EXERGOECONOMIC AND ENERGY EFFICIENCY ANALYSIS OF CASCADE SOLAR STILL USING A SUN TRACKING

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This study presents theoretical and experimental exergoeconomic and thermal efficiency of weir-type cascade solar still using sun tracking. The results show that the average energy and exergy efficiencies in tracking and fixed systems reached about 36 % and 14 % , for fixed system 33 % and 11%, respectively. Measured data for the average production obtained as 4.8 kg / m^2 for the tracking system and 3.9 kg / m^2 for the fixed system. The cost of distilled water obtained for sun tracking and fixed tracking as 0.049 $ and 0.065 $ for 1 kg / m^2 / day.

Keywords: exergy analysis; solar still economic analysis; heat transfer; cascade solar still; sun tracking.

1. Introduction

Extended urbanization and population growth in the Middle East have been caused to the increase of fresh water and energy consumption in these regions. All the countries of the Middle East, average annual rainfall is lower than the global average. High temperature, lack of water resources, too much sun exposure, and besides, arid and anhydrous lands are the prominent features of these areas. Solar energy can be utilized as a hybrid system in thermal processes of desalination procedure and also directly applied in solar desalination plants. The average energy consumption of industrial desalinations to produce 1 m^3 of water from seawater is 3-10 kWh; very salty and hot brine of desalinations activities will be influenced in the coastal ecosystems and the neighbor environment seriously. Greenhouse gases are another effective hazard occurred by desalinations activities. According to the issues mentioned above, energy efficiency regulations with the least rate of environmental damages are prepared in European institutes.

Historically, the first and large solar distillation unit was designed by a Swedish engineer named Carlos Wilson in the late 19th century. Oladiran [1], considered that the total annual radiation received in optimized tilt angle for azimuth angles between 0° and 30°, in Nigeria. Khalifa and Al-Mutawalli [2]

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investigated the effect of the two-axis tracking system on compound parabolic concentrators (CPC); they reached an increase in concentered energy of up to 75% and compared with fixed CPC. Jafarkazemi [3] studied the effect of orientation and the amount of solar radiation on the optimum tilt angle of solar collectors and solar panels; solar radiation was calculated at different tilt angles ($-20 \leq \beta \leq 90$) and different orientations ($-90 \leq \gamma \leq 90$); the yearly optimum tilt angle ($\beta opt = 22°$) was almost close to Abu Dhabi latitude ($\varphi = 24.4°$), and the optimum orientation angle was in the south direction.

Petela [4] studied the existing formulae for calculation of the thermal radiation exergy; Petela discussed formulae for heat radiation exergy are those derived by Spanner and Jeter; based on this analysis some other researchers presented several available formulae for the estimation of such radiation exergy. Kianifar et al. [5], evaluated exergy and economic analysis of a pyramid-shaped solar water purification system; they reported that the exergy efficiency is higher when the water depth in the basin is lower, and the economic analysis shows a considerable reduction in production cost of the water (8–9%) when the active system is used. Tiwari et al. [6], presented an exergoeconomic and enviro-economic analysis for PVT-FPC active solar distillation system; the hourly thermal, exergy, electrical, overall exergy and overall thermal efficiency evaluated, and the results showed that thermal exergy is lower than electrical and overall exergy. Tyagi et al. [7] evaluated the exergy output, exergetic and thermal efficiencies in concentrating type solar collectors; they reported that for the low value of the solar intensity, the exergetic efficiency first increases and then decreases as the concentration ratio increased. Fujiwara [8] studied exergy analysis for the performance of solar collectors; by treating the friction process as exergy loss, the optimum operating conditions were considered. Various exergy efficiencies defined and output exergy efficiency used to determine the optimum flow rate of a typical collector allowing for the pressure drop in tubes.

