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2nd International Electronic Conference on Entropy and Its Applications
15-30 November 2015

www.sciforum.net/conference/ecea-2

Conference Proceedings Paper – Entropy

Thermodynamic and resource utilization efficiency analysis of a low thermal desalination system

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Published: 5 November 2015

Abstract: A near vacuum low thermal desalination system was studied which evaporates freshwater from saline water at very low grade temperatures. The low pressure is achieved naturally in the head space of water columns of a height equal to the local barometric head. This paper presents the energy, exergy and emergy analyses of this process to evaluate thermodynamic and resource utilization efficiencies and identify the process elements that cause major exergy destruction and that help maximize resource utilization (emergy). For energy and exergy analysis, three different heat sources were considered. They are namely direct solar (SSV), photovoltaic energy (SSPV) and a low grade thermal energy source (SSL) were considered. Exergy analysis showed that most of exergy is destroyed in the condenser where the latent heat of the water vapor to produce freshwater is lost to the environment. The overall exergy efficiencies were 0.04%, 0.051%, and 0.78% respectively for SSV, SSP, and SSL configurations. Emergy analysis was performed on the three different configurations to assess resource utilization efficiencies, environmental impacts, and sustainability. The emergy analysis considered five factors such as renewable and non-renewable energy input to the desalination process, process benefits to consumers, and capital and operating costs of different configurations. The emergy indices derived in this study indicated that the configuration utilizing thermal energy from low grade thermal energy source (such as a solar water heater) was found to be the most promising sustainable technology. Findings from this analysis suggest that more efforts should be dedicated to the configuration powered by low grade solar thermal energy source via a water heater and further refining the process components to function under multiple effects.

Keywords: solar energy; exergy; emergy; desalination; resource utilization; (3-10 keywords separated by semi colons)

1. Introduction

Desalination processes are energy-intensive [1]. Thermal energy is essential for processes such as multi stage flash distillation – MSF, multi effect distillation – MED and mechanical vapor compression – MVC while electrical energy in the form of mechanical energy (pressure) is required for pressure-driven membrane processes. Although, specific energy requirements for freshwater production in desalination processes have been lowered significantly over the past two decades, the overall energy demands are still high to meet the current freshwater needs at global levels whereas the demands for freshwater supplies continue to escalate with population growth and industrialization [2,3].

Abundant solar energy source is available in most of the water scarce regions providing opportunities for solar energy utilization in desalination processes. Solar still (SS), the most basic desalination process, makes use of the direct incident solar energy. However, SS is very inefficient in utilizing the solar energy due to accommodation of evaporating and condensing surfaces in a single glass roofed vessel. As a result, several modifications to the SS design have been studied to increase its energy efficiency and product yield in single and multi-effect stills. One of the configurations resulted in high distillate yields by separating the evaporation and condensing chambers. Energy efficiency of the SS can be further improved if they can be operated at lower temperatures in the 40–55°C as compared to the common range of 60–75°C [4,5].

A novel low thermal desalination process was studied to reduce the heat losses from the evaporation chamber there by increasing the freshwater yield. This process operates under very low operating pressures (near-vacuum conditions) created by exploiting natural principles of gravity and barometric head as further explained in the next section. Results of a proof-of-concept study of this process configuration and the first law analysis of the process were reported in our previous publications [6–10].

The goal of this study is to evaluate the sources of inefficiency in the process to identify operational parameters to maximize thermodynamic performance of this process and to evaluate emergy (resource utilization) performance. This evaluation is done through exergy analysis of the major components in the process. Exergy and emergy analysis of low temperature desalination process utilizing direct solar energy, photovoltaic energy and a low-grade heat source are presented.

2. Description of the Process and Methods

A schematic arrangement of the desalination system based on the principle of gravity and barometric head is shown in Figure 1(a). The desalination system includes an evaporation chamber (EC), a condenser (CON), a heat exchanger (HE), and three 33-ft tall water columns. Once in operation, these columns are filled with saline water; brine; and freshwater, each with its own constant-level holding tank. These holding tanks are positioned at the ground level while the EC and condenser are placed at the top of the columns. A Torricelli's vacuum is created in the headspace by displacing the water content in the columns. The top of the EC is exposed to sunlight in a configuration where direct solar energy is utilized for evaporation as shown in Figure 1a. The condenser, which is connected to the freshwater column operates at ambient temperatures. The heat supply increases the temperature of the saline water in the EC by about 15–20 °C above the ambient temperature which causes the freshwater to evaporate in the form of water vapor to be condensed in the condenser and flow into the freshwater column. More details on the principles of operation can be found in our previous publications [6,8]. Figure 1b shows the process schematic for a configuration utilizing low-grade heat source such as thermal energy from solar collectors, Photovoltaic modules or process waste heat.

