Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.20630

74 (2017) 21–34
May

Emergy, energy and exergy analysis of a solar powered low temperature desalination system

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Received 12 October 2016; Accepted 22 February 2017

A B S T R A C T

A low temperature phase change desalination process was studied in which, saline water is desalinated by evaporation at near-ambient temperatures under low pressures. The low pressure is achieved naturally in the head space of water columns of a height equal to the local barometric head. We present the energy, exergy and emergy analysis of this process to evaluate the thermodynamic efficiency of its major components and to identify suitable operating conditions that minimize exergy destruction and maximize resource utilization (emergy). For energy and exergy analysis, three different heat sources such as direct solar energy (SSV), photovoltaic energy (SSPV) as well as a low grade heat source (SSL) were considered. Exergy analysis showed that the major exergy destruction occurs in the condenser where the latent heat of the water vapor is lost to the environment. The overall exergy efficiencies were 0.04%, 0.051% and 0.78%, respectively, for SSV, SSPV and SSL configurations. Exergy performance of individual process components and recommendations to further improve the exergy efficiency of the proposed process were discussed. Emergy analysis was performed on the three different configurations to assess their resource utilization efficiencies, environmental impacts and sustainability. Six different indices based on the emergy approach took into account factors such as renewable and non-renewable energy used by the process, benefit of the process to society and economics of the process. Based on the indices estimated in this study, the configuration utilizing thermal energy from SSL (such as a solar water heater) was found to be the most promising sustainable technology. Results of this study indicate that future research and development work on the barometric distillation process should focus on further refining the configuration utilizing thermal energy from other SSLs.

Keywords: Desalination; Energy; Exergy; Emergy; Resource utilization; Thermodynamics; Sustainability; Transformity

1. Introduction

Desalination technologies including thermal and membrane processes demand large quantities of energy, which can place a concomitant demand on the limited energy sources [1]. Thermal technologies (multi-stage flash distillation – MSF, multi-effect distillation – MED and mechanical vapor compression – MVC) require energy in the form of heat while membrane technologies require electrical energy to produce freshwater. Although energy consumption in the desalination technologies has been reduced significantly over the past two decades, current global energy resources are still not adequate to support the desalination processes as the demand for freshwater on the global scale is expected to rise sharply [2,3].

Fortunately, water scarce regions around the world have high solar insolation which is suitable for thermal energy harvesting by solar collectors. Direct solar energy (SSV) can be utilized in the simplest configuration of thermal desalination technology, known as, solar still (SS). However, SS is

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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 which separate the evaporation and condensing chambers resulted in high distillate yields. Energy efficiency of the SS can be further improved if they can be operated at lower temperatures in the range of 40°C–55°C as compared with the common range of 60°C–75°C [4,5].

A new low temperature desalination process was developed to reduce the heat losses from the evaporation chamber (EC) there by increasing the freshwater yield. This process operates under near vacuum pressures created by exploiting natural forces 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 first law and second law of thermodynamics (available work) have been discussed for various desalination systems to understand the energy efficiency of the processes both quantitatively and qualitatively [11,12]. But the emergy analysis of desalination systems has not been discussed to date for renewable energy powered or waste-heat-based low temperature desalination systems.

Emergy theory, concepts and analytical procedures were proposed by the American Ecologist Odum in 1983 [13–15]. Emergy is defined as the total amount of solar energy utilized directly or indirectly by any given resource, product or service, in units of solar em Joules (seJ). Various forms of energy which differ in quantity and quality can be expressed into solar energy known as solar emergy by using a conversion factor called transformity [14]. The representative quality value of matter and energy is expressed as transformity.

Emergy analysis includes all the resources and their quality that have been utilized to manufacture a product [16]. Emergy similar to exergy accounts for the quality of energy by the use of a transformity factor [17]. The transformity factors for calculation of emergy are found from the network as the number of solar equivalents that it has cost to construct the considered organism (from an ecological point of view) or a system or manufacturing of a product [16–18]. In exergy analysis, the ecological impacts cannot be included. Emergy analysis presents an energetic basis for quantification or valuation of goods and services from ecosystems. Valuation methods in environmental and ecological economics estimate the value of ecosystem inputs in terms that have been defined narrowly and anthropocentrically, while emergy tries to capture the ecocentric value. It attempts to assign the "correct" value to ecological and economic products and services based on a theory of energy flow in systems ecology and its relation to systems survival [16].

Emergy analysis can provide a common scale for measuring and comparing different substances, energy types, environmental impacts and economic indicators. This method can also be used to evaluate the sustainability of many engineered systems. Emergy concepts have been developed recently to evaluate the sustainable use of natural resources by many researchers [19–21]. Emergy analysis/evaluation can be used to determine the sustainability of industrial sectors and renewable energy production systems such as biofuels and biogas production, biomass CHP, biorefineries, ethanol production, hydrogen and hydropower and wind power production [22–31]. Water and wastewater treatment systems at regional levels, wetlands, decentralized rural sewage treatment system, district heating, net-zero energy building, municipal solid waste management have also been evaluated using this method [19,20,32–38]. Emergy concepts can be used in combination with other evaluation tools such as geographic information system, geoinformatics, life cycle analysis to derive more meaningful indices that are suitable for design and planning considerations [32,39,40].

