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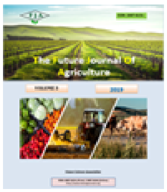

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ENERGY, EXERGY, ECONOMICAL AND ENVIRONMENTAL (4E) ANALYSES FOR A PYRAMID SOLAR STILL AUGMENTED WITH AIR-COOLED GLASS COVER

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ABSTRACT: In the present study, the energy, exergy, economic and environmental (4E) analyses were performed on basis of a previous experimental study on Pyramid Solar Still (PSS) incorporated with a novel air-cooled glass system. This study is an attempt to obtain deep insights into the effect of the air-cooled glass cover with PSS on the efficacy of energy conversion, economic feasibility and the contribution to mitigating CO_2 emissions. The experimental data obtained formerly was used for these analyses. The 4E analyses were done for two operation modes; PSS without cooled-glass cover (PSS1) and PSS with air-cooled glass cover (PSS2). The obtained results from the present study revealed that PSS2 improves the daily productivity and energy efficiency by 19.77 and 19.75%, respectively over the PSS1 with a relatively lower daily exergy efficiency of 10.7%. However, PSS2 enhances the annual productivity by 19.72% over PSS1 with an approximately equivalent cost for unit production (~0.0133 $/L/m^2), although the relatively high total annual cost of PSS2. The exergoeconomic parameter of PSS2 based on exergy has been reduced by 11.92% than PSS1, which means low costs of exergy losses for PSS2. The total CO_2 emission mitigation (1237.25 kg) and the total net CO_2 mitigation (8.312 tons) for PSS2 throughout its lifetime (10 years) are higher than PSS1 by 12.30% and 21.31%, respectively. The earned carbon credit of PSS2 (120.53$) is higher than PSS1 by 21.30% and the energy payback time (1.295 years) is shorter than PSS1 by 8.80%. Hence, the novel integration of the air-cooling system with PSS is promised from the technical, economic and environmental aspects taking into consideration to use of low power for the cooling process in future works for better performance.

Key words: Pyramid solar still, air-cooled glass, energy, exergy, economics, CO_2 mitigation.

INTRODUCTION

Freshwater availability is the crucial secret of life on earth. Water covers about 70% of the land, however, more than 97% of the water is brackish and salty, while freshwater represents about 2.53%, and only ~ 0.36% can be used in daily life **(Sharshir *et al.*, 2016; Xiao *et al.*, 2013)**. The world's population is expected to increase by 2 billion people in the next three decades, from 7.7 billion currently in 2019 to 9.7 billion in 2050 **(United Nations, 2019)**. Therefore, the above-mentioned portion of freshwater is expected to be retarded due to the rapid increase of population all over the globe and their activities, resulting in inadequate amounts of potable/drinkable water for humanity. Basically, the arid and semi-arid regions are suffering from the shortage and contamination of freshwater either for surface sources of freshwater such as; rivers, ponds and lakes or the underground water **(Tawfik, 2012)**. Also, the coastal regions may suffer from the same problem due to the deficiency of the surface freshwater resources or salinity of the underground water. Moreover, the high cost of freshwater transportation is a very tough barrier to provide these regions with freshwater and considered an uneconomical and unreliable option **(Tawfik, 2018; Abd Allah and Tawfik, 2019)**. Therefore, desalting the seawater, brackish water and saline water is considered a promised solution to solve this problem. Since the desalination process requires a substantial amount of energy, thus harnessing renewable energy for this process is considered the best economical solution to produce freshwater at low costs **(Kabeel *et al.*, 2019)**. Accordingly, societies over the globe will necessarily be subject to major challenges regarding energy and water demands. Desalination is a high consumptive process of energy and requires massive amounts of energy, so the full depending on using the fossil fuels to provide desalination process in the large-scale plants with the required power will rise up the GHG emissions **(Chafidz *et al.*, 2014)**. In this case, the use of large amounts of fossil fuels in the desalination process to meet the required heat for this sector will lead to major concerns from the economical and environmental aspects. To achieve the desirable balance between the desalting process, energy and environment, there is an urgent need for shifting to renewable energy as a sustainable, clean and economical energy source for desalination. Out of the diverse renewable energy resources, solar energy is one of the sustainable, clean energy sources that can be utilized for different applications **(Kumar *et al.*, 2018)**. The large-scale desalination plants is unsuitable for the population in isolated, remote and coastal areas which have less freshwater demands, so utilizing the solar energy for producing freshwater at small-scale in such areas using the stand-alone solar powered desalination systems is very promised **(Chafidz *et al.*, 2016).** Solar still is considered a simple rout to produce potable water from saline water with relatively low cost in structure, operation and maintenance **(Velmurugan and Srithar, 2011; Ayoub *et al.*, 2012 and Omara *et al.*,2014).** The design of pyramid-shaped solar still doesn't require orientation or tracking mechanism as well as cheap, simple in structure, large condensation area, high productivity, no shadowing on the basin brine **(Nayi and Modi, 2018)**. The thermal efficiency of this design can be reach up to 50% **(Wassouf *et al.*, 2011)**. Cooling the solar still glass cover one of the most effective technique for enhancing the fresh water productivity (**Kalidasa Murugavel *et al.*, 2008)**. The common technique for cooling solar still glass cover was conducted using water, however, the improper flow rate of cooling water, salt accumulation and wasting a considerable portion of freshwater for cooling process may reduce the effectivness of this technique. From literature, there are very limited works relevant to cooling the solar still's glass cover using air streaming such as; (**Rubio *et al.*, 2000; El-Sebaii, 2004 and Al-Garni, 2012)**, especially for the Pyramid Solar Still (PSS). Due to the mentioned advantages of the PSS, a previous experimental study was performed on this design to investigate the effect of the air-cooled glass cover on its thermal performance **(Tawfik, 2018)**. In this study, the thermal performance of a PSS retrofitted with air-cooled system for the glass cover was evaluated under different levels of air velocity and exposure time tactics compared to the same solar still without air-cooling using brackish water (15000 ppm) and brine depth of 4 cm. The obtained results showed that, the parameters of water-inner glass temperature difference, hourly productivity (at noon), accumulated yield and instantaneous efficiency were 21°C, 0.645 L/m^2.h, 3.545 L/m^2.day and 43.2%, respectively at air velocity over the glass covers of 5 m/s and cooling tactic of 20minon -10min off, whereas the same parameters were 10°C, 0.505 L./m^2.h, 2.905 L/m^2.day and 32.4% for the solar still without cooling, respectively. Recently, several researchers were focused not only on improving the productivity of solar still but also on the assessment of the energy and exergy based on the first and second law of thermodynamic. Further advanced exergy-based approaches like those of exergoeconomic and exergoenvironmental methods can be used to assess the quality of energy transformation methods of the solar still **(Yousef and Hassan, 2019)**. There is no doubt that solar still contributes to CO_2 mitigation, consequently, reducing global warming. Moreover, the environmental cost analysis in terms of enviroeconomic analysis is considered a vital method to describe the economic befits of reducing CO_2 emission. In the same context, the economic analysis is a very important approach to evaluate the feasibility of solar still which can influence the propagation of the proposed design of solar still. In the present study, the 4E analyses, including Exergy, Energy, Economic and Environmental analysis for the PSS integrated with this novel air-cooling system were done for the first time. Hence, this study aims to use the 4E analyses for evaluating the previous work of a PSS augmented with an air-cooled glass cover that presented by **(Tawfik, 2018)**, due to its promised thermal performance. Thus, performing the missing 4E analyses for the above mentioned previous work will provide good insights on the economic and environmental impact of this design that can help for more propagation and adaptation among common consumers/farmers as an attractive desalting system. In the present study, the 4E analyses were carried out in terms of energy efficiency, exergy efficiency, economic analysis, total CO_2 mitigation, earned carbon credit and energy payback time.