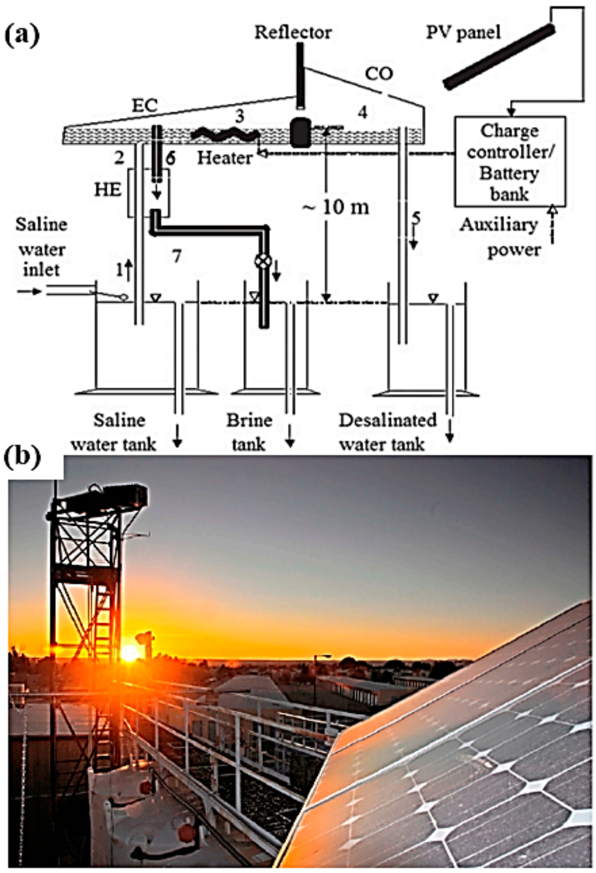

Figure 1. (**a**) Schematic of the proposed desalination process; (**b**) Photo of the experimental unit.

Energy, exergy and emergy analysis for three different configurations utilizing direct solar energy, photovoltaic electrical energy and a low grade heat source (water heater) were performed. Details regarding energy and exergy analyzes are presented elsewhere [7]. The following section discusses the experimental results and findings and a comparison among the three configurations.

3. Results and Analysis

Freshwater yields for the different configurations are shown in Figure 2a. Solar still with natural vacuum pressures (SSV) produces about 5 l d^{-1} m^{-2} of distillate, which is about twice the productivity of a conventional SS [4,5]. This indicates the efficient energy utilization by the SSV configuration. In

SSV, freshwater can evaporate at much lower temperatures due to the low pressure conditions thus reducing energy losses and offering higher energy efficiency. When a reflector was included to enhance the solar energy thermal effect, SSR produced about 7.5–8 l d^{-1} m^{-2} of distillate, which is three times the productivity of a conventional solar still. As the solar insolation incident on the SS was intensified by the reflector, the saline water temperature increased at a faster rate and contributed to higher evaporation rates. The low thermal desalination process powered by direct solar and photovoltaic energy SSP produced over 12 l d^{-1} when fitted with a reflector. Photovoltaic area required for this scheme was 6 m^2. Photovoltaic energy generated during the day is sufficient to produce freshwater of 4–5 l d^{-1} during the night time. The efficiency of the PV modules is 14%. Figure 2b shows the specific energy requirements for freshwater production through these configurations. The process can be designed to produce freshwater continuously with a backup thermal energy source such as a thermal energy storage tank when solar energy is not available [9,10].