The objective of this study is to evaluate the sources of inefficiency in the process to identify and discuss the operational parameters to maximize the thermodynamic performance of this process (through energy and exergy analysis) 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 SSV, SSPV and a low-grade heat source are presented. Energy, exergy and emergy analysis is critical to determine both thermodynamic efficiency and resource utilization performance of a desalination process which also serves as a sustainability indicator. This methodology can be easily and widely adopted to any desalination process driven by any type of energy source.

2. Description of the low temperature desalination system

A schematic arrangement of a desalination system based on the above principles is shown in Fig. 1(a). Components of the desalination unit include an EC, a natural draft condenser (CON), a heat exchanger (HE) and three 10-m tall columns. These three columns serve as the saline water column; the brine withdrawal column and the freshwater column, each with its own constant-level holding tank, SWT, BT and FWT, respectively. These holding tanks are installed at the ground level while the EC is installed atop the saline water and brine withdrawal columns at the barometric height of about 10 m above the free surface in the holding tanks to create a Torricelli's vacuum in the head space of the EC. The top of the EC is exposed to sunlight in a configuration where SSV is utilized for evaporation as shown in Fig. 1(a). The top of the freshwater column is connected to the outlet of the condenser (CO). When the temperature of the saline water in the EC is increased by about 15°C–20°C above the ambient temperature, water vapor will flow from the EC to the CON where it will condense and flow into the freshwater column. By maintaining constant levels in the holding tanks with suitable withdrawal rates of brine and distilled water, this configuration enables the desalination process to be run without any mechanical energy input for fluid transfer or holding the vacuum. The purpose of HE is to preheat the saline water entering the EC by the brine stream withdrawn from the EC. Fig. 1(b) shows the process schematic for a configuration utilizing low-grade heat source such as thermal energy from solar collectors, photovoltaic (PV) cells or process waste heat or a geothermal energy source [41].

2.1. Energy and exergy analysis

For the purpose of this study, we focus on the following three components of the proposed desalination process: the

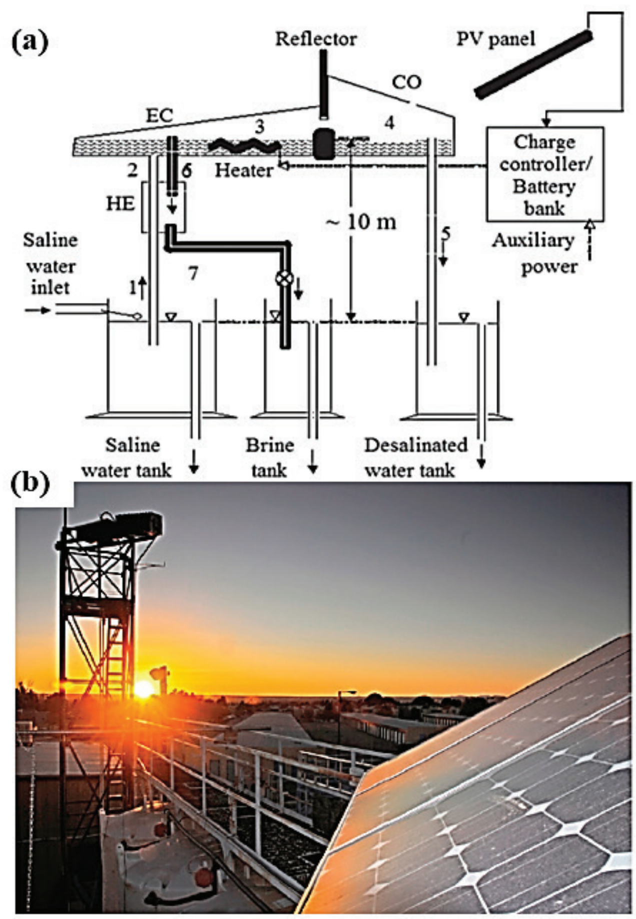

Fig. 1. Schematic of the proposed desalination process (a) and photo of the experimental unit (b).

