00
24 volt DC heater	1	5.90	5.90
Plastic rope	30 m	RM 12.00/roll	3.60
Transparent tape	1	2.50	2.50
Total cost			332.40

US$ 1≈RM 3.25

Table 2: Specifications of DC water heater, solar charge regulator and photovoltaic module used in this study

Parameters	Values of DC water heater	Values of solar charge regulator	Values of photovoltaic module
Maximum voltage (Vm)	24V	24 V	18.22 V
Maximum power output (Pm)	50 W	720 watts	50 watts
Current at max power (Im)	2.08 A	30 A	2.8 A
Open circuit voltage (Voc)	…	…	21.82 V
Short circuit current (Isc)	…	…	3.06 A

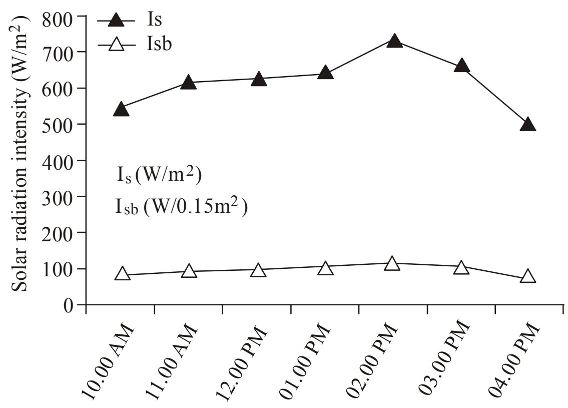

Fig. 4: Diurnal variation of solar radiation intensities per 1 m² (I_s) and the solar radiation intensities on 0.15 m² basin area of each solar still (I_{sb}) on day 1 (April 4, 2013)

The values of solar radiation intensity on the basin area of 0.15 m² (I_{sb}) was calculated using following Eq. (2) which was shown in Fig. 4 and 5:

$$I_{sb} = I_s \times 0.15 \tag{2}$$

The following two experiments were conducted in Universiti Teknologi PETRONAS campus in Malaysia to study the performance of the four solar stills.

Experiment 1: Solar stills S1, S2 and S3 were exposed to similar solar radiation in an open field.

Experiment 2: On the following day, solar stills S1 and S4 were exposed to similar solar radiation at the same location as Experiment 1.

A digital thermometer was used to measure temperatures of water, inner cover of solar stills and

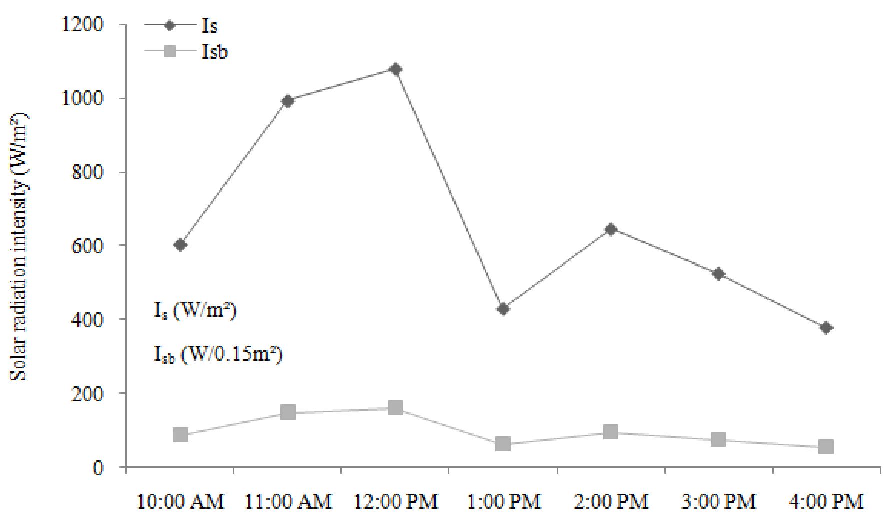

Fig. 5: Diurnal variation of solar radiation intensities per 1 m² (I_s) and the solar radiation intensities on 0.15 m² basin area of each solar still (I_{sb}) on day 2 (April 5, 2013)