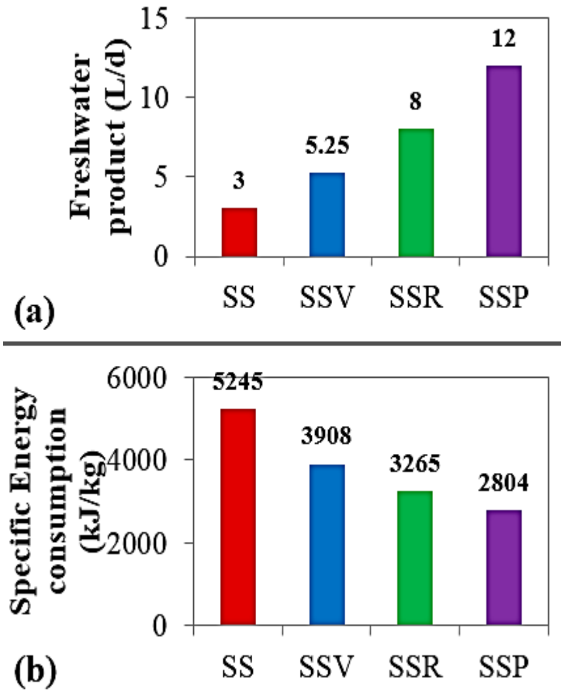

Figure 2. (a) Freshwater production and (b) specific energy consumption for SS, SSV, SSR, SSP configurations

3.1. Energy Analysis of Low Thermal Desalination System

Figure 3a shows the solar energy utilization patterns of the low temperature desalination process for the SSV, SSR, SSP and SSPV configurations. The entire solar energy incident on the EC is not used for evaporation. Incident solar energy passes through the glass top (some reflected back) and is absorbed by the saline water (about 89%). Total solar energy, energy available after optical losses, energy utilized for freshwater production and the useful latent heat in the product are shown for each of the configurations. For the SSV experimental set, the total amount of solar energy available was 21.6 MJ which is equal to 6 kWh m^{-2} d^{-1}. About 19.2 MJ (89%) of the total solar energy was available for conversion into thermal energy after optical losses. Out of this available solar energy, 12.1 MJ

(63%) was utilized for evaporation of freshwater of 5.25 l from saline water after the heat losses from the evaporation chamber and condenser to the surroundings (Figure 3a). Traditional solar stills typically have energy efficiencies around 30% which may be increased up to 45% [4,5]. Conventional solar still operating at an efficiency of 45%, will require 5040 kJ/kg of thermal energy to produce freshwater while the proposed SSV scheme has a specific energy consumption of 3900 kJ kg^{-1} of freshwater due to higher energy efficiency (Figure 2b).