HE; the EC and the CO. The general steady-state energy and exergy balance equations for these three components yield the following expressions [6,11]:

- Heat exchanger:
  Energy balance:

$$0 = \dot{m}_s h_1 + \dot{m}_w h_6 - \dot{m}_s h_2 - \dot{m}_W h_7 \tag{1}$$

Exergy balance:

$$\begin{aligned}\dot{E}_{D,HE} = \dot{m}_s\left[(h_1-h_2)-T_o(s_1-s_2)-w_s(\mu_1-\mu_2)\right]\\ +\dot{m}_W\left[(h_6-h_7)-T_o(s_6-s_7)-w_W(\mu_6-\mu_7)\right]\end{aligned} \tag{2}$$

- Evaporation chamber:
  Energy balance:

$$0 = \dot{Q}_{in} + \dot{m}_s h_2 - \dot{m}_W h_6 - (\dot{m}_s - \dot{m}_W)h_4 \tag{3}$$

Exergy balance:

$$\begin{aligned}E_{D,EC} = \left[1-\frac{T_o}{T_3}\right]\dot{Q}_{in} + \dot{m}_s\left[(h_2-h_4)-T_o(s_2-s_4)+w_s(\mu_2-\mu_4)\right]\\ -\dot{m}_W\left[(h_6-h_4)-T_o(s_6-s_4)+w_W(\mu_6-\mu_4)\right]\end{aligned} \tag{4}$$

When the heat source is provided by solar energy, the Petela expression can be used to calculate the exergy of solar radiation:

$$\dot{E}_s = AI_s\left[1+\frac{1}{3}\left(\frac{T_o}{T_s}\right)^4-\frac{4}{3}\left(\frac{T_o}{T_s}\right)\right] \tag{5}$$

- Condenser:
  Energy balance:

$$0 = -Q_{out} + (\dot{m}_s - \dot{m}_W)h_4 - (\dot{m}_s - \dot{m}_W)h_5 \tag{6}$$

Exergy balance:

$$\begin{aligned}\dot{E}_{D,EC} = -\left[1-\frac{T_o}{T_3}\right]\dot{Q}_{out} + (\dot{m}_s - \dot{m}_W)\\ \times\left[(h_4-h_5)-T_o(s_4-s_5)+(w_s-w_W)(\mu_4-\mu_5)\right]\end{aligned} \tag{7}$$

Energy efficiency of the desalination system is given as:

$$Th_{eff} = \frac{m_f h_v}{Q_{in}} \tag{8}$$

Exergy efficiency based on the latent heat (available energy or exergy) in the water vapor (steam) generated from EC:

$$Ex_{eff} = \frac{m_f h_v\left(1-\frac{T_o}{T}\right)}{Q_{in}} \tag{9}$$

Overall exergy efficiency based on available energy or exergy in the freshwater condensed in CO (final product).

Exergy balance:

$$Ex_{eff} = \frac{m_f\left\{(h_5-h_o)-T_o(s_5-s_o)\right\}}{Q_{in}} \tag{10}$$

2.2. Emergy analysis of solar powered desalination system

Emergy is defined as the amount of useful energy obtained by an investment in energy to obtain that energy. It is the ratio of energy acquired to the energy spent on receiving that energy. Odum [42,43] first presented the emergy values for both agricultural and municipal waters and the emergy evaluation of environment and ecology. Other researchers studied the emergy analysis of electricity production and renewable energy sources [44,45].

Fig. 2(a) shows the emergy flows of a generic process where emergy input flows into a transformation process (a natural process or an engineered system) through which an output emergy is produced and emergy lost in various forms. Fig. 2(b) shows the emergy flows in and out of the proposed desalination process and the water supply source. The emergy measured for this method is expressed in terms of some common form of energy such as sunlight. Emergy is usually expressed in terms of seJ. Also, emergy can be