MATERIAL AND METHODS

The design of solar still

The measured data of the previous work obtained by evaluating the thermal performance of PSS augmented with air-cooled glass cover was utilized to carry out the 4E analyses for the proposed solar still. The design, construction and components of solar still were described in detail in the previous work presented by **(Tawfik, 2018)**. Therefore, these details are not repeated here. A Pictorial view of the used PSS in the previous study is showed in Fig.1. In the current study, the 4E analyses were used for comparing the performance of the PSS without cooling cover (natural cooling by wind) (PSS1) and with air-cooled glass cover (PSS2) using the best cooling tactics of 20_{min} On- 10_{min} Off at stream air velocity of 5 m/s. The practical data of the previous work was collected under brackish water (15000 ppm) and brine depth of 4 cm in the basin.

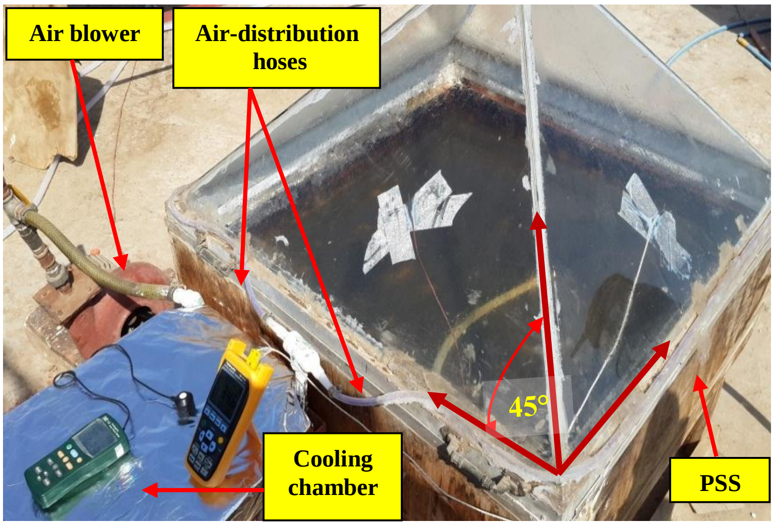

Fig.1. PSS with air-cooling system (the case of PSS2) presented by (Tawfik, 2018).

The 4E analyses

Energy analysis

The hourly and daily energy efficiency of solar still in the present study represents an internal energy efficiency. In general, the energy efficiency is the ratio of water evaporative heat to the total incident solar radiation on the solar still in a typical day. The hourly ($\eta_{EN,hourly}$) and daily energy efficiency ($\eta_{EN,daily}$) of solar still are based on the first law of thermodynamics and can be calculated in (%) **(Rahbar *et al.*, 2012)** as:

For the PSS without cooling cover (PSS1):

$$\eta_{EN,hourly} = \frac{\dot{m}_{ev}\times h_{fg}}{I(t)\times A_b} \times 100 \qquad (1)$$

$$\eta_{EN,daily} = \frac{\sum(\dot{m}_{ev})\times h_{fg}}{\sum I(t)\times A_b} \times 100 \qquad (2)$$

For the PSS with air-cooled cover (PSS2) **(Rahbar *et al.*, 2016)**:

$$\eta_{EN,hourly} = \frac{\dot{m}_{ev}\times h_{fg}}{I\times A_b + W_b} \times 100 \qquad (3)$$

$$\eta_{EN,daily} = \frac{\sum(\dot{m}_{ev})\times h_{fg}}{\sum I(t)\times A_b + W_b} \times 100 \qquad (4)$$

where $\dot{m}_{ev}$ is hourly distilled water productivity (kg/h); h_{fg} is the water latent heat of evaporization (kJ/kg); *I(t)* is the hourly irradiance (kJ/m^2.h); A_b is the surface area of brine basin (m^2); W_b is the hourly consumed energy by the air blower (kWh). However, h_{fg} is the required heat to evaporate the water, and then, it depends on the salty water temperature T_w (°C) which can be calculated as **(Cengel and Boles, 2007)**:

$$h_{fg,water=}\ h_{g,water} - h_{f,water} = (2501.30 + 1.82T_w) - 4.196T_w \qquad (5)$$

$$h_{fg,water=} 2501.30 - 2.376T_w \qquad (6)$$

Exergy analysis

Exergy is a quantitative assessment that describes the quality of the energy based on the second law of thermodynamics involves the irreversibility that represents the maximum amount of useful work obtained from the solar still when it moves from a certain state to the equilibrium state with the surrounding. Exergy is a good parameter that describes, how the solar still reaches its ideal performance. The hourly exergy efficiency ($\eta_{EX,hourly}$) of the solar still (%) is the ratio between the hourly output exergy of the evaporated water ($\dot{E}_{x,evp}$) associated with the fresh water to the hourly exergy input ($\dot{E}_{x,in}$) as follows **(Petela, 2003)**:

$$\eta_{EX,hourly}=\frac{\dot{E}_{x,output}}{\dot{E}_{x,input}}=\frac{\dot{E}_{x,evp}}{\dot{E}_{x,in}}\times 100 \qquad (7)$$

The hourly output exergy of evaporated salty water ($\dot{E}_{x,output}$) can be estimated as **(Kianifar *et al.*,2012)**:

$$\dot{E}_{x,output}=\dot{E}_{x,evp}=\dot{m}_{ev}\,.\,h_{fg}\left(1-\frac{T_a}{T_w}\right) \qquad (8)$$

where T_a and T_w are the ambient and brine temperatures, respectively (°C).