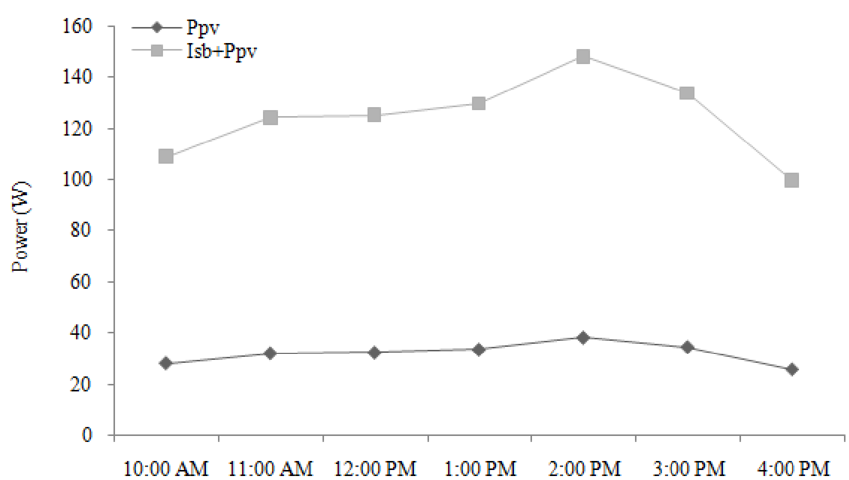

Fig. 6: Diurnal variation of the output power of 50 W photovoltaic module (P_{pv}) and the cumulative power of I_{sb} and P_{pv} on day 1 (April 4, 2013)

ambient air (Fig. 3). A solarimeter (SL200) was used to measure the solar radiation intensity (Fig. 3). Each solar still basin was filled with 4.5 L/day of lake water (3 cm depth) for the experiments. Water vapor condensed on the transparent cover was collected (Fig. 2) and its volume was measured to determine the still productivity.

RESULTS AND DISCUSSION

Effect of solar radiation intensities on the area of PV module, temperatures of water and inner cover of solar still and ambient air temperatures: Figure 4, 6 and 7 show the diurnal variation of solar radiation intensity on 1 m² basin area (Is), solar radiation intensity on 0.15 m² basin area of each solar still (I_{sb}), output power of 50 W photovoltaic module (P_{pv}), the cumulative power of I_{sb} and P_{pv} (I_{sb}+P_{pv}), temperatures of ambient air and temperatures of water and inner cover for solar stills S1, S2 and S3, respectively during Experiment 1 on Day 1 (4th April, 2013). The highest T_{W1}, T_{W2}, T_{W3} and Ta were observed when I_S and I_{sb} peaked at around 2:00 pm (Fig. 4 and 7). With increase in I_S and I_{sb} from 540 W/m² and 81 W at 10:00 am to 733 W/m² and 109.95 W at 2:00 pm respectively, the values of T_{W1}, T_{W2} and T_a also reached their maximum values of 47, 48 and 32°C, respectively; the corresponding maximum inner cover temperatures T_{ic1}, T_{ic2} were 39, 39°C respectively. T_{W2} is generally higher than T_{W1} during the day which is due to the application of sea sand as internal heat storage material in S2 basin acting as a compensative heat energy source to maintain water temperature during intensity solar radiation periods (Tabrizi and Sharak, 2010) (Fig. 4 and 7). The external energy from PV module-DC heater (P_{pv}) was added to the available solar radiation intensity on S3 basin to increase the water temperature. The hourly output power of PV module (P_{pv}) was calculated using Eq. (1) which is shown in Fig. 4 and 6. It is revealed that with increase in I_s from 540 W/m² at 10:00 am to 733 W/m² at 2:00 pm the values of I_{sb} and P_{pv} increased from 81 and 27.99 W to 109.95 and 37.99 W respectively. It is observed that the total cumulative value of I_{sb} and P_{pv} from 10:00 am to 2:00 pm increased from 108.99 W to the maximum value of 147.95 W, respectively which is higher than the maximum value of I_{sb} of 109.95 W in S1 and S2. The average I_{sb}+P_{pv} of 124.13 W for S3 is higher than the average I_{sb} of 92.25 W for S1 and S2. Therefore, the increase of I_{sb}+P_{pv} in S3 basin is due to the application of 50 Watts PV module-DC heater as additional external energy source which caused a higher maximum of T_{W3} than T_{W1} and T_{W2} at 2:00 pm respectively (Fig. 4, 6 and 7). The corresponding maximum inner cover temperature T_{ic3} was 40°C. It is also obtained that T_W reached to the higher values in S3 basin than T_W in S1 and S2 basins from 1:00 pm to 3:00 pm respectively when the higher values of solar radiation intensities are being harnessed by S3 basin water and the photovoltaic module. It is observed that the maximum T_{W3} is higher than the maximum values of T_{W1} and T_{W2} at highest solar radiation intensities as well. It is also shown that the average T_{W3} reached to the higher value than average T_{W1} and $T_{W2}$with the aid of 50 Watts PV module-DC heater during intensity solar radiation periods (Fig. 4 and 7) (Riahi *et al*., 2013).