The exergoeconomic evolution has been applied for the cost of the maximum amount of the available work or quality of energy which includes all methods dealing with the combination of exergetic and economics analysis by Abusoglu et al. [9]. Gaur and Tiwari [18] used exergy efficiency analysis to optimize hybrids flat-plats collectors that combined with conventional solar still; their study showed that mass flow rate (kg/s) had a greater impact than on the intensity of radiation in the exergy efficacy. Ibrahima et al.[21] an exergoeconomic optimization studied to evaluate the cost parameters in a solar distillation; by optimizing exergy destructions, they reported 45% improvement of the exergoeconomic cost of the freshwater (product).

The purpose of this study is the simultaneous exergetic and economic evaluation in a cascade solar still. Exergy analysis is called "availability" or "maximum available work" is used to optimize thermodynamic systems. This assessment could be used to optimize the design of cascade solar still with a sun tracker. Researchers always desire to get maximum solar energy for their systems. But the most solar system is designed as a fixed model without any sun tracker. This study would be of great help in finding an economic way to the use of a sun tracker in solar stills, especially in cascade solar stills.

2. Experimental setup

Solar distillations are classified into two types : single-effect and multi-effect, whereas single-effect type is classified into two categories : passive and active; a passive type is activated directly by the sunlight, while active type can usually include a preheating/coolant such as wind or heating/cooling absorption surface such as photovoltaic panels. In this study a weir type cascade solar still (WTCSS) and sun tracking system was designed and fabricated in Ilkhchi Branch, Islamic Azad University, and Tabriz, Iran [14] used to investigate the exergy and economic costs in the hourly sun tracking system. It seems that the system should be as an active system to be divided. The fabricated system is shown in Fig 1. This device connects to on vertical axis which can rotate on the axis of the East to West and vice versa. The path of rotation systems is shown in Fig 2. The Sun tracking system used in this study is included two axes. The first axis adjusts the tilt angle and second axis, azimuth angles. In this experiment, the second axis was rotated by electromotor. In cascade solar stills, the slope of stairs are usually designed based on the optimal annual slope. Rarely, can be used for monthly optimal slope. The optimal tilt angle on April, for Ilkhchi Branch, Islamic Azad University is 25 °. The optimal tilt angle was controlled manually and fixed by 34°. The average monthly and yearly optimum tilt angles are given in Fig 3. In this paper, solar radiation was measured in hourly azimuth angles with the tracking system and compared with the fixed azimuth angle and estimated the performance of WTCSS. Solar radiation measurements used on MIC-98206 Solar power meter that its accuracy was 0.1 W/m².

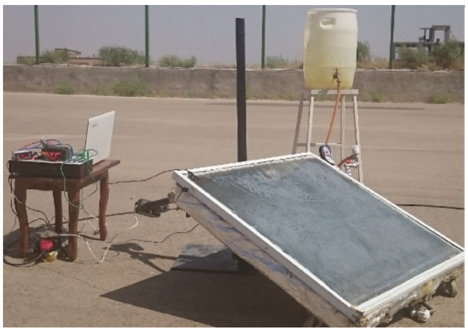

Fig. 1. Fabricated hourly sun tracking.

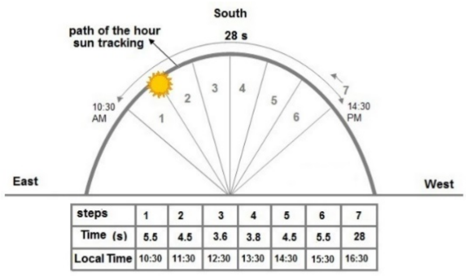

Fig. 2. Path of sun tracking.

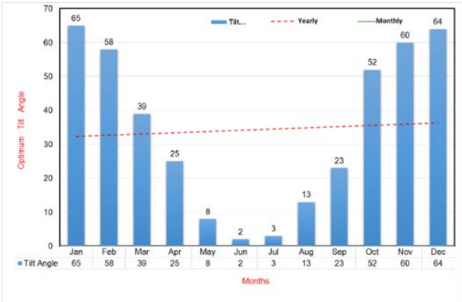

Fig .3. The optimal monthly and annual tilt angles.