The hourly exergy input to solar still ($\eta_{Ex,in}$) by irradiance($\eta_{Ex,sun}$)/and external device (*Wb*) can be calculated by **(Sharshir *et al.*, 2017)**:

For PSS1:

$$\dot{E}_{x,in}=\dot{E}_{x,sun}=A_b.I(t)\left[1-\frac{4}{3}\left(\frac{T_a+273}{T_s}\right)+\frac{1}{3}\left(\frac{T_a+273}{T_s}\right)^4\right] \qquad (9)$$

For PSS2:

$$\dot{E}_{x,in}=\dot{E}_{x,sun}+W_b \qquad (10)$$

where $I(t)$ is the hourly irradiance (kJ/m^2.h); T_s is the sun surface temperature (6000 K).

Accordingly, the daily exergy efficiency ($\eta_{EX,daily}$) can be estimated in (%) for PSS either with or without cooling cover as:

$$\eta_{EX,daily}=\frac{\Sigma\dot{E}_{x,output}}{\Sigma\dot{E}_{x,input}}=\frac{\Sigma\dot{E}_{x,evp}}{\Sigma\dot{E}_{x,in}}\times 100 \qquad (11)$$

Economic analysis

Generally, the main aim of the economic analysis is to predict the cost of producing 1 litre of freshwater by solar still in the entire of its lifetime. This analysis has a vital role in the approach of developing the solar still through enhancing the productivity alongside minimizing the cost. In the present study, the economic analysis was done to evaluate all relevant costs of the PSS throughout its lifetime taking into account the time value of money and utilizing the interest rate (*i*) as well as the required future costs (operation and maintenance costs) and considering the salvage cost. The economic analysis is mainly based on the total capital cost(P_s), as showed in Table (1).

Table 1. The capital costs(P_s) for PSS1 and PSS2

Component and dimensions	Material	Cost ($)	
		PSS1	**PSS2**
Container (1000 L×1000 W×170 Height mm) & trestles (600 mm H)	Wood	23	23
Brine basin (800 L× 800 W×70 Depth mm) - 2 mm thickness	Iron sheet	8.40	8.40
Black matt paint- 0.25 kg	Synthetic	1.00	1.00
Insulation- 50 mm Thickness	Glasswool	11.90	11.90
Covers- 3 mm Thickness/ 4 covers (total area 0.75m^2)	Flat glass	12.70	12.70
Plastic tank for brine - 30 L capacity	PVC	5.50	5.50
Hoses (1/4$^{//}$) and 1ball stainless steel valve for brine tank (3/4$^{//}$)	HDPE	3.00	3.00
Cooling system including 2 air stainless valves for cooling system (3/4ˋˋ	Steel&Copper	-	14.50
Assembly, transportation and installation wage	-	20	21
Total capital cost* ($)		85.50	101

* The whole calculations are based on the Egyptian local market prices in August 2017.

The First Annual Cost (*FAC*) or the fixed yearly cost ($/year) can be determined as **(Agrawal and Rana, 2019)**:

$$FAC = P_s \times CRF \qquad (12)$$

where *CRF* is the capital recovery factor and expressed as **(Yousef *et al.*, 2019)**:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (13)$$

where *i* is the interest rate, which is 9.25%; *n* is the lifetime of PSS and air-cooling system (assumed to be 10 years).

The annual maintenance and operating cost (*AMC*) supposed to be 15% of the *FAC* ($/year) as **(Esfahani *et al.*, 2011)**:

For PPS1:

$$\mathrm{AMC}_{PSS1} = 0.15 \times \ \mathrm{FAC} \qquad (14)$$

For the present case, Eq.12 was modified for PPS2 to include the annual maintenance and operating cost of cooling system to be 20% of the *FAC* ($/year) as:

$$\mathrm{AMC}_{PSS2} = 0.20 \times \ \mathrm{FAC} \qquad (15)$$

Moreover, the annual salvage cost (*ASC*) in ($/year) can be estimated as (**Abd Elbar and Hassan, 2019)**:

$$ASC = S \times SFF \qquad (16)$$

where the *S* is salvage value ($) assumed to be 20% of the *FAC* (0.20FAC); *SFF* is the sinking fund factor, which can be estimated as:

$$SFF = \frac{i}{(1+i)^n - 1} \qquad (17)$$

The total annual cost (TAC) of the PSS (\$/year) can be calculated as follows **(Kabeel *et al.*, 2010)**:

$$TAC = FAC + AMC - ASC \qquad (18)$$

Hence, the cost of producing 1 litre of freshwater (C_p) in \$/L/m^2 using the PSS can be estimated as (**Abd Elbar *et al.*, 2019):**

$$C_p = \frac{TAC}{M} \qquad (19)$$

where M is the average annual productivity of freshwater (L/m^2.year), assuming 340 sunny days for a typical year of experimental work (at location of Zagazig, Egypt 30.58°N, 31.50°E in the present study) as there are some cloudy days of year with lack of productivity.

The exergoeconomic analysis is a very important tool to investigate the cost efficacy of desalination process in function of output energy and exergy of solar still. The exergoeconomic parameter is the ratio of the annual output energy and exergy to the total annual cost of the solar still (*TAC*). The exergoeconomic parameter can be calculated as (**Yousef *et al.*, 2019)**:

$$R_{En} = \frac{(E_{en})_{out}}{TAC} \qquad (20)$$

$$R_{Ex} = \frac{(E_{ex})_{out}}{TAC} \qquad (21)$$

where R_{En}; R_{Ex} are the exergoeconomic parameter based on the energy and exergy, respectively; while $(E_{en})_{out}$ and $(E_{ex})_{out}$ are the annual output energy and exergy produced by the solar still, respectively wherein; $(E_{en})_{out}$ can be calculated as:

$$(E_{en})_{out} = \sum\left(\dot{m}_{ev}.\ h_{fg}\right) \qquad (22)$$

Environmental analysis

The average carbon dioxide equivalent intensity for electricity generation from coal is approximately 0.98 kg of CO$_2$ per kWh at source **(Sovacool, 2008)**. If the transmission and distribution losses for Egyptian conditions are taken as 40% and domestic appliances losses are around 20%, then the total CO$_2$ will be 1.58 **(Dwivedi and Tiwari, 2012)**. So, the total CO$_2$ emission (kg CO$_2$) and total CO$_2$ emission mitigation (kg CO$_2$) by solar still over its lifetime can be calculated using the following equations **(Kumar and Kurmaji, 2013)**:

$$\text{Total CO}_2\text{ emission over lifetime of solar still} = E_{in} \times 1.58 \qquad (23)$$

$$\text{Total CO}_2\text{ emission mitigation over lifetime of solar still} = E_{out} \times 1.58 \times n \qquad (24)$$

where n is the lifetime of solar still (years); E_{out} is the annual output energy (annual gained energy) from the solar still (kWh/m^2) and E_{in} is the embodied energy of solar still (kWh).