Figure 5, 8 and 9 show the diurnal variation of solar radiation intensity on 1 m² basin area (Is), solar radiation intensity on 0.15 m² basin area of each solar still (I_{sb}), output power of 50 W photovoltaic module (P_{pv}), the cumulative power of I_{sb} and P_{pv} (I_{sb}+P_{pv}), temperatures of ambient air and temperatures of water and inner cover for solar stills S1 and S4 respectively during Experiment 2 on Day 2 (5th April, 2013). The temperature increase corresponded to the increase in solar radiation intensity. At 12 noon, when I_s and I_{sb} reached the maximum values of 1078 W/m² and 161.7 W respectively, the highest T_{W1}, T_{W4} and T_a were

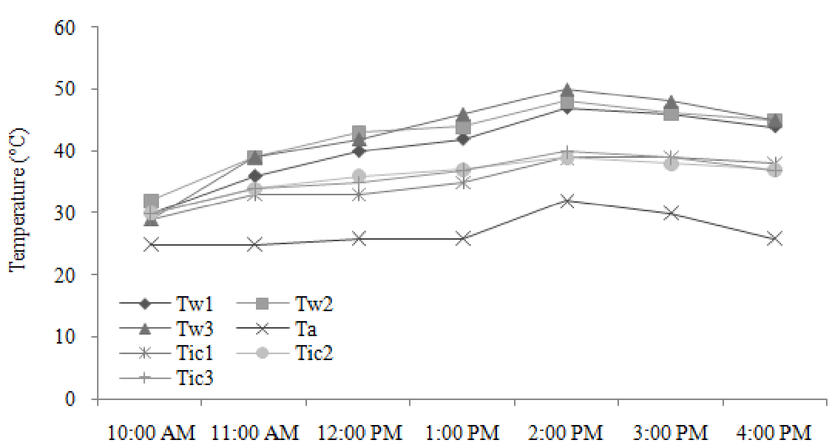

Fig. 7: Diurnal variations of temperatures of water, inner cover of solar stills and ambient air on day 1 (April 4, 2013)

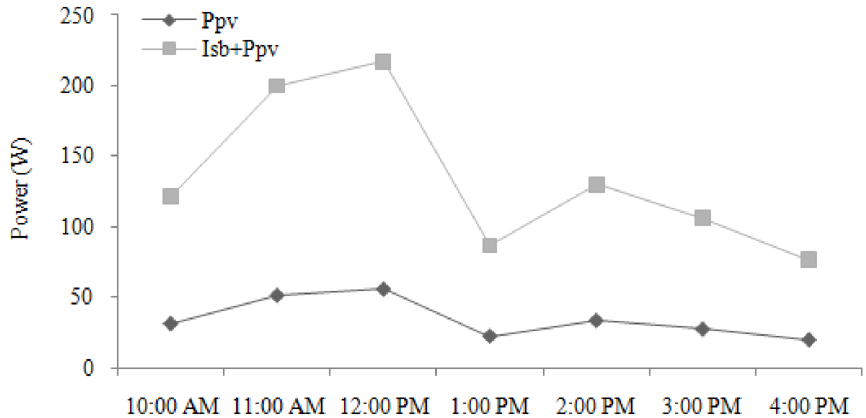

Fig. 8: Diurnal variation of the output power of 50 W photovoltaic module (P_{pv}) and the cumulative power of I_{sb} and P_{pv} on day 2 (April 5, 2013)