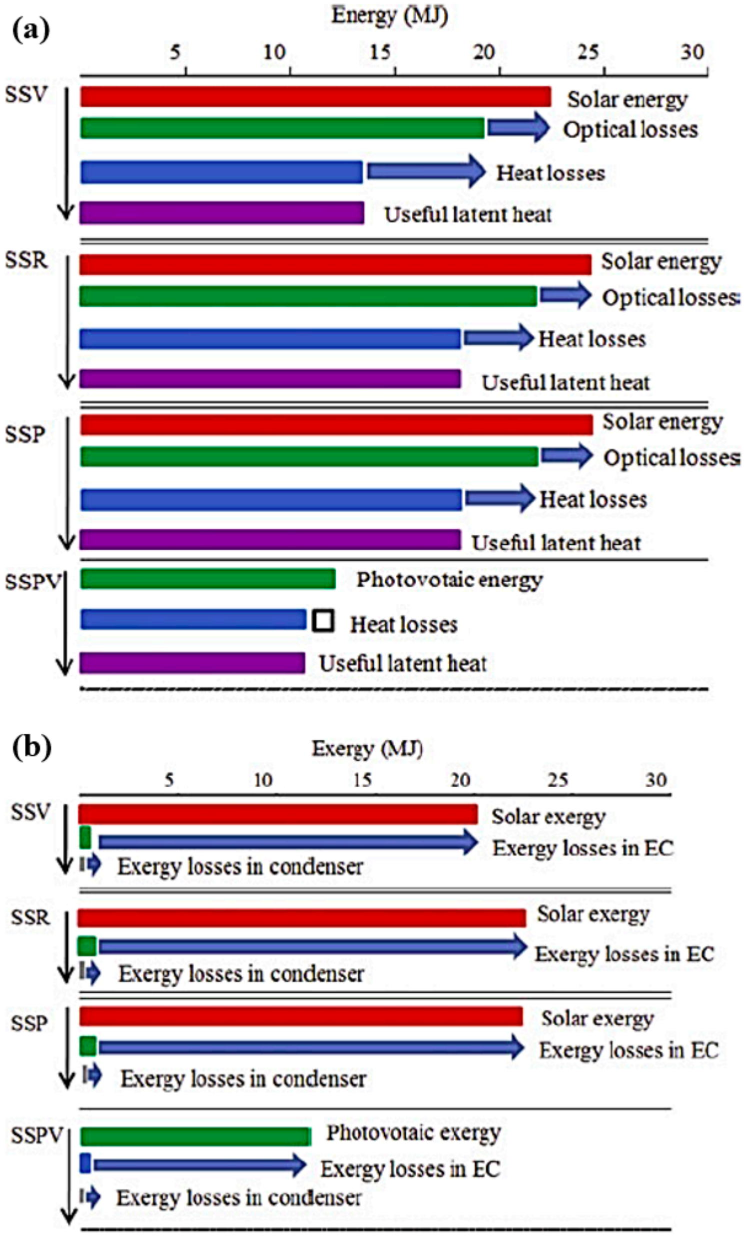

Figure 3 Energy analysis (a) and exergy analysis (b) of the low temperature desalination system using direct solar and photovoltaic energy.

Incident solar energy available for SSR experimental set was 24.1 MJ (6.7 kWh m^{-2} d^{-1}). About 21.4 MJ of solar energy has passed through the glass cover and the saline water body to cause evaporation. Out of this available energy, 17.3 MJ was utilized to produce freshwater. Thermal efficiency of SSR was between 70% and 80% with an energy requirement of 3200 kJ kg^{-1}. The energy demand for the photovoltaic energy powered scheme (SSP) is between 2800 and 3000 kJ kg^{-1} and energy efficiencies were between 80% and 90%. In conventional SS and SSV configurations, major energy losses occur through the glass cover during sunlight hours. However, for SSPV (SSP during non-sunlight hours), the glass cover can be covered with insulation during non-sunlight hours to reduce energy losses to the ambient. In addition, a higher thermal gradient is available during non-sunlight hours due to lower ambient temperatures which will enhance transfer and condensation of freshwater vapors from the evaporation chamber to the condenser side.

3.2. Exergy Analysis of Solar Powered Desalination System

The solar exergy utilization patterns of the low temperature desalination process for SSV, SSR, SSPV configurations are shown in Figure 3b. Total available solar exergy available after optical losses, exergy utilized (exergy losses in the evaporation chamber) for freshwater production and the exergy losses in the condenser (due to latent heat dissipation) and exergy available in the product are shown for each of the configurations. In a few studies, the solar exergy value is taken same as the energy value, given that the temperature of the sun is very high in relation to the ambient temperature. In this study we used the Petela equation to account for actual solar exergy value. Available solar exergy for SSV configuration was 20.1 MJ. Although, some portion of this exergy was utilized to evaporate freshwater, the exergy losses in the evaporation chamber were 19.2 MJ. The exergy available in the latent heat of the freshwater vapor was 0.9 MJ. Finally, exergy available in the condensed water vapor (freshwater) was only 0.008 MJ. Thus, exergy efficiency of the SSV process configuration was around 0.04% (using Eq. (10)). If the exergy associated with the water vapor is considered, the exergy efficiency of the SSV process configuration was 4.6% indicating the efficiency of the evaporation chamber (using Eq. (9)). For SSR configuration, the solar exergy was 22.5 MJ. The exergy losses in the evaporation chamber were 20.9 MJ. The exergy available in the latent heat of the freshwater vapor was 1.6 MJ. Finally, exergy available in the condensed water vapor (freshwater) was only 0.012 MJ. Thus, exergy efficiency of the SSR process configuration was around 0.05% (using Eq. (10)). Since, this is a single stage configuration, if the exergy associated with the water vapor is considered, the exergy efficiency of the SSR process configuration was 7.0% which is the efficiency of the evaporation chamber (using Eq. (9)).