In the present case, the embodied energy is total energy consumed in manufacturing of the PPS1 and PSS2. E_{in} has been determined by multiplying mass of each component of PSS1 and PSS2 with their energy density **(Kumar and Tiwari, 2009)**; as showed in Table (2).

Table 2. The embodied energy for the components of PSS1 and PSS2

Component	Material	Mass (kg)	Energy Density (MJ/kg)	Embodied Energy	
				MJ	**kWh**
Container with trestles	Wood	31	45	1395	387.50
Brine basin	Iron sheet	13.60	35	476	132.22
Black matt paint (solvent based)	Synthetic	0.25	98.10	24.52	6.82
Insulation	Glasswool	2	14.60	29.2	8.12
Covers	Flat glass	15.70	15	235.5	65.42
brine tank	PVC	3	70	210	58.34
Hoses	HDPE	1.50	60	90	25
1ball valve for brine tank (3/4$^{//}$)	Stainless Steel	0.370	32	11.84	3.28
Total embodied energy (E_{in}) for PSS1				**2472.06**	**686.68**
Air cooling system: 1) Blower+ Electric motor+ cooling chamber	Iron	5	35	175	48.61
1) Coils for electric motor	Copper	2	70	140	38.88
2) Pipes & 2 air valves	Stainless steel	1	32	32	8.90
Total embodied energy (E_{in}) for PSS2				**2819.06**	**783.07**

The net CO_2 mitigation (*NCEM*) over the lifetime of solar still (tons) is estimated as **(Dwivedi and Tiwari, 2012)**:

$$NCEM = \frac{((E_{out} \times n) - E_{in}) \times 1.58}{1000} \qquad (25)$$

Currently, the cost of CO_2 traded is estimated at approximately 14.5 \$ per ton. The Earned Carbon Credit (ECC) is the price of mitigated amount of CO_2 (\$) by the solar still over its lifetime, which can be calculated as:

$$ECC = NCEM \times 14.5 \qquad (26)$$

Eventually, the Energy Payback Time (EPBT) is the required time (years) to recover the invested energy in the solar still, which can be estimated as **(Kumar and Kurmaji, 2013)**:

$$EPBT = \frac{E_{in} \times 3600}{(E_{EN,out})_{annual}} = \frac{E_{in} \times 3600}{M \times h_{fg}} \qquad (27)$$

where $(E_{EN,out})_{annual}$ is the annual output energy of solar still (kWh/year).

RESULTS AND DISCUSSION

Temperatures and productivity of PSS

The extended analyses of energy, exergy, economic and environmental (4E) for the previous work of Pyramid Solar Still (PSS) integrated with an air-cooled glass cover are mainly based on the experimental results of the thermal evaluation of this solar still presented by **(Tawfik, 2018)**. The present study is considered a good insight into the potential and efficacy of the integrated PSS with a novel air-cooled system for the glass cover compared to the same solar still without cooling the glass cover (natural cooling) regarding the energy conversion, economic feasibility and its contribution to CO_2 mitigation as an eco-friendly design of solar still. In the present case, the 4E analyses were done to compare two operation modes of PSS; the first one is PSS without cooled glass cover (PSS1) and PSS with air-cooled glass cover (PSS2) using brackish water (15000 ppm) and brine depth of 4cm. Regarding PSS2, results of the best cooling tactic of 20min On-10min Off and air velocity of 5 m/s over the glass cover in the mentioned previous work were taken into consideration in this study. Previously, the solar still was investigated for four consecutive days in September 2018 for each operating mode of PSS1 and PSS2. The obtained data of hourly ambient air (T_a), brine (T_w) temperatures, as well as irradiance (I), were averaged for the two modes and plotted as depicted in Fig.2.

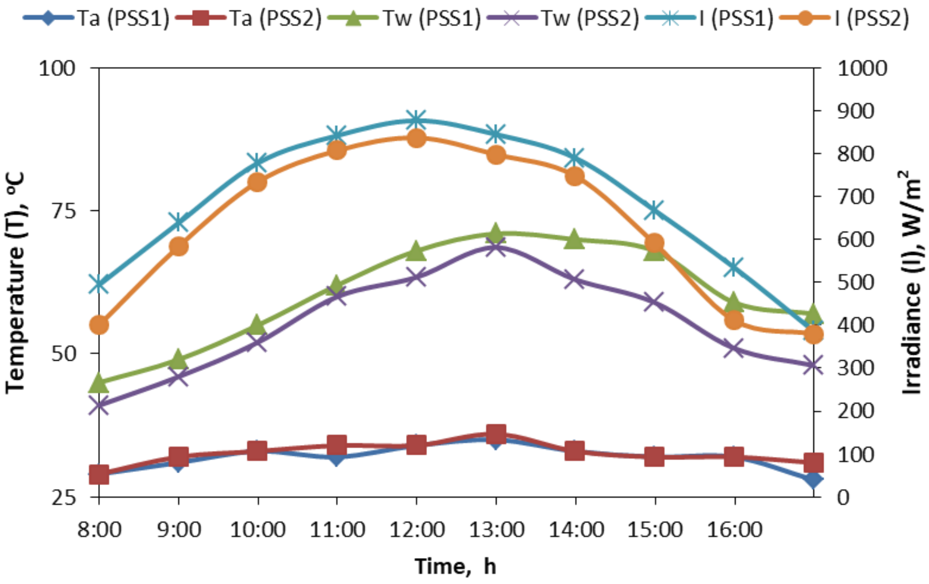

Fig.2. The average hourly temperatures of ambient (T_a) and brine (T_w) with corresponding irradiance (I) for the typical days of experiments.

Fig.2 shows the distribution of the average hourly temperatures of ambient and brine temperature as well as the irradiance with respect to the experiment time from 8:00 to 17:00 in the typical days for two operation modes; PSS1 and PSS2. The findings indicated the average of the brine and ambient temperatures were increased continuously from the experiment starting hour of typical days until its peak value of 71°C and 68.80°C at 13:00 h (afternoon) for PSS1 and PSS2, respectively while the same trend was observed for the irradiance values that reached its ultimate value of 845 W/m^2 and 798 W/m^2 at the noon hour (12:00 h) for both cases, respectively. Afterwards, the brine and ambient temperatures were decreased slowly until the end of the experimental day (17:00 h) to be 57-28°C and 48-31°C for PSS1 and PSS2, respectively in accompanied with explicit reduction in irradiance values. Despite the average value of ambient temperature for both operation modes is approximately the same (~32± 0.03°C), the brine temperature for PSS1 is relatively higher than PSS2 due to higher irradiance of the typical days of the experiments of PSS1 compared to PSS2. Hence, it is obvious that the heat retention inside the PSS has high relationship with the irradiance.