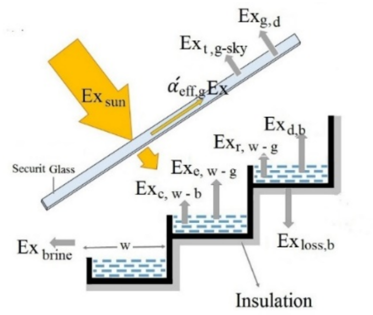

Fig .4. The exergy model of the system.

According to data from Tehran University Geophysics Institute on April 22 to 23, 2017 in Ilkhchi Branch, Islamic Azad University, Tabriz, Iran, the time of solar noon occurs at 13: 31 to 13:26 pm(12 pm central standard time), average humidity 35%, average wind speed 22 mph, in test location (37° 57′ 13.72″ N, 46° 5′ 59.9″ E). The duration of the experiment was 6 hours based on solar times. Three hours was calculated before solar noon and three hours after it. The time of the test of sun tracking started from 10:32 am to 4:32 pm. Hourly angles (h) rotated on the earth’s surface at 15° at 1 hour. Electric motors of the tracking system were controlled by the computer program and PLC for each hour. So the rotation domain axis of the system was adjusted 0° to 90° and the azimuth angle at the morning (10:32 pm) is γ= - 45°.

3. Exergy analysis

The exergy of a thermodynamic system is the maximum theoretical useful work available that can be done by the system when it brings the system into equilibrium undergoes reversible in balance with the environment. Exergy analysis has been recently used as a powerful method for design, simulation, and optimization in the thermodynamic systems. In simple and single effect systems, exergy is analyzed based on the second law of thermodynamic total exergy inflow-outflow. The exergy model of this system is shown in Fig 4. Irreversibility of the processes is considered with destruction and losses rates. Klein and Theilacker [25] presented a method (according to the KT model), this model used to the calculation the global and diffuse daily solar radiation on inclined. For general exergy balance in a single system or each part of a hybrid system can be written as:

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} = \sum \dot{Ex}_{des} + \sum \dot{Ex}_{loss} \quad (1)$$

For the exergy of solar radiation (Petela expression) can be written [11]:

$$EX_{sun} = I(t)A\left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_{sun}}\right)\right] \quad (2)$$

Where T_a is the temperature of the atmosphere, T_{sun} is the sun temperature (= 6000(K)), $I(t)$ is total radiation and A is the area of the device that is placed against radiation. This study $I(t)$ is an incident solar radiation. Xu et al. [12], reported that exergy efficiency increase with the increase in the Direct Normal Irradiance (DNI); its maximum values depend on the optimal slope. For example, Ozturk et al. [13], in a similar location where the solar radiation $\dot{I}$ varied in the range of 450-1100 W/m^2, used the mean of values as 773 in “Eq (2)” for $I(t)$.

Unconcentrated solar radiation exergy, Petela [31] reported that the exergy factor for exergy analysis of thermal radiation processes:

$$\psi = 1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 \quad (3)$$

Where T and T_0 are temperatures of the radiation reservoir and the environment, respectively. Similar results have been obtained by Landsberg, Press, Beretta, and Gyftopoulos. The exergy factor of the radiation emitted by a source of the geometric factor for unconcentrated solar radiation is [30]:

$$\psi = 1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\frac{1}{f}\left(\frac{T_0}{T}\right)^4 \quad (4)$$

Where $f \geq \frac{T_a^3}{T_{sun}^3}$, Eq. (4) is valid [31]. In spherical collector f = 1 (f is factor captures the geometrical relation between the radiation source and the solar collector). Eq. (4) reduces Carnot efficiency, Eq. (3) and Eq. (4) was as blackbody radiation (BBR) [19]. Exergy evaporation Ex_{ew} is defined as:

$$Ex_{ew} = h_{ew}A_w\left(T_w - T_g\right)\left(1 - \frac{T_a + 273}{T_w + 273}\right) \quad (5)$$

For the cascade solar still with tracking, full exergy expressed as:

$$\dot{E}x_{full} = \dot{m}_{sw}\dot{E}x_{sw} + \dot{E}x_{sun}[WTCSS] + \dot{E}x_{motor} \quad (6)$$

Where $\dot{E}x_{sw}$ is exergy saline water (J / kg) and according to Re[15] equal zero. In the case of this study is used fabricated model is active solar still, but instead of the pump is used from the electric motor jack force to rotation WTCSS.