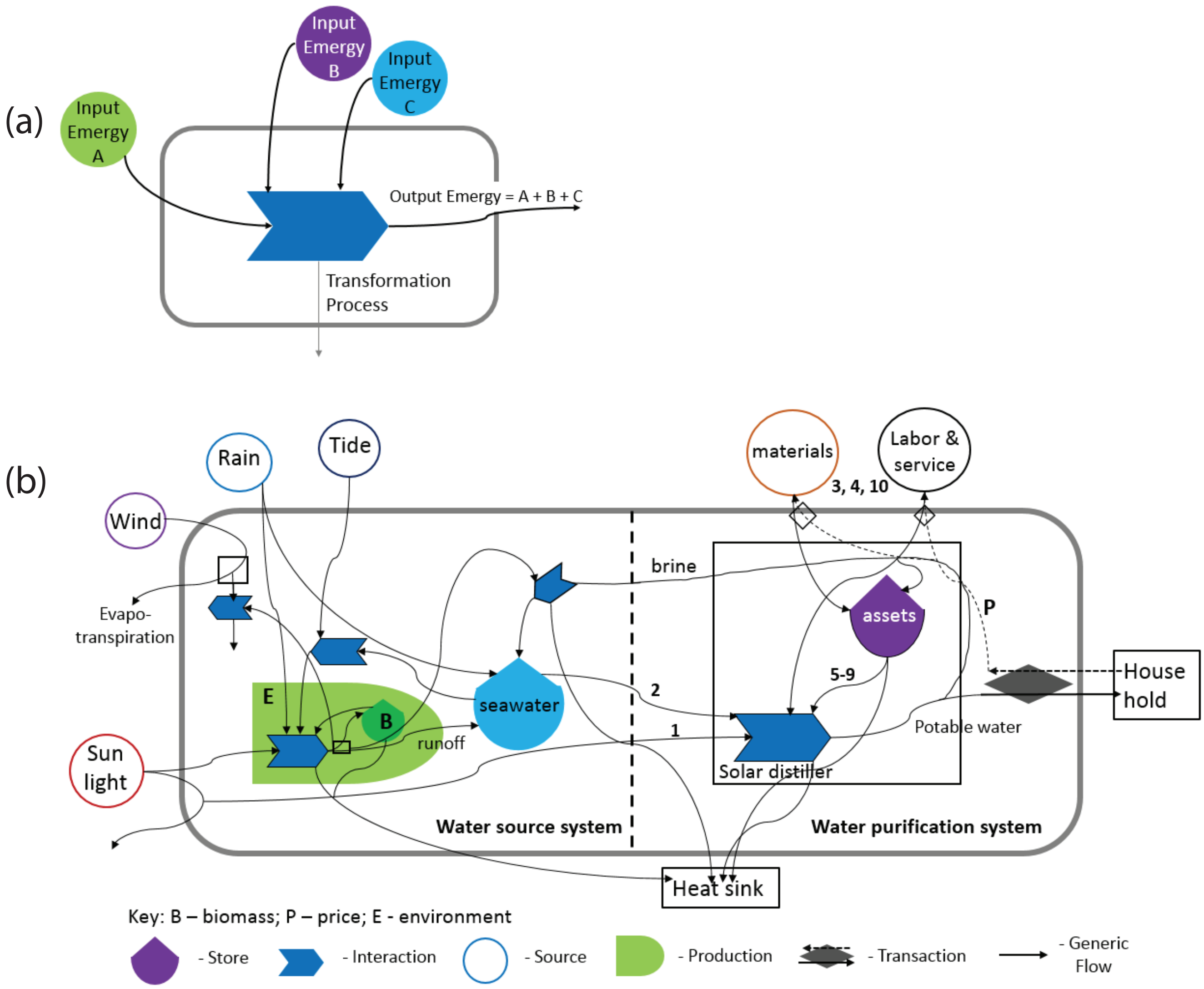

Fig. 2. Generic schematic of emergy flow in a process (a) and emergy flow in the proposed desalination system (b).

complimented by life cycle assessment but not replaced by it for the evaluation of desalination systems.

Different types of emergy indices such as emergy investment ratio (EIR), emergy yield ratio (EYR), percentage of renewable emergy (% R), emergy benefit to the purchaser (EBP) and emergy dollar per volume (Em \$ m^{-3}) and transformity were used to evaluate the sustainability of a system [44,46].

EIR is the ratio of purchased inputs (P) and services (S) to the non-renewable (N) and renewable resources (R). It reflects the impact of a system or service on the ecosystem. With a lower EIR, the system is more sustainable and vice versa.

EYR is the ratio of emergy yield of a product or service to the sum of the purchased inputs (P) and services (S). It is a measure of the ability of the process to exploit local resources. With a higher EYR the system is more beneficial to the society or economy. An EYR close to unity implies that no net emergy is contributed to the society by the product or service.

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.

The marginal emergy delivered in a product relative to the monetary worth of payment a purchaser makes is called EBP. Hence, higher values of EBP more than lower values. The logic behind this parameter is that the environment is not compensated monetarily for its resources, and hence the marginal value of emergy becomes crucial for every purchaser.

Em dollars per unit volume is defined as the ratio of solar emergy yield of the product or service to the product of volume of water produced and Em dollar ratio. This index gives us the cost of producing the water. The process is more effective with a lower Em dollar to volume ratio. Generally, the Em dollar per cubic meter is more than the dollar per cubic meter, because the monetary values do not include the value of work done by the nature for a particular process.

Transformity is a measure of the efficiency of the process. With lower transformity, the efficiency of the process is higher.

2.3. Evaluation procedures

The procedure for evaluating a technology or a process is as follows [47]:

- Define the boundary of the system and developing the system diagrams for sources, components, processes and products arranged from left to right in the order of transformity.
- Prepare the emergy evaluation tables with a line item for each item identified in the system diagrams. Determine the total emergy flow, storages and yields of each line item. Determine the em dollar (Em \$) equivalent of emergy values. An Em \$ is the proportion of the gross economic product determined from the portion of the nation emergy budget. Microcomputer models of the system may be run, which generate trends over time for different assumptions and alternatives. Emergy, Em \$ and transformity graphs may be generated by these simulations.
- Compare results using emergy indices such as net yield ratios, investment ratios, exchange ratios, emergy/money ratios, etc. Recommend for policy choices those alternatives which contribute the most real wealth, measured by emergy, to the combined system of environment and economy.
- For primary energy sources, use the net EYRs to select the ones that contribute most. For determining what uses are appropriate for an energy type, use the transformity value. For necessary process is that consume the primary sources, use the EIR to predict which are likely to be economical.