Fig.3 depicts the average hourly and daily productivity of fresh water for PSS1 and PSS2 with respect to the period time of the typical days of experiments. It was observed that the average hourly production has the same trend of brine temperature and ambient temperature. The obtained results show an explicit increase in average hourly production for PSS2 over PSS1. The maximum hourly productivity of fresh water was 0.782 and 0.606 kg/m^2.h at noon hour for PSS2 and PSS1, respectively, whereas the daily productivity of fresh water was 4.22 and 3.39 kg/m^2.day. Hence. the integrated air-cooling system with the PSS2 enhances the maximum hourly and daily productivity by about 22.50% and 19.77%, respectively over the PSS1.This due to the increase of condensation rate for the case of PSS2, because the potent impact of air-cooling stream over the glass cover which reduces the glass temperature, and consequently the temperature difference between the brine and inner surface of glass cover was reduced, especially during the highest glass temperatures period throughout the noon window.

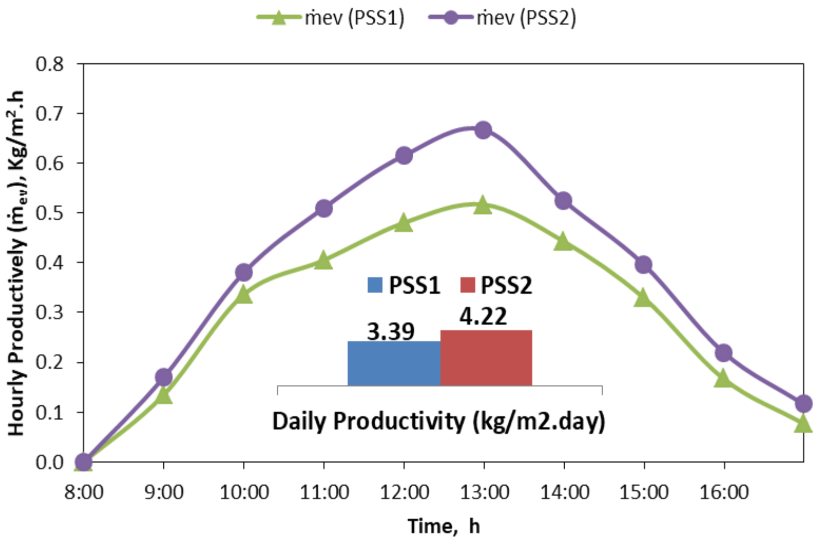

Fig.3. The average hourly and daily productivity of fresh water for PSS1 and PSS2.

Energy and exergy efficiencies of PSS

Fig.4 illustrates the distribution of hourly energy efficiency of PSS1 and PSS2 throughout the time of the experiment alongside the average daily energy efficiency for the two mentioned operation modes of PSS. It was observed that, as the time passes, the hourly energy efficiency of PSS1 and PSS2 increased apparently during the forenoon period until reaches its maximum value at the afternoon hour of 13:00 h with the advantage of rapid rate for the PSS2 compared to PSS1, thereafter the hourly energy efficiency declined to its minimum value at end hour of the experiment. As seen in Fig.4, there is an explicit enhancement in the hourly energy of PSS2 over the PSS1 during the entire period of the experiment. The data shows that the maximum values of hourly energy efficiency for PSS1 and PSS2 were 46.46% and 63.62%, respectively, whilst the values of daily energy efficiency were 26% and 32.40%, respectively. This can be attributed to the high condensation rate in PSS2 compared to PSS1 due to the cooled glass cover wherein; the highest gap between the two operation modes is obvious during the hottest hours of the experimental day (the noon window), although the measured irradiance in the experimental days of PSS2 is lower than of PSS1's days. Hence, the air-cooled glass cover proves an effective role in improving the maximum hourly and daily energy efficiency for PSS2 by 26.98% and 19.75%, respectively over PSS1.

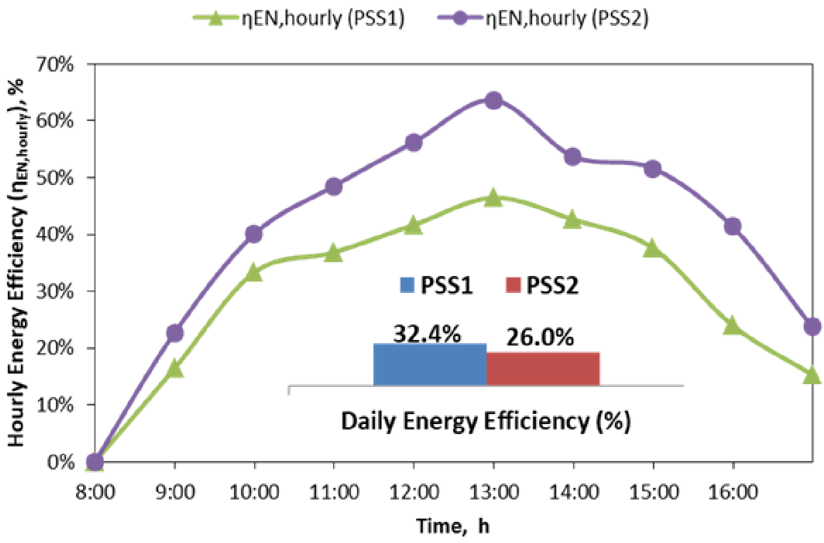

Fig.4. The average hourly and daily energy efficiency for PSS1 and PSS2.