Although, energy efficiency of the photovoltaic powered process was higher (90%) than other configurations, the exergy efficiency was lower than other configurations (0.039%, using Eq. (10)). This is due to high exergy value (=1) of electrical energy generated by the photovoltaic modules. Therefore, it is clear that high quality form of energy is not appropriate for desalination processes due to enormous quantities of exergy destruction in the condenser. However, the exergy efficiency can be slightly improved in a multi-effect configuration. A recent study incorporated solar collectors to provide heat source to the flash chamber at low pressures. The reported first law efficiency was 19%. Exergy efficiency of the system varied between 15% and 26% when the solar radiation ranged from 400 to 900 W m^{-2} considering energy harvested in the solar collectors. Freshwater production rate of 8.5 l d^{-1} was obtained with a solar collector area of 2 m^2. Although the operating principle was very similar to this process (vacuum created by a pump and varied between 0.05–1 bar), the solar energy was harvested by the circulating fluid in the solar collector as such the solar exergy was supplied to the inlet saline water (circulating fluid inlet and outlet temperatures were 20°C and 80°C respectively) with exergy recovery from the condenser whereas in the proposed process the solar exergy was directly utilized in the evaporation chamber for evaporation of freshwater from the saline water at around 50°C with no energy recovery from the condenser. Higher exergy efficiencies were reported in other studies due to energy recovery between the stages. If exergy losses can be recovered from the condenser, the exergy performance of the proposed process can be improved significantly.

3.3. Exergy Analysis of Desalination using Low Grade Heat Source

When a low grade heat source was utilized to run the low temperature desalination process, freshwater production rate of 0.250 kg h^{-1} was obtained. The withdrawal rate was fixed at 0.250 kg h^{-1}, while the heat source temperature was 60°C. The amount of concentrated saline water removed from evaporation chamber to maintain the salt concentration is defined as withdrawal rate (details shown in [7]). The heat source in the heat exchanger entered at 60.1°C and exited at 50.3°C at a flow rate of 19 kg h^{-1}. Thermal energy efficiency of the evaporation chamber was around 75%. The main process components are the heat exchanger # 1, evaporation chamber and condenser. Exergy destruction (loss %), irreversibility and second law efficiencies were analyzed for the process components. The results show that heat exchanger #1 operates at close to 20% exergy efficiency even though its energy efficiency was around 80%. However, it was noted that the amount of exergy loss is very small when compared to the exergy losses in the evaporation chamber and condenser. The exergy loss in the evaporation chamber is 40.61% (29.39 kJ h^{-1}) and the exergy loss in the condenser is 98.69% (42.43 kJ h^{-1}). From this analysis, it can be concluded that the highest quantity of exergy loss occurs in the condenser in the form of latent heat dissipation from the water vapor to the environment. Overall exergy efficiency of the process is 0.78% (using Eq. (10)) which is higher than the process configurations utilizing direct solar and photovoltaic energy.

3.4. Emergy Analysis of Solar Powered Desalination System

Emergy represents the amount of energy utilized in manufacturing a product. It is therefore the amount of work done or energy consumed in the past to deliver a product [11]. There are several types of emergy expressed in terms of various natural resources such as solar emergy, coal emergy, and geothermal emergy and others. Emergy is universally expressed in terms of solar emergy. Similar to exergy, emergy is also measured at a reference level. Degraded energy which does not have the capacity to produce work (available energy) is not considered emergy. Expressing all the forms of available energy in terms of solar emergy (solar equivalent joules, (sej)) would be beneficial in assessing the real benefits produced by certain work and to develop policies that improve sustainability and to complement life cycle assessment. Emergy also serves as a useful to evaluate the impact of a product on the ecological systems [12–15].

Emergy performance can be expressed in different forms of indicators namely emergy investment ratio (EIR), emergy yield ratio (EYR), % of renewable emergy (% R), emergy benefits to the purchaser (EBP) and emergy dollar per volume (Em $/ m^3) are used to evaluate the sustainability of a system [12,13]. The following definitions would be useful to perform emergy analysis on the desalination system under study.

EIR is defined as the quantities of inputs (investment) and services (benefits) to the quantity of renewable (R) and non-renewable resources (N). It could be referred to as the potential impact of a product to the ecological system. The lower is the EIR, the more sustainable will be the product or a system. In this case the product refers to freshwater and the system is low thermal desalination unit.

EYR is defined as the ratio of emergy yield of the freshwater through desalination system to the resources (P) and labor (S) that have been invested into its production. It is an indicator for embedding the local resources into a product. The higher is the EYR, the more sustainable is the product and the more profitable to local community or economy. If the EYR ratio is one, then the product is said to not have a positive impact on the local eco-system or in other words, it did not provide additional emergy benefits to the society.

Percentage of renewable emergy (% R) is the ratio of renewable emergy used to the emergy yield of the product or service. The sustainability of a system is directly proportional to percentage of renewable emergy ratio.