The steps involved in emergy analysis are as follows [47,48]:

- Developing the necessary emergy diagrams which can display the ideology that is being followed and which can also give a clear picture of process flow.
- Constructing the emergy analysis tables (Tables 1–3) from diagrams.
- Calculating the emergy indices and comparing the results for economic feasibility and environmental sustainability of the process.

3. Results and discussion

Daily freshwater production rates for the different configurations are shown in Fig. 3(a). The low temperature desalination process as an SS configuration (SSV) produces freshwater of about 5 L d^{-1} m^{-2}, nearly 1.5–2 times that of a conventional SS [4,5]. This improvement can be attributed to the reduction in

Table 1
Emergy evaluation of SSPV configuration

	Energy data unit/year	Emergy/unit seJ/unit	Solar emergy seJ $year^{-1}$	Em m^{-3}
Renewable resources				
1. Sunlight, J	2.52E+13	1	2.52E+13	5.76E+12
2. Saline water, J	3.98E+06	3.19E+04	1.25E+11	2.86E+10
Purchased and operational inputs				
3. Constructional and operational costs, \$	74.46	5.40E+11	4.02E+13	9.18E+12
4. Work to carry seawater 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. Poly vinyl chloride (PVC), g	16,964.60	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	4,380,000	1.61E+08	7.04E+14	1.61E+14
15. Potable water without 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 \$ $\$^{-1}$		5.06
20. Em \$ value of water		Em \$ m^{-3}		297.84
21. Transformity of water		seJ J^{-1}		3.3E+07
22. Emergy per m^3 of potable water		seJ m^{-3}		1.6E+14

Table 2
Emergy evaluation of SSV configuration

	Energy data unit/year	Emergy/unit seJ/unit	Solar emergy seJ year^{-1}	Em m^{-3}
Renewable resources				
1. Sunlight, J	2.52E+13	1	2.52E+13	1.41E+13
2. Saline water, J	2.13E+06	3.19E+04	6.80E+10	3.80E+10
Purchased and operational inputs				
3. Constructional and operational costs, $	30.4	5.40E+11	4.02E+13	9.18E+12
4. Work to carry seawater to distiller, J	2.05E+07	6.76E+06	1.38E+14	7.73E+13
5. Stainless steel, kg	100	1.80E+12	1.80E+14	1.01E+14
6. Aluminum, kg	6.67	1.25E+10	8.33E+10	4.66E+10
7. Glass, kg	1.47	8.40E+08	1.23E+09	6.89E+08
8. Concrete cement, kg	180.00	1.23E+12	2.21E+14	1.24E+14
9. PVC, g	16,964.60	5.85E+09	9.92E+13	5.55E+13
10. Land lease, $	50	5.40E+11	2.70E+13	1.51E+13
Emergy per unit of distilled water				
12. Potable water, m^3	1.78	3.45E+14	6.17E+14	3.45E+14
13. Potable water, J	8.84E+06	6.98E+07	6.17E+14	3.45E+14
14. Potable water, g	1.79E+06	3.45E+14	6.17E+14	3.45E+14
15. Potable water without services, J	8.84E+06	4.83E+07	4.27E+14	2.39E+13
Emergy indices and ratios for SSV				
		Expressions		Quantity
16. Emergy investment ratio		(P + S)/(N + R)		23.38
17. Emergy yield ratio		Y/(P + S)		1.04
18. % Renewable emergy		100 (R/Y)		4.10
19. Emergy benefit to purchaser		Em $ $$^{-1}$		11.97
20. Em $ value of water		Em $ m^{-3}		638.54
21 Transformity of water		seJ J^{-1}		6.98E+07
22. Emergy per m^3 of potable water		seJ m^{-3}		3.45E+14

energy losses by the low temperature desalination process. The near vacuum pressures created by natural means of gravity and barometric head allow for the evaporation of freshwater to occur at low temperatures resulting in higher energy efficiency. This configuration, when fitted with a reflector solar still with reflector (SSR) produced about 7.5–8 L d^{-1} m^{-2} of distillate, which is three times that of a typical SS. As the solar insolation incident on the SS was intensified by the reflector, the saline water temperatures rose quickly resulting in evaporation of freshwater. The low temperature process powered by SSV and solar still with photovoltaic (SSPV/SSP) modules produced over 12 L d^{-1} when fitted with a reflector. Photovoltaic area required for this configuration was 6 m^2. SSPV 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%. Fig. 3(b) shows the specific energy requirements for freshwater production through these configurations. The process can be designed to operate round the clock with a backup external heat source such as thermal energy storage tank when solar energy is not available [7,10,49].

3.1. Energy analysis of solar powered desalination system

Fig. 4(a) 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 EC and CO to the surroundings (Fig. 4(a)). Traditional SS have a thermal efficiency of about 30% and rarely exceed 45% [4,5]. Normal SS operating with an efficiency of 45% will require 5,040 kJ of thermal energy per kilogram of freshwater produced. The proposed process SSV operates at higher thermal efficiencies with a specific energy consumption of 3,900 kJ kg^{-1} of freshwater (Fig. 3(b)).