Fig.5 shows the variation of hourly exergy efficiency of PSS1 and PSS2 with respect to time during the experimental days as well as the average value of daily exergy efficiency. It can be seen that the average value of hourly exergy efficiency continuously increases from the beginning of the experimental day until reaching its peak value at the afternoon hour of 13:00 h, afterwards the value declines at descending rate, which is the same trend of hourly energy efficiency. The obtained data declared that the maximum values of hourly exergy efficiency for PSS1 and PSS2 were determined as 23.75% and 4.64%, respectively, while the values of daily energy efficiency were estimated to be 15.40% and 10.70%, respectively. The exergy efficiency is based on the energy quality concept involving the irreversibility during the analysis of solar still instead of the energy conservation concept. Thus, the exergy analysis is a powerful tool to identify the causes, locations and magnitude of the system inefficiencies **(Sharshir *et al.*, 2017)**, and can provide a precise measurement of how the solar still approaches the ideal performance **(Dincer and Rosen, 2007)**. Accordingly, the reason which led to high values of hourly and exergy efficiency of PSS1 compared to PSS2, although the high condensation rate of the latter is may be referred to use of an oversize electric motor as a power source for the integrated air-cooling system with PSS2. Hence, the exergy efficiency of PSS2 can be improved by reducing the input power of the electric motor in future works for development such design of solar still.

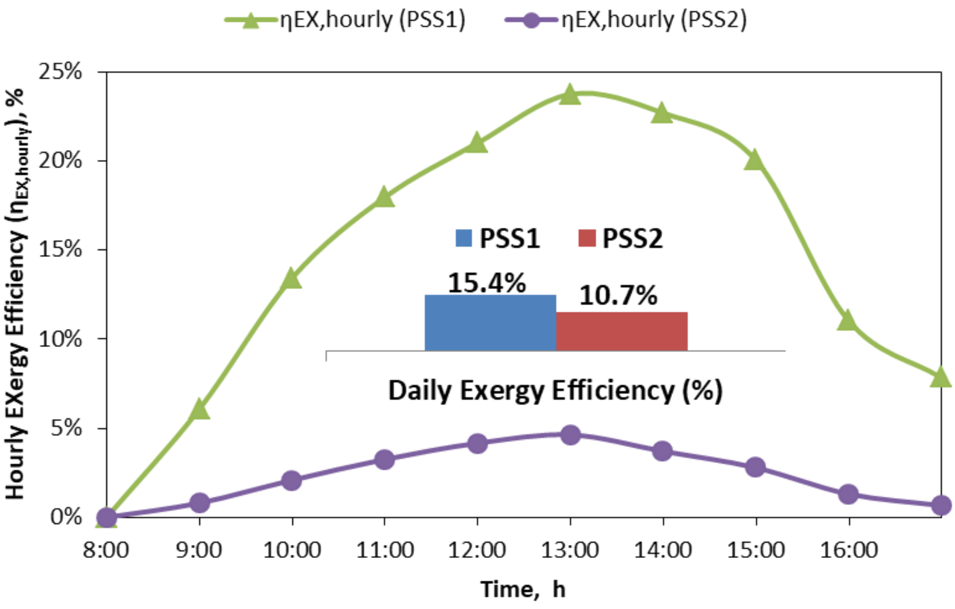

Fig.5. The average hourly and daily exergy efficiency for PSS1 and PSS2.

The economic analysis

Table (3) presents the results of cost analysis for PSS1 and PSS2 based on the reported capital costs for both operation modes of PSS as displayed in Table (1). Due to using the electric motor for cooling the glass cover in case of PSS2, the whole relevant costs including the capital cost, annual fixed cost and annual maintenance, and consequently, the total annual cost will be higher compared to costs of PSS1. Because the annual salvage cost and the high annual productivity of fresh water for the case of PSS2 is higher than PSS1, the cost of fresh water production is approximately equal for both operation modes of PSS1 and PSS2. As seen in Table (3), the annual production of fresh water and annual salvage costs were 1151.48 L/m^2.year and 0.175 \$/year for PSS1 and 1434.37 L/m^2.year and 0.207 \$/year, respectively. Hence, the air-cooling system enhances the annual productivity by about 19.72%. Accordingly, the cost of producing 1 litre of fresh water seems to be equal (~0.0133 \$/L/m^2) for PSS1 and PSS2.

Table 3. Cost analysis for PSS1 and PSS2

Item	PSS1	PSS2
P_s ($)	85.5	101
FAC ($/year)	13.45	15.91
AMC ($/year)	2.02	3.18
S ($)	2.69	3.18
ASC ($/year)	0.175	0.207
TAC ($/year)	15.31	18.89
M (L/m^2.year)	1151.48	1434.37
C_p ($/L/$m^2$)	0.0133	0.0132

Table (4) reports the determined values of the exergoeconomic parameters for PSS1 and PSS2 based on the energy and exergy of the desalting system. In general, the exergoeconomic parameter is mainly calculated as the amount of loss of exergy from thermal and energy systems divided by unit cost **(Yousef and Hassan, 2019)**. Furthermore, the exergoeconomic parameter based on the energy of the thermal system was calculated in the present case as the amount of loss of energy from the energy system of the solar still divided by the unit cost for the two operating modes; PSS1 and PSS2. In other words, the exergoeconomic parameters based on the energy and exergy of the system are the ratio of annual output energy and exergy to the annual cost of the solar desalting system, respectively. As seen in Table (4), the annual output energy and exergy of PSS2 were 944.30 and 386.64 kWh/m^2. year, respectively, which are higher than the annual output energy and exergy of PSS1 by about 20.13 and 7.96%, respectively. Furthermore, the exergoeconomic parameter of PSS2 based on the energy of 50 kW/$.$m^2$ is relatively higher than the parameter of PSS1 by about 1.52%, whilst exergoeconomic parameter of PSS2 based on the exergy of 20.47 kW/$.$m^2$, which is lower than PSS1 by about 11.92%. This means that the PSS2 has a lower cost for the exergy losses, and consequently using the air-cooling glass cover has potential feasibility.

Table 4. Values of exergoeconomic parameters for PSS1 and PSS2

Item	PSS1	PSS2
n (year)	10	10
i (%)	9.25	9.25
TAC ($/year)	15.31	18.89
E_{en} (kWh/m^2.year)	754.15	944.3
E_{ex} (kWh/m^2.year)	355.85	386.64
R_{En} (kWh/$.$m^2$)	49.24	50.00
R_{Ex} (kWh/$.$m^2$)	23.24	20.47

The environmental analysis

Results of the environmental analysis as well as the energy payback time for PSS1 and PSS2 are presented in Table (5). The environmental analysis is mainly based on the calculations of the energy consumed for manufacturing the different components of PSS1 and PSS2 that represented in the term of embodied energy as depicted in Table (2). It is expected that the embodied energy of PSS2 is higher than PSS1 due to the integrated air-cooling system. However, PSS2 achieved higher total CO_2 emission mitigation (1237.25 kg CO_2) and net CO_2 mitigation (8.312 tons CO_2) for 10 years of the lifetime of solar still by about 12.30% and 21.31%, respectively over PSS1. This can be attributed to the high annual gained energy by PSS2 compared to PSS1 because of the clear enhancement of the annual productivity. There is no doubt about the crucial role of the air-cooling process in this enhancement. To reveal the economic benefit of mitigating the CO_2 emissions through the lifetime of the solar still, the higher earned carbon credit of 120.53$ was achieved by PSS2 compared to PSS1

(94.85$) by about 21.30%. Table (5) depicts the payback period time for PSS1 and PSS2 with respect to the energy of solar still. The data showed that the energy payback time was 1.42 years and 1.295 years for PSS1 and PSS2, respectively. It is clear that the integrated air-cooling system with PSS2 shortens the required time to recover the invested energy by about 8.80% compared to PSS1 due to the high annual output energy of PSS2.