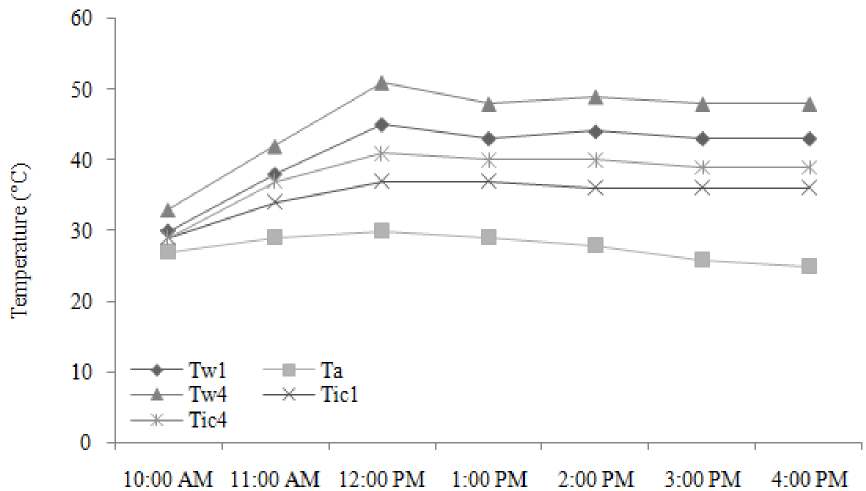

Fig. 9: Diurnal variations of temperatures of water, inner cover of solar stills and ambient air on day 2 (April 5, 2013)

45, 51 and 30°C respectively (Fig. 5, 8 and 9). The higher maximum T_{W4} than T_{W1} and T_a was observed from 10:00 am to 12:00 pm due to the increase in output power of 50 Watts PV module-DC heater connected to the S4 basin, the rise in heat energy storage of sea sand in the basin as well as increase of available solar radiation intensity respectively. The maximum inner cover temperatures T_{ic1} and T_{ic4} were 37 and 41°C respectively. A sharp decrease of I_S and I_{sb} to 428 W/m² and 64.2 W occurred respectively during the next 1 h which caused a moderate decrease of T_{W1}, T_{W4} and T_a to 43, 48 and 29°C, respectively. It is observed that T_{W4} is still higher than T_{W1} due to the heat energy storage of sea sand inside the basin to maintain the basin water temperature of S4, while there is a sharp decrease of output power of PV module from 55.88 W at 12:00 pm to 22.18 W at 1:00 pm. Mild fluctuations in solar radiation intensity were observed beyond this time. T_{W4} values were always higher than T_{W1} throughout the day. It is due to the application of sea sand as heat storage materialin S4 basin as well as the use of 50 Watts PV module and DC heater which acted as internal and external heat energy source respectively to increase water temperature during low and high intensity solar radiation periods (Fig. 5, 8 and 9).

Effects of solar radiation and water temperature on hourly water production: Figure 10 shows the hourly water production for solar stills S1 (W_{h1}), S2 (W_{h2}) and S3 (W_{h3}) on Day 1 corresponding to solar radiation intensities and water temperatures shown in Fig. 4, 6 and 7. It is observed that with increase in solar radiation intensity and water temperature, the hourly water production also increased during the experiment. The maximum W_{h1}, W_{h2} and W_{h3} were 0.24, 0.31 and 0.39 L/m², respectively, obtained at 2 pm. It can be concluded that both modifications to the conventional solar still i.e., inclusion of sea sand in the basin and use of PV-DC heater were instrumental in enhancing water production from the stills. The effect of PV-DC heater