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

Table 3
Emergy evaluation of SSL configuration

	Energy data unit/year	Emergy/unit seJ/unit	Solar emergy seJ year^{-1}	Em m^{-3}
Renewable resources				
1. Sunlight, J	2.52E+13	1	2.52E+13	5.76E+12
2. Saline water, J	3.98E+06	3.19E+04	1.25E+11	2.9E+10
Purchased and operational inputs				
3. Constructional and operational costs, $	74.46	5.40E+11	4.02E+13	9.18E+12
4. Work to carry seawater 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	16,964.60	5.85E+09	9.92E+13	2.27E+13
10. Solar water heater, auxiliaries, $	45	5.40E+11	2.43E+13	5.55E+12
1.1 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	1.45E+14	6.34E+14	1.45E+14
13. Potable water, J	2.16E+07	2.93E+07	6.34E+14	1.45E+14
14. Potable water, g	4,380,000	1.45E+08	6.34E+14	1.45E+14
15. Potable water without services, J	2.16E+07	1.97E+07	4.27E+14	9.75E+13
Emergy indices and ratios for SSL				
		Expressions		Quantity
16. Emergy investment ratio		(P + S)/(N + R)		24.01
17. Emergy yield ratio		Y/(P + S)		1.04
18. % Renewable emergy		100 (R/Y)		4.0
19. Emergy benefit to purchaser		Em $ $$^{-1}$		9.21
20. Em $ value of water		Em $ m^{-3}		268.08
21. Transformity of water		seJ J^{-1}		2.93E+07
22. Emergy per m^3 of potable water		seJ m^{-3}		1.45E+14

utilized to produce freshwater. Thermal efficiency of SSR was between 70% and 80% with a specific energy consumption of 3,200 kJ kg^{-1}. The specific energy required for the configuration with SSPV SSP is only 2,800–3,000 kJ kg^{-1} of freshwater with thermal efficiencies ranging between 80% and 90%. In the case of traditional SS and SSV, 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 the energy losses to the ambient. Additionally, lower ambient temperatures during non-sunlight hours favor the convection and condensation of freshwater vapors from the EC to the CO side.

3.2. Exergy analysis of solar powered desalination system

The solar exergy utilization patterns of the low temperature desalination process for SSV, SSR and SSPV configurations are shown in Fig. 4(b) [11]. Total available solar exergy available after optical losses, exergy utilized (exergy losses in the EC) for freshwater production and the exergy losses in the CO (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 EC 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 EC (using Eq. (9)). For SSR configuration, the solar exergy was 22.5 MJ. The exergy losses in the EC 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 EC (using Eq. (9)).

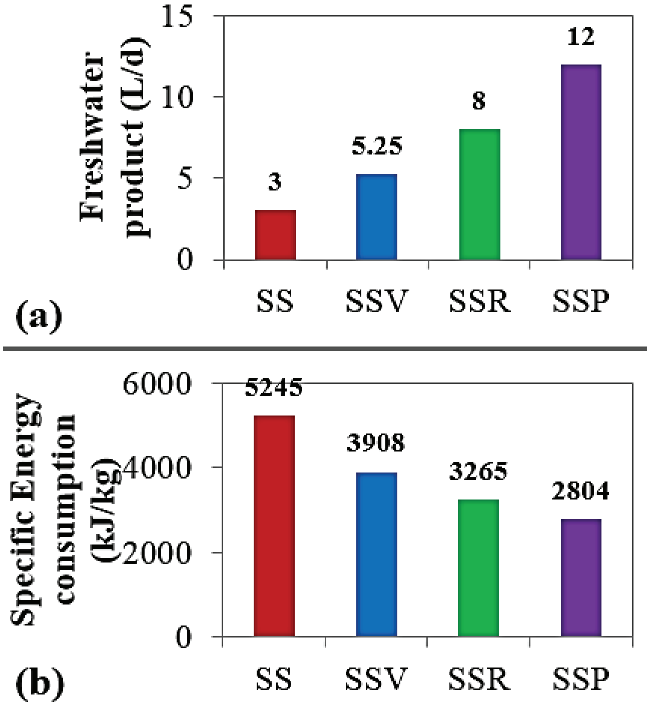

Fig. 3. Freshwater production (a) and specific energy consumption (b) for SS, SSV, SSR and SSP configurations.

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 CO. 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 [50]. 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 and 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 CO whereas in the proposed process the solar exergy was directly utilized in the EC for evaporation of freshwater from the saline water at around 50°C with no energy recovery from the CO. Higher exergy efficiencies were reported in other studies due to energy recovery between the stages. If exergy losses can be recovered from the CO, the exergy performance of the proposed process can be improved significantly [51].