Energy and Exergy Efficiency

The exergy efficiency of a solar distillation with sun tracking system is the rate of output exergy to input exergy and motor exergy that is equal total evaporation (productivity rate) heat transfer rate to the total power input including the sun exergy and tracking motor exergy. The instantaneous exergy is defined as [16]:

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = \frac{Ex_{ew}}{Ex_{sun} + Ex_{motor}} \quad (7)$$

To measure the energy efficiency of the system, evaporated water must be obtained; the effect of the sun tracking is on increasing its evaporation rate. The hourly yield of solar still may be estimated [15]:

$$\dot{m}_{e.w} = \frac{h_{ew} A_w (T_w - T_g) 3600}{h_{fg}} \quad (8)$$

Exergy efficiency associated with solar distillations has been compared with energy efficiency. The expression for the overall instantaneous exergy efficiency and energy efficiency can be written as:

$$\eta_{ex.i} = \frac{\dot{m}_t h_{fg} (1 - \frac{T_a}{T_w})}{\dot{E}x_{sun} + (\dot{E}x_{pump})} \quad (9)$$

$$\eta_d = \frac{\sum \dot{m}_{ew} \times h_{fg}}{\sum_{t=1}^{24} (A_g \times I_s(t)) + \dot{W}_{TE}} \quad (10)$$

Where A_g is an area of the glass cover, in conventional solar still glass area about is equal with basin area, but in WTCSS, the basin area isn't equal with glass cover. However, absorbed solar intensity depends on the per area of glass in per unit area of any solar stills. Hence in this model is better that is used glass area instead of the basin area. $\sum_{t=1}^{24} (A_g \times I_s(t))$, This term in during experiment started from morning to evening (tracking 10:30 am to 4:30 pm) but after evening through due to the reduction of the ambient temperature continued condenses presses. The exergy efficiency of active solar distillation obtained as:

$$\eta_{Ex.(active)} = \frac{\dot{m}_{ew} Ex_{ew}}{\sum \dot{E}x_{sun} + \dot{E}x_{pump}} \quad (11)$$

The daily exergy for non-tracking solar still is evaluated into account all evaporation exergy, destruction exergy and sun exergy, for hourly exergy, can be written as:

$$\eta_{hourly.exergy} = \frac{h_{e.w-g} \times A_b \times \left[(T_w - T_{gi}) - (T_a + 273) \times \ln \left(\frac{T_w + 273}{T_{gi} + 273} \right) \right]}{0.933 \times (A_g \times I_s(t))} \times 100 \quad (12)$$

Where, $I_s(t)$ is the solar intensity with non-tracking solar still.

4. Economic model

The purpose of economic analysis, it would be possible to estimate the cost of 1 kg of distilled water per one square meter of the solar collector (glass area of TWCSS but for other systems plate area). In addition to the capital cost of TWCSS, sun tracking system, amortization costs and current costs and other parameters such as sinking factor, should be considered [17]. The general economic balance equations can be given by:

$$cost\ input + cost\ generation - cost\ output = cost\ accumulation \quad (13)$$

For cost generation,

$$cost\ generation = captial\ cost\ of\ equipment + all\ other\ and\ maintenance\ costs \quad (14)$$

The capital recovery (CRF) and sinking fund (SFF) factors are given [22]:

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n} \quad (15)$$

$$SFF = \frac{i}{(1+i)^{n-1}} \quad (16)$$

In Europe, for electricity consumption in the household sector (2014), the average price is 0.206 dollar per 1 kWh [27]. In desalination applications, the cost of fresh water per liter can be calculated as:

$$CPL = \frac{AC}{M} \quad (17)$$

$$AC = FAC + AMC + ASV \quad (18)$$

Where M is the average annual yield of solar desalination system, that this system with sun tracking and fixed tracking assumed 730 kg / m^2 and 643 kg / m^{2,} respect FAC is fixed annual cost, AMC is annual maintenance operational cost of the system, ASV is annual salvage value. For sun tracking systems, the *levelized* cost of energy (LCOE) for EW tracking PV was about 0.2 $ / kWh. However, the energy needed for tracking and maintenance costs were disadvantages of EW and NS tracking relative to the non-tracking system. Table 1 shows the cost of fabricated TWCSS and amount of salvage value for different units of systems. In the large scales, feed water intake and the choice of distillation system affect significantly on the total cost of the pure water production. Table 2. presents the cost compression of different solar distillation systems such as passive, active, and hybrid for the cost of 1 kg distilled water. In a solar distillation, the main components of the annual average cost of distilled water are defined by Tiwari et al. [13] as:

$$C = \frac{10I\ (IA + MR + TI) + 1000(OC)}{A(Y_d + Y_c)} + C_s \quad (19)$$

Where, A is the solar still area (m^2), *c* is the cost of labor (\$.mean-h^{-1}), C is the cost of distilled water (\$.m^{-3}), C_S is the fixed and operating costs of salt water supply (\$.m^{-3}), *I* is the total capital investment (\$), O is the annual operating labor (mean-h), Y_c is the annual unit yield of distilled water (m^3/ m^2), and TI is the average annual taxes and insurance charges.

Table 1.

Cost of fabricated weir type cascade solar with sun tracking in the present study

unit	Cost of the unit ($)	salvage value
Cascade solar still's materials and fabrication	520 $	97 $
Sun tracking system (without measurements tools)	75 $	18 $
Power 220 V	16 $	-
Water tank	22 $	3 $
pipes	33 $	4 $
pipe fitting	35 $	-
Total cost	701 $	122 $

Table 2.

The cost compression of different solar distillation.

Type of solar still	Interest rate (%)	A P (kg /m^2)	CRF	FAC	SFF	ASV	AMC	CPL($/kg/m^2)
Cascade solar still (sun tracking)	12.51	6.3	0.180	108.85	0.045	5.18	16.32	0.06
Cascade solar still (fixed tracking)	12.51	5.7	0.180	84.3	0.045	4.51	12.61	0.048
Active solar still	12	6.9	0.177	27.2	0.057	1.71	3.83	0.042
Single slope solar still [24]	12	4.2	0.177	49	0.057	3.5	7.5	0.035
Active solar still (with PV) [18] (n=30)	12	4.4	0.045	202	0.025	13	30.1	0.18

5. Results and discussion

The average production of passive and active solar stills has been reported between 2 to 14 liters per square meter. For the analysis of WTCSS, saline water was used with 35 g / kg salt. Obtained Results-based and other data are for the city of Tabriz in North West Iran on April 22 and 23, 2017. Fig. 5, presents the measured data of the hourly solar radiation that is compared with a fixed sun tracking system and horizontal surface. In both experiments, the optimum tilt angle was adjusted based on yearly optimal tilt angle as 34 °. It is observed that the maximum values obtained at solar noon and the values of fixed sun tracking system during 8 am to 12 am and 2 pm to 7 pm are less than sun tracking system, but these values were about equal during solar noon for fixed azimuth and tracking systems. As can be found these results that values of the hourly solar radiations of the sun-tracking mode were about 5 to 12 % more than fixed tracking system and the values of horizontal surface about were 10 to 30 % less than tracking system in during the day. In the similar systems used sun tracking, these results are an agreement with presented results by and Sefa et al. [20]. For analysis errors, the measured date of solar radiation and calculated data has been evaluated by the relative percentage error (RPE):