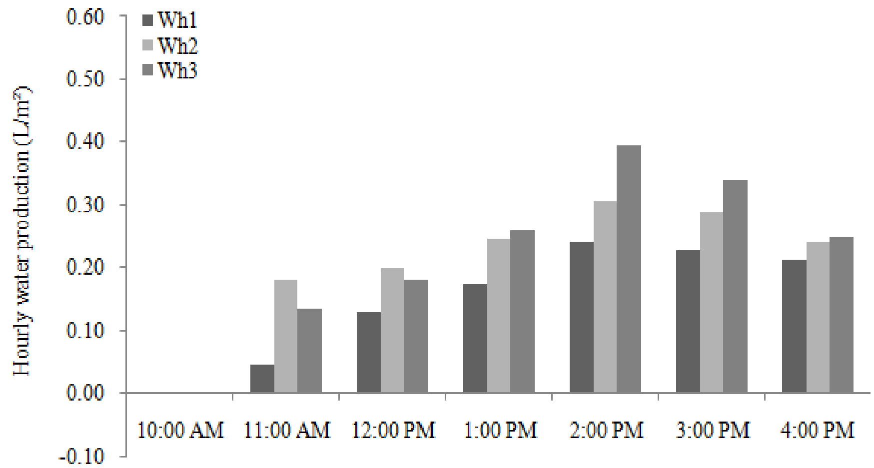

Fig. 10: Hourly water production of solar stills S1, S2 and S3 on day 1 (April 4, 2013)

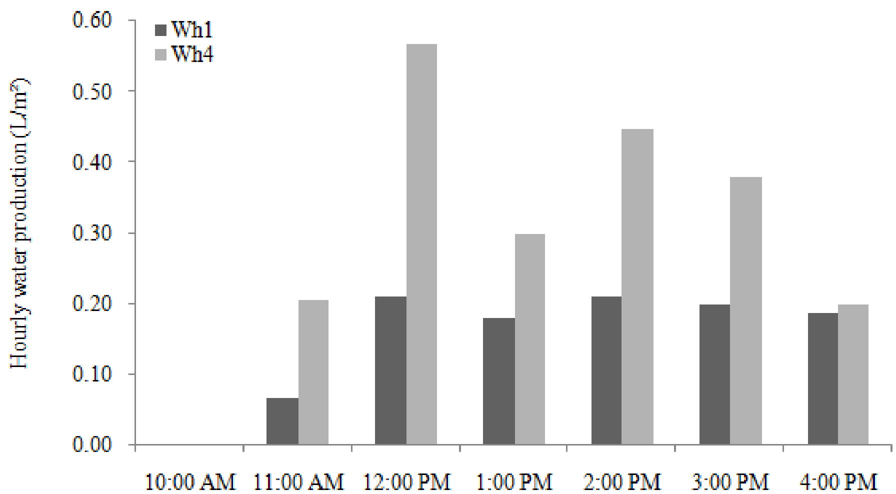

Fig. 11: Hourly water production of solar stills S1 and S4 on day 2 (April 5, 2013)

was clearly stronger due to higher input of energy for water evaporation. Similar observations were made at 12:00 pm on Day 2 for solar stills S1 and S4 (Fig. 5, 8, 9 and 11). The maximum water production was 0.21 and 0.57 L/m² from S1 and S4 respectively. The strategy of including sea sand in the solar still basin together with the use of PV-DC yielded the maximum amount of water among all configurations studied.

Cumulative water production: Figure 12 shows the cumulative water production from S1, S2 and S3 on Day 1. Water produced from S1 was the least throughout the day. From 11:00 am to 1:00 pm, W_{C2} was higher than W_{C3} owing to the higher initial temperature T_{W2}. As time progressed, T_{W3} gradually became higher than T_{W2} due to energy input from the PV-DC heater. This resulted in greater amount of water production from S3. At termination of the experiment, the total amount of water produced from S1, S2 and S3 was 1.03, 1.46 and 1.56 L/m², respectively. It showed the cumulative productivity of solar still using PV-DC heater is higher than the productivity of solar still using sea sand layer in basin and conventional solar still (Riahi *et al*., 2014). Figure 13 shows the cumulative water production from S1 and S4 on Day 2. It was observed that W_{C4} was higher than W_{C1} throughout the day. The cumulative water production from S1 and S4 at the end of the day was 1.05 and 2.10 L/m² respectively. Despite difference in hourly water production from S1 on Day 1 and 2, the cumulative water production over the study duration of 6 h (11 am to 4 pm) was approximately the same. In other words, overall effect of solar radiation on the solar stills was similar for both days. Thus, a comparison of results obtained from the solar stills on the two days is justifiable. W_{C4} being the highest amount of water produced from all solar stills, confirms that the configuration adopted in S4 was the most effective.