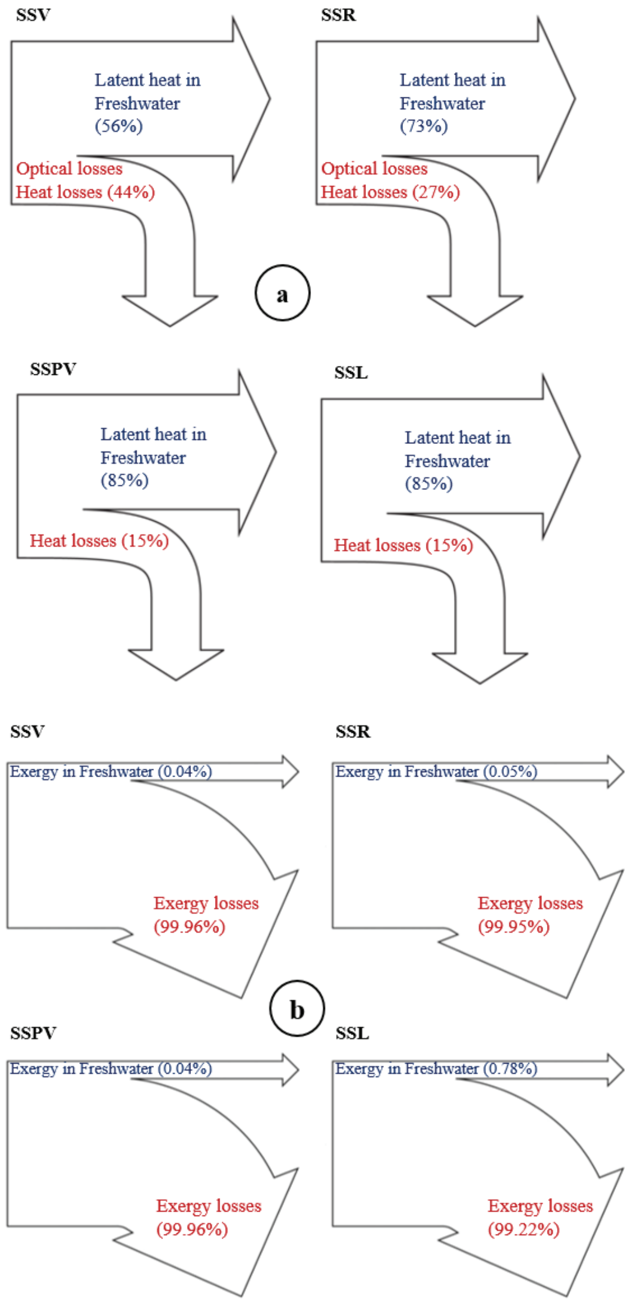

Fig. 4. Energy analysis (a) and exergy analysis (b) of the low temperature desalination system using direct solar (SSV, SSR) and photovoltaic energy, SSPV and a low grade heat source, SSL.

3.3. Exergy analysis using low grade heat source

When a low grade heat source (SSL) 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 EC to maintain the salt concentration is defined as withdrawal rate (details shown in [6,7,52]). The heat source in the HE 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 EC was around 75%. The main process components are the HE #1, EC and CO. Exergy destruction (loss %), irreversibility and second law efficiencies were analyzed for the process components. The results show that HE #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 with the exergy losses in the EC and CO. The exergy loss in the EC is 40.61% (29.39 kJ h^{-1}) and the exergy loss in the CO 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 CO 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 SSV and SSPV.

3.4. Emergy analysis of solar powered desalination system

Low temperature desalination process configurations powered by SSV, SSL (solar water heater) and PV modules (SSP) were compared in terms of emergy performance (Fig. 5). Illustrations of the emergy evaluations for SSP, SSV and SSL configurations are shown in Tables 1–3. Sample calculations are shown in Table 4 for SSL configuration [6,48].