Emergy benefit to the purchaser is the emergy that is benefitted by the purchaser for the cost paid to purchase a product. In this case, the emergy delivered in the form of freshwater to the purchaser will be the measure of EBP. It is desirable to have higher values of EBP.

Em-dollars per unit volume is the ratio of solar emergy yield of the investment in the form of materials and labor to the freshwater produced and Em dollar ratio. This index gives us the cost of producing the water. If the Em-dollars per unit volume of product is lower, the more profitable is the process. Generally, the Em \$ per m^3 is higher than the \$ per m^3, because the monetary values included for the work done by the nature for a particular process.

Transformity is a measure of the emergy per unit of available energy of another kind (in this case solar emergy) and it is an indicator of process efficiency. Higher transformity means the process is highly efficient.

Low temperature desalination process configurations powered by direct solar energy (SSV), low grade heat source (solar water heater, SSL) and PV modules (SSPV) were compared in terms of emergy performance (Figure 4). An illustration of the emergy evaluation for SSPV configuration is shown in Table 1.

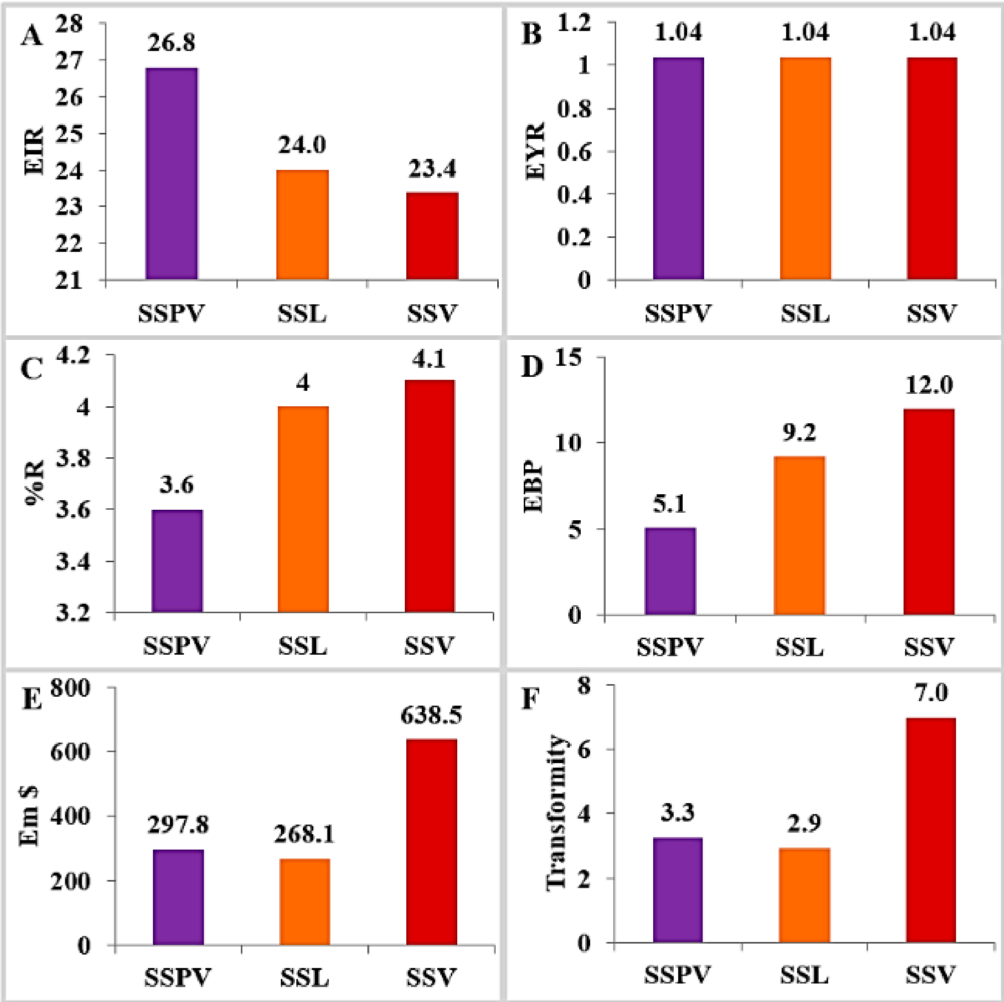

Figure 4 Emergy indices for SSV, SSL, SSPV configurations

Illustration

Table 1. Emergy evaluation of SSPV configuration

	Energy Data Unit/Yr	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Em/m^3
Renewable Resources				
1 Saline Water, J	3.98E+06	3.19E+04	1.25E+11	2.9E+10
2 Sunlight, J	2.52E+13	1	2.52E+13	5.76E+12
3 Constructional & Operational Costs, $	74.46	5.40E+11	4.02E+13	9.18E+12
4 Work to carry Sea Water to Distiller, J	2.05E+07	6.76E+06	1.38E+14	3.16E+13
5 Stainless Steel, kg	100	1.80E+12	1.80E+14	4.11E+13
6 Aluminum, kg	6.67	1.25E+10	8.33E+10	1.90E+10
7 Glass, kg	1.47	8.40E+08	1.23E+09	2.81E+08

8 Concrete Cement, kg	180.00	1.23E+12	2.21E+14	5.05E+13
9 PVC, g	16964.60	5.85E+09	9.92E+13	2.27E+13
10 Other Purchased Assets, $	133.33	5.40E+11	7.20E+13	1.64E+13
11 Land Lease, $	50	5.40E+11	2.70E+13	6.16E+12
Emergy Per Unit of Distilled Water				
12 Potable Water, m^3	4.38	1.61E+14	7.04E+14	1.61E+14
13 Potable Water, J	2.16E+07	3.26E+07	7.04E+14	1.61E+14
14 Potable Water, g	4380000	1.61E+08	7.04E+14	1.61E+14
15 Potable Water W/o Services, J	2.16E+07	1.97E+07	4.27E+14	9.75E+13

Emergy Indices and Ratios for SSPV		
	Expressions	Quantity
16 Emergy investment ratio	(P+S)/(N+R)	26.78
17 Emergy yield ratio	Y/(P+S)	1.04
18 % Renewable emergy	100(R/Y)	3.60
19 Emergy benefit to purchaser	Em $/$	5.06
20 Em-$ value of water	Em $/m^3$	297.84
21 Transformity of water	sej/J	3.3E+07
22 Emergy per m^3 of potable water	sej/m^3	1.6E+14