Table 5. Results of the environmental analysis and energy payback time for PSS1 and PSS2

Item	PSS1	PSS2
n (years)	10	10
Total E_{en} (kWh)	4826.6	6043.9
E_{in} (kWh)	686.68	783.07
Total CO_2 emission mitigation (kg)	1084.95	1237.25
Net CO_2 Mitigation, NCEM *(*tons)	6.54	8.312
Earned Carbon Credit , ECC ($)	94.85	120.53
Energy Payback Time, EPBT (years)	1.42	1.295

CONCLUSION

The present study aims to assess the performance of a Pyramid Solar Still (PSS) that was evaluated experimentally in a previous work under the local meteorological conditions of Zagazig, Egypt (30.58°N, 31.50°E) from the energetic, exergetic, economical and environmental (4E) aspects. The 4E analyses were carried out to investigate the influence of air-cooled glass cover of PSS on the efficacy of energy conversion, economic feasibility and mitigation of CO_2 compared to the same solar still without cooling (natural cooling) on basis of the experimental data of a previous work presented by **(Tawfik, 2018)**. The 4E analyses were mainly done for two operation modes; PSS without cooled-glass cover (PSS1) and PSS with air-cooled glass cover (PSS2) using air velocity of 5 m/s over the glass covers and cooling tactic of 20_{min} on -10_{min} off. The major results can be enlisted as:

- The maximum hourly productivity for PSS1 and PSS2 were 0.782 and 0.606 kg/m^2.h, respectively, while the daily productivity was 4.22 and 3.39 kg/m^2.day, respectively, although the irradiance in the experimental days of PSS2 is lower than those of PSS1.
- The maximum hourly energy efficiency for PSS1 and PSS2 were 46.46% and 63.62%, respectively, whilst the daily energy efficiency found to be 26% and 32.40%, respectively.
- The maximum hourly exergy efficiency for PSS1 and PSS2 were found to be 23.75% and 4.64%, respectively, while the daily energy efficiency was 15.40% and 10.70%, respectively.
- The annual production of fresh water was 1151.48 and 1434.37 L/m^2.year for PSS1 and PSS2, respectively, accordingly the cost per 1 litre of fresh water for PSS1 and PSS2 found to be approximately equal ~ 0.0133 $/L/$m^2$, although the annual capital cost of PSS2 is higher than PSS1 by about 18.95% due to the costs of the air cooling system.
- The exergoeconomic parameter based on the energy found to be 49.24 and 50 kW/$.$m^2$ for PSS1 and PSS2, respectively, whilst the exergoeconomic parameter based on the exergy were 23.24 and 20.47 kW/$.$m^2$, respectively. This means that PSS2 has the lower cost regarding the exergy losses.
- PSS2 mitigates the CO_2 emissions throughout its entire lifetime (10 years) by about 8.312 tons, correspondingly, PSS1 mitigates these emissions by about 6.54 tons.
- PSS2 achieved earned carbon credit of 120.53$ higher than PSS1 of 94.85$ and energy payback time of 1.295 years, where this period found to be 1.42 years for the case of PSS1.

In light of the above, using the integrated novel air-cooling system with PSS is very promised under the local climate of Egypt with the advantages compared to the PSS with natural cooled glass cover from the technical, economic and environmental aspects taken into consideration to reduce the capacity of power source of the cooling system in future works for better performance.

REFERENCES

Abd Allah, W.E. and Tawfik, M.A. (2019). Design and operating assessment of solar PV underground water pumping system in upper Egypt. Misr J. Ag. Eng., 36(2): 565-586. https://doi.org/10.21608/mjae.2019.94684.

Abd Elbar, A. R.; Yousef, M. S. and Hassan, H. (2019). Energy, exergy, exergoeconomic and enviroeconomic (4E) evaluation of a new integration of solar still with photovoltaic panel. J. Clean. Prod., 233:665-680. https://doi.org/10.1016/j.jclepro.2019.06.111.

Abd Elbar, A.R. and Hassan, H. (2019). An experimental work on the performance of solar still incorporating with wind turbine and thermal energy storage unit. Desalin. Water Treat., 165, 24–34. http://dx.doi.org/10.5004/dwt.2019.24492.

Agrawal, A. and Rana, R. S. (2019). Theoretical and experimental performance evaluation of single-slope single-basin solar still with multiple V-shaped floating wicks. Heliyon, 5(4): e01525. https://doi.org/10.1016/j.heliyon.2019.e01525.

Al-Garni, A. Z. (2012). Productivity enhancement of solar still using water heater and cooling fan. J. Solar Energy Eng., 134(3):031006. https://doi.org/10.1115/1.4005760.

Ayoub, G.M. and Malaeb L. (2012). Developments in solar still desalination systems: A critical review. Crit. Rev. Environ. Sci. Technol., 42(19): 2078–2112. https://doi.org/10.1080/10643389.2011.574104.

Cengel, Y.A. and Boles, M.A. (2007). Thermodynamics: an Engineering Approach 8th Editon (SIUnits), The McGraw-Hill Companies, Inc., New York.

Chafidz, A.; Al-Zahrani, S.; Al-Otaibi, M. N.; Hoong, C. F.; Lai, T. F. and Prabu, M, (2014). Portable and integrated solar-driven desalination system using membrane distillation for arid remote areas in Saudi Arabia, Desalination 345:36-49. https://doi.org/10.1016/j.desal.2014.04.017.

Chafidz, A.; Kerme, E. D.; Wazeer, I.; Khalid, Y.; Ajbar, A. and Al-Zahrani, S. M. (2016). Design and fabrication of a portable and hybrid solar-powered membrane distillation system, J. Clean. Prod., 133:631-647. https://doi.org/10.1016/j.jclepro.2016.05.127.

Dincer, I. and Rosen, M.A. (2007). Exergy, energy, environment and sustainable development, 2nd Ed., Elsevier, Amsterdam

Dwivedi; V.K. and Tiwari, G.N. (2012). Thermal modeling and carbon credit earned of a doubleslope passive solar still. Desalin. Water Treat., 13: 400–410. https://doi.org/10.5004/dwt.2010.856.