$$PRE = \frac{H_{i.c} - H_{i.m}}{H_{i.m}} \times 100(\%) \quad (20)$$

RPE for solar radiation in the experiment for hourly sun tracking and fixed tracking were 3.5 and 2.9, respectively. The hourly productivity rate of TWCSS with tracking and fixed systems are reported in Fig 6. It is clear from Fig .6 that hourly productivity increases with the increase in solar intensity. The maximum productivity rate hourly approximately occurred between the times 1 pm to 3 pm. Total production of WTCSS with tracking and fixed systems reach to 4.8 kg / m^2 /day and 3.9 kg / m^2 /day, respectively. The same behavior has also been obtained from the analysis of active solar distillation by Kumar and Tiwari [16], and Tiwari et al. [15]. Similar results for cascade solar still has been reported by Tabrizi et al. [28], Velmurugan et al.[23], Zoori et al. [29], Kabeel et al. [22].

Received sun exergy (exergy input) on WTCSS with sun tricking and fixed systems are shown in Fig 7. Received sun exergy in WTCSS depend on solar radiation intensity, glass thickness, and direction of radiation propagation. It is found that the sun exergy of the tracking system is higher than the fixed tracking system. It has been observed from Fig. 7, that the received sun exergy increases with increasing solar radiation. Increasing solar radiation causes the evaporation rate increased. Therefore, the highest distilled water is expected from WTCSS. Values of the input exergy of the tracking system are about 4 to 10 % more than fixed TWCSS and 25 % more than the horizontal surface.

Fig. 8, shows the variation of hourly evaporation exergy for tracking and fixed systems that flow rates are is about 0.0003 kg /s. It is seen that the highest evaporation exergy occurred from 1pm to 3 pm (after solar noon). The maximum values for tracking and fixed systems reached to 36 W and 31 W, respectively. Evaporation process in TWCSS depends on flow rate and solar intensity. Low flow rate and high solar radiation due to evaporation exergy increased. The same behavior for WTCSS was reported by Zoori et al. [29]. The hourly overall instantaneous exergy and energy efficiencies of WTCSS are presented in Fig 9. It is seen that the values of energy and exergy efficiencies are about 3 to 14 % and for exergy 2 to 7 %, more than the fixed system. The hourly maximum values of energy and exergy efficiencies were 41 % and 16 % for the fixed system, 43 % and 18 % for tracking systems. The trend of increasing energy efficiency in the sun tracking system is much more than the exergy efficiency. The same behavior has also been reported in studies by Zoori et al. [29] and Tiwari et al. [15]. Fig. 10 compares the average cost of different types of solar distillation systems for 1 kg of fresh water. It is found that the minimum values belong to passive systems such as single slope and the maximum values belong hybrid systems that designed with PV. Similar results were reported by Kabeel et al. [22] and kianifar et al. [12].

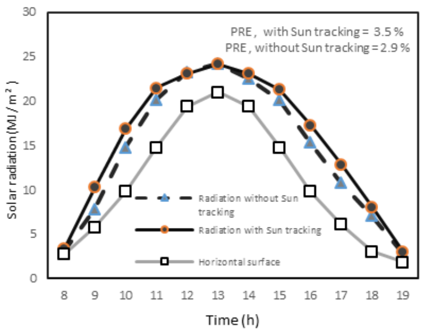

Fig. 5. Measured solar radiation on the system.

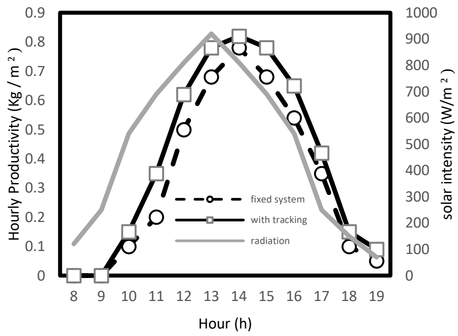

Fig.6. Measured hourly productivity rate.