Among the three configurations, the EIR values for the SSPV are higher than those for the other configurations. This indicates that the SSV configuration is the most sustainable when compared to SSL and SSPV. It can be noted that the EYR values for all the configurations are slightly higher than 1 which indicates that more emergy is contributed to the society or economy. The % R index shows that the SSV configuration consumes high renewable energy sources compared to the others. Higher EBP values also indicate that the product is more beneficial to the consumer, *i.e.*, more emergy is received by the consumer for the amount of money paid or invested. The emergy dollars per unit product of freshwater is higher for the SSV configuration due to lower process efficiency and yields. Finally the transformity ratio of the SSV configuration is also higher than other configurations. The lower is the transformity ($\times10^7$) value, the higher will be the process efficiency in resource utilization. The SSL configuration seems to have higher transformity due to the use of low grade heat source and higher thermodynamic efficiency from the source to the product. Considering the above metrics from Figure 4, it can be concluded that the SSL configuration is more sustainable process with acceptable EBP, Em $ and transformity values compared to SSPV and SSV configurations. While external resource utilization is lower for SSV configuration, its productivity (product yield) and transformity (resource utilization efficiency) are lower than other configurations, while the SSPV configuration involves EIR and lower % R values due to their manufacturing process. The above results suggest that further improvements in SSL configuration will enhance the emergy efficiency of the proposed solar powered low temperature desalination system.

4. Conclusions

Energy, exergy and emergy performance analysis of a low temperature desalination process utilizing direct solar energy, photovoltaic energy and low grade heat source was presented. It was observed that the overall exergy efficiency of the desalination process was very low. For the single stage operation of the low temperature desalination process, the overall exergy efficiencies were 0.04%, 0.051%, and 0.039% respectively for SSV, SSR, and SSP configurations. For the system utilizing low grade heat source, the exergy efficiencies were 59.39%, 19.88%, and 1.31% for heat exchanger, evaporation chamber, and condenser respectively. The overall exergy efficiency of the process was 0.78%. The greatest amount of exergy destruction occurred in the condenser for this process. The emergy analysis also shows that SSL configuration is more beneficial in terms of emergy invested and the product yields. This study proves that utilizing low grade heat sources such as process waste heat can result in higher energy and exergy efficiencies and improve the emergy benefits of the low temperature desalination process.

Author Contributions

All the authors contributed to this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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