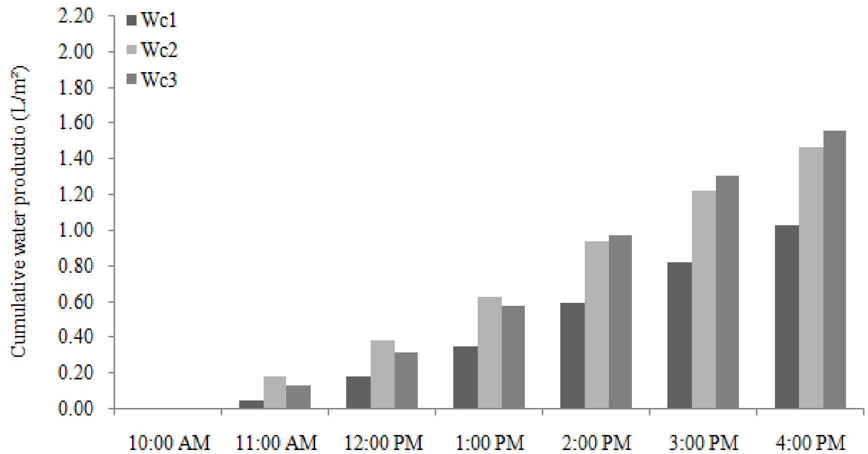

Fig. 12: Cumulative water production of solar stills S1, S2 and S3 on day 1 (April 4, 2013)

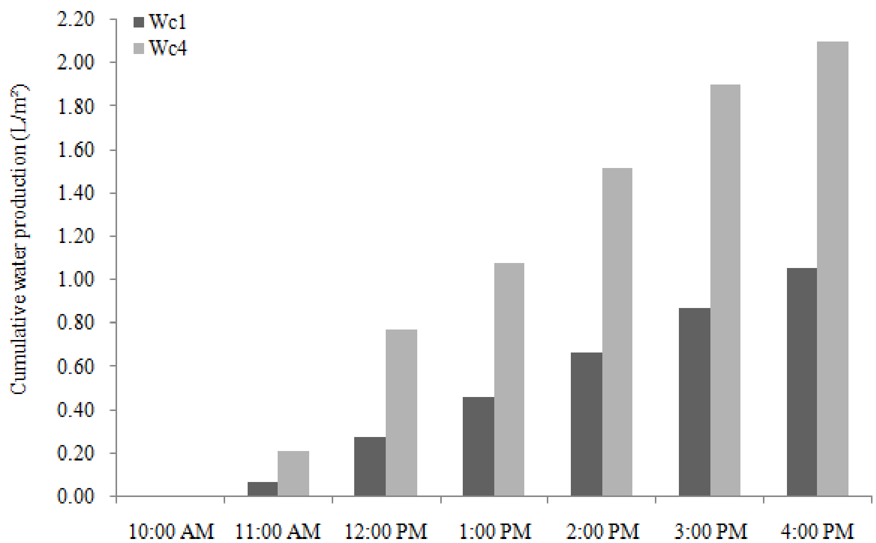

Fig. 13: Cumulative water production of solar stills S1 and S4 on day 2 (April 5, 2013)

Table 3: Reported solar still productivity improvement

Enhancement method	Water production enhancement (%)	References
Productivity improvement using double basins in solar still	37	Al-Karaghouli and Alnaser (2004)
Solar still using parabolic-trough concentrator	95	Saettone (2012)
Asymmetrical solar still using dry sawdust as best thermal insulation material	35	Mohamad *et al.* (1995)
Double slope solar still using 3/4 in sized quartzite rock as more effective heat storage material	17.6	Murugavel *et al.* (2010)
Water production increase using sand as heat reservoir in conventional solar still basin	75	Tabrizi and Sharak (2010)
Productivity augmentation of modified single slope solar still by using fin, sand and sponge in the basin	75	Velmurugan *et al.* (2008)
Solar still consisting of aluminum floating plates	61	Panchal and Shah (2012)
Productivity increase using shading screen to cool the covers of double slope solar still	11.8	Zeroual *et al.* (2011)
A pyramid shape solar still applying solar fan powered by PV	25	Taamneh and Taamneh (2012)
Solar still with PV-DC heater and sea sand	100	This study