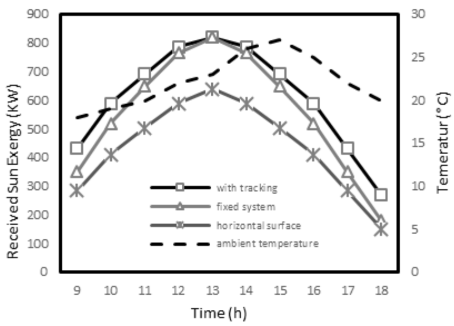

Fig. 7. Received sun exergy on WTCSS.

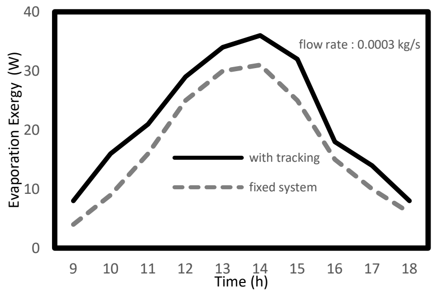

Fig. 8. Variation of hourly evaporation exergy.

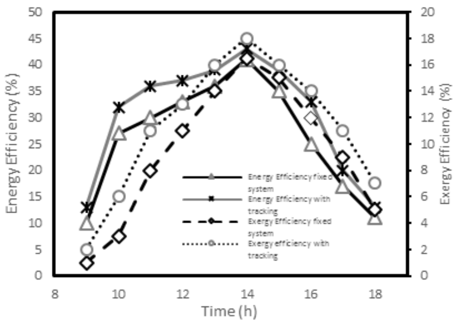

Fig. 9. hourly overall exergy and energy efficiencies

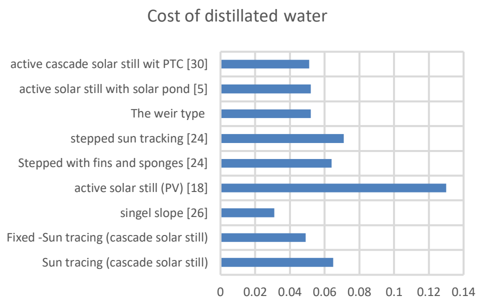

Fig. 10: cost of different types of solar distillation.

6. Conclusion

The development of solar distillation can be used to water shortages. Since the solid salt is collected, solar still has less environmental hazard. In economic terms, no expenditure is charged for solar energy usage. However, the composition and usage of innovative technologies can enhance the efficiency of solar energy. This study considers exergy and economics cost of an hourly sun tracking solar distillation system. The hourly sun tracking weir type cascade solar still system (WTCSS) that was studied in our present research includes cascade solar still with 2-axes (an axis for tilt angles, another axis for azimuth angles), mini PC (Lab-TAB), electromotor, solar meter, and other measuring tools. The system was fabricated and experimentally tested during two continuous days. The experimental investigation carried out just with hourly sun tracking and fixed sun tracking (with fixed optimal tilt angle) to analyze improved the efficiency of solar radiation on the WTCSS. The hourly productivity rates and solar radiation were measured in sun tracking and fixed systems. The control system was controlled by PLC and Lab-TAB based on meteorological and geographical data and the period each step motor's circulation given to it. The main conclusion which can be extracted from this investigation are as follows:

- The highest measured solar radiation for sun tracking and fixed systems were about 23.5 MJ / m^2, on 22 April.
- Total received sun exergies to the tracking system was about 190 W higher than the fixed tracking system.
- The experimental results showed the average hourly humidity rate with sun tracking system is about 7 % more than fixed tracking system (constant azimuth angle).
- The energy and exergy efficiencies for tracking and fixed (for six hours) systems were 37.5 % and 13.3 % and for fixed system 31.3 % and 10.1 %.
- Unit cost of distilled water for 1 kg / m^2 / day in the weir type cascade solar still using sun tracking and fixed system are around 0.065 $ and 0.049 $, respectively.

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