El-Sebaii, A. A. (2004). Effect of wind speed on active and passive solar stills. Energy Convers. Manage., 45(7-8): 1187-1204. https://doi.org/10.1016/j.enconman.2003.09.036.

Esfahani, J. A.; Rahbar, N., and Lavvaf, M. (2011). Utilization of thermoelectric cooling in a portable active solar still—an experimental study on winter days. Desalination, 269(1-3): 198-205. https://doi.org/10.1016/j.desal.2010.10.062.

Kabeel, A. E.; Dawood, M. M. K.; Ramzy, K.; Nabil, T.; Elnaghi, B. and Elkassar A. (2019). Enhancement of single solar still integrated with solar dishes: An experimental approach. Energy Convers. Manage., 196:165-174. https://doi.org/10.1016/j.enconman.2019.05.112.

Kabeel, A. E.; Hamed, A. M. and El-Agouz, S.A. (2010). Cost analysis of different solar still configurations. Energy 35 (7): 2901–2908. https://doi.org/10.1016/j.energy.2010.03.021.

Kalidasa Murugavel, K.; Chockalingam, K.K. and Srithar, K. (2008). Progresses in improving the effectiveness of the single basin passive solar still. Desalination, 220 (1-3):677–686. https://doi.org/10.1016/j.desal.2007.01.062.

Kianifar, A., Zeinali Heris, S. and Mahian, O. (2012). Exergy and economic analysis ofa pyramid-shaped solar water purification system: active and passive cases. Energy, 38: 31–36, https://dx.doi.org/10.1016/j.energy.2011.12.046.

Kumar, S. and Kurmaji, K. T. (2013). Carbon credit earned by some designs of solar stills. Desalin. Water Treat., 51: 4699-4708. https://doi.org/10.1080/19443994.2013.770269.

Kumar, S. and Tiwari, G.N. (2009). Life cycle cost analysis of single slope hybrid (PVT) active solar still. Appl. Energy, 86:1995–2004. https://doi.org/10.1016/j.apenergy.2009.03.005.

Kumar, S.; Kumar, A. and Yadav, A. (2018). Experimental investigation of a solar cooker based on evacuated tube collector with phase change thermal storage unit in Indian climatic conditions. Int. J. Renew. Energy Technol., 9(3): 310–336. https://doi.org/10.1504/IJRET.2018.093007.

Nayi, K. H. and Modi, K. V. (2018). Pyramid solar still: a comprehensive review. Renew. Sustain. Energy Rev., 81: 136-148. https://doi.org/10.1016/j.rser.2017.07.004.

Omara, Z.; Kabeel, A. and Younes, M. (2014). Enhancing the stepped solar still performance using internal and external reflectors. Energy Convers. Manage., 78:876 881. https://doi.org/10.1016/j.enconman.2013.07.092.

Petela, R. (2003). Exergy of undiluted thermal radiation. Sol. Energy, 74(6): 469-488. https://doi.org/10.1016/S0038-092X(03)00226-3.

Rahbar, N. and Esfahani, J. A. (2012). Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module. Desalination, 284: 55-61. https://doi.org/10.1016/j.desal.2011.08.036.

Rahbar, N.; Esfahani, J. A. and Asadi, A. (2016). An experimental investigation on productivity and performance of a new improved design portable asymmetrical solar still utilizing thermoelectric modules. Energy Convers. Manage., 118: 55-62. https://dx.doi.org/10.1016/j.enconman.2016.03.052.

Rubio, E.; Porta, M. A. and Fernández, J. L. (2000). Cavity geometry influence on mass flow rate for single and double slope solar stills. App. Therm. Eng., 20(12): 1105-1111. https://doi.org/10.1016/S1359-4311(99)00085-X.

Sharshir, S. W.; El-Samadony, M. O. A.; Peng, G.; Yang, N.; Essa, F. A.; Hamed, M.H. and Kabeel A.E. (2016). Performance enhancement of wick solar still using rejected water from humidification-dehumidification unit and film cooling. Appl. Therm. Eng., 108:1268–1278. https://doi.org/10.1016/j.applthermaleng.2016.07.179.

Sharshir, S. W.; Elsheikh, A. H.; Peng, G.; Yang, N.; El-Samadony, M. O. A. and Kabeel, A. E. (2017). Thermal performance and exergy analysis of solar stills–A review. Renew. Sustain. Energy Rev., 73: 521-544. https://doi.org/10.1016/j.rser.2017.01.156.

Sovacool, B. K. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy, 36(8): 2950-2963. https://doi.org/10.1016/j.enpol.2008.04.017.

Tawfik, M. A. (2012). Improving the performance of a pyramid-shaped solar still. Misr J. Ag. Eng., 29(4): 1239-1254. https://doi.org/10.21608/mjae.2012.100472.

Tawfik, M. A. (2018). Performance of a pyramid solar still using air-cooled glass cover: an experimental study. Misr J. Ag. Eng., 35(1):359-376. https://doi.org/10.21608/mjae.2018.96205.

United Nations (2019). Department of Economic and Social Affairs, Population Division. World Population Prospects 2019: Highlights (ST/ESA/SER.A/423), Last access 30/6/2019. https://www.un.org/development/desa/publications/world-population-prospects-2019-highlights.html.

Velmurugan, V. and Srithar, K. (2011). Performance analysis of solar stills based on various factors affecting the productivity-A review. Renew. Sustain. Energy Rev., 15 (2): 1294–1304. https://doi.org/10.1016/j.rser.2010.10.012.

Wassouf, P.; Peska, T.; Singh, R. and Akbarzadeh, A. (2011). Novel and low cost designs of portable solar stills. Desalination 276(1-3):294-302. https://doi.org/10.1016/j.desal.2011.03.069.

Xiao, G.; Wang, X.; Ni, M.; Wang, F.; Zhu, W.; Luo, Z. and Cen, K. (2013). A review on solar stills for brine desalination. Appl. Energy 103:642–652. https://doi.org/10.1016/j.apenergy.2012.10.029.

Yousef, M. S. and Hassan, H. (2019). Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system. Energy Convers. Manage., 179:349-361. https://doi.org/10.1016/j.enconman.2018.10.078.

Yousef, M.S.; Hassan, H. and Sekiguchi, H. (2019). Energy, exergy, economic and enviroeconomic (4E) analyses of solar distillation system using different absorbing materials. Appl. Therm. Eng., 150: 30–41. http://dx.doi.org/10.1016/j.applthermaleng.2019.01.005.