Therefore, a maximum productivity enhancement of 100% was achieved when a 50 Watts PV module, 50 Watts DC water heater and a sand layer were incorporated into the conventional double slope single basin solar still. Table 3 shows water production enhancement reported in various studies (Al-Karaghouli and Alnaser, 2004; Saettone, 2012; Mohamad *et al*., 1995; Murugavel *et al*., 2010; Tabrizi and Sharak, 2010; Velmurugan *et al*., 2008; Panchal and Shah, 2012; Zeroual *et al*., 2011; Taamneh and Taamneh, 2012).

It is observed that S4 yielded a cumulative water production of 2.10 L/m² over 6 h (about 0.35 L/m².h) with an average solar radiation intensity of 663 W/m², while a modified solar distillation system in Jordan (Taamneh and Taamneh, 2012) produced 2.99 L/m² over 10 h (about 0.299 L/m².h) despite a higher solar radiation intensity of 700 W/m². This study also shows higher water productivity compared to solar still studies in Malaysia (Ahsan *et al*., 2014), India (Vinoth and Kasturi Bai, 2008), Turkey (Aybar and Assefi, 2009) and Jordan (Tarawneh, 2007).

CONCLUSION

Despite daily fluctuations due to cloud coverage, solar energy can be effectively harnessed as sustainable energy and converted to electrical energy for clean water production using solar stills equipped with PV-DC heaters and sand layers in the still basin. The conventional solar still using direct sun radiation only produced 1.05 L/m² of clean water, while the solar distillation system with added sand layer produced 1.46 L/m² and that equipped with a 50 Watts PV and 50 Watts DC heater produced 1.56 L/m² under Malaysia's meteorological conditions. Water production can be enhanced to 2.10 L/m² by integrating a PV-DC heater and sand layer into the conventional type solar still. The integrated solar still used in this study produced twice as much water as the conventional still. The still can be employed in coastal and rural areas with lack of sustainable clean water and electricity supply. Future studies can be conducted with PV cells with higher rating to power Alternative Current (AC) or Direct Current (DC) heaters with higher power rating and use of heat storage methods such as including sand in the still basin or painting the basin black.

NOMENCLATURE

T_{w1} : Temperature of water of solar still S1 (°C)
T_{w2} : Temperature of water of solar still S2 (°C)
T_{w3} : Temperature of water of solar still S3 (°C)
T_{w4} : Temperature of water of solar still S4 (°C)
T_a : Temperature of ambient air (°C)
T_{ic1} : Temperature of inner cover of solar still S1 (°C)
T_{ic2} : Temperature of inner cover of solar still S2 (°C)
T_{ic3} : Temperature of inner cover of solar still S3 (°C)
T_{ic4} : Temperature of inner cover of solar still S4 (°C)
I_s : Solar radiation intensity on 1 m² basin area (W/m²)
I_{sb} : Solar radiation intensity on the basin area of 0.15 m² (W)
P_{pv} : Output power of photovoltaic module (W)
η_{pv} : Photovoltaic module efficiency (%)
A_{pv} : Area of photovoltaic module (m²)
W_{h1} : Hourly water production of solar still S1 (L/m²)
W_{h2} : Hourly water production of solar still S2 (L/m²)
W_{h3} : Hourly water production of solar still S3 (L/m²)
W_{h4} : Hourly water production of solar still S4 (L/m²)
W_{c1} : Cumulative water production of solar still S1 (L/m²)
W_{c2} : Cumulative water production of solar still S2 (L/m²)
W_{c3} : Cumulative water production of solar still S3 (L/m²)
W_{c4} : Cumulative water production of solar still S4 (L/m²)

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