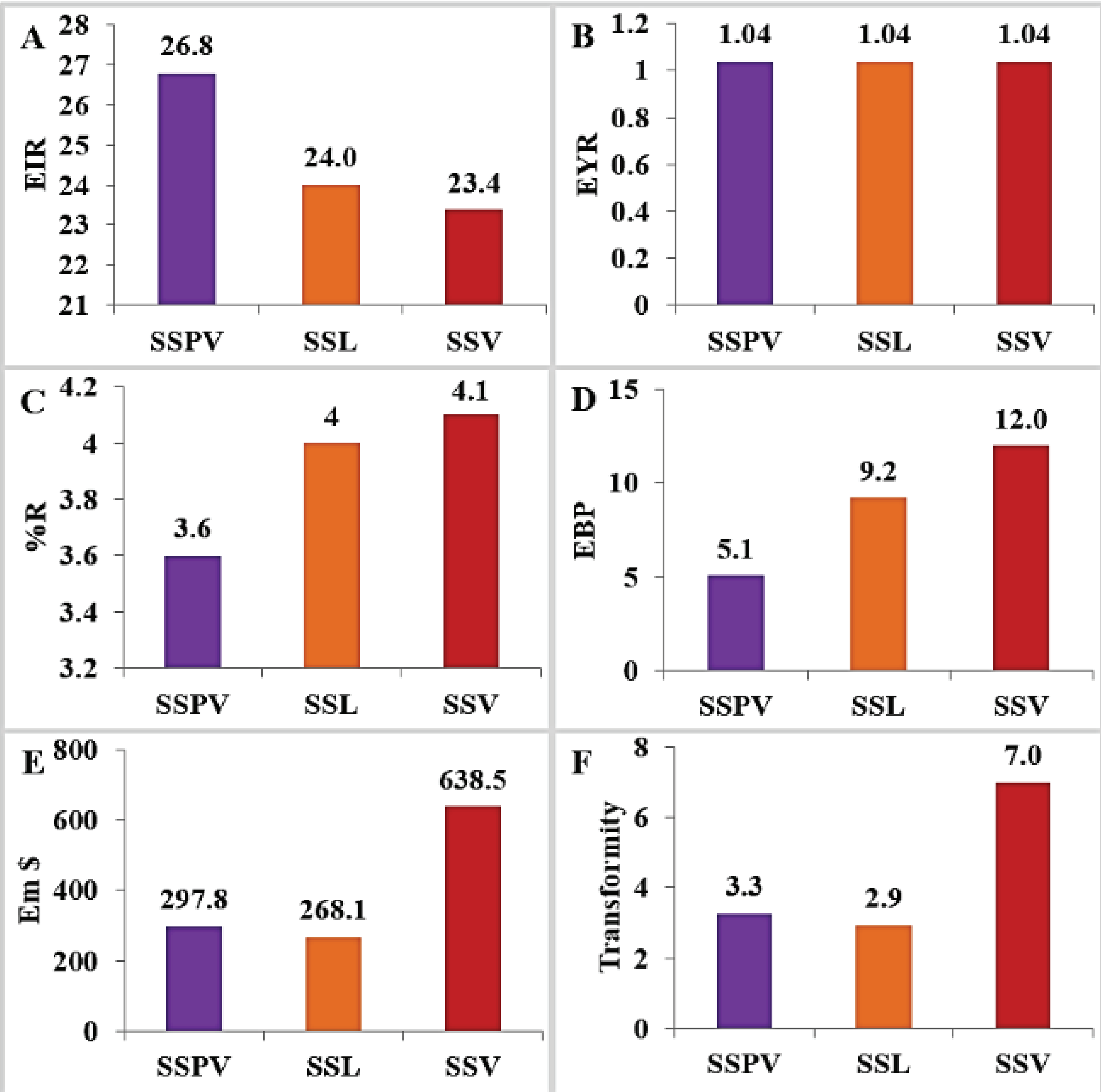

Fig. 5. Emergy indices for SSV, SSL and SSPV configurations.

Table 4
Sample calculations for emergy evaluation of SSP configuration

1	Solar radiation, J		
	Average surface solar radiation in Las Cruces, kcal m^{-2} $year^{-1}$	6.03E+09	[7]
	Average surface solar radiation in LC, J m^{-2} $year^{-1}$	2.52E+13	Average surface solar radiation (4,186.8 J $kcal^{-1}$)
	Evaporating surface area per distiller, m^2	1	[7]
	Average solar radiation per unit per year, J $year^{-1}$	2.52E+13	average surface solar radiation (evaporation area)
	Transformity, seJ J^{-1}	1	[7]
2	Saline water, J		
	Average fresh water produced per d, L m^{-2} d^{-1}	12	[7]
	Evaporating area per distillation system, m^2	1	[7]
	Freshwater produced per unit per year, L $year^{-1}$	4,380	(L d^{-1}) × (365 d $year^{-1}$)
	Efficiency of the system, %	81%	[7]
	Salt water used per year, L $year^{-1}$	5,407.41	(L d^{-1}) (% recovery) × 100
	Mass of salt water used per year, g $year^{-1}$	5.52E+06	(L $year^{-1}$)(1,020 kg m^{-3})(1E–3 m^3 L^{-1}) (1,000 g kg^{-1})
	Average total dissolved solids (TDS) of salt water used, ppm	30,000	Measured
	Average Gibbs free energy of water, J g^{-1}	7.13E–01	[(8.33 J mol^{-1} °C^{-1})(290 K)/(18 g mol^{-1})] *ln(1E6-TDS in ppm/965,000 ppm)
	Energy of salt water used, J $year^{-1}$	3.93E+06	(g $year^{-1}$)(J g^{-1})
	Transformity, seJ J^{-1}	3.19E+04	[53]
3	Constructional and operational costs		
	Total cost of water production, \$ L^{-1}	0.017	Assumed
	Freshwater produced per unit/year, L $year^{-1}$	4,380	Same as 1
	Annual cost of water production, \$ $year^{-1}$	74.46	Cost of water production (freshwater production/year)
	Emergy per dollar ratio in 2,000, seJ \$$^{-1}$	5.40E+11	Projected from 1993 seJ \$$^{-1}$ ratio in [42] using 5.7% decrease/year)
4	Work to carry seawater to distiller		
	Salt water required per week, L $week^{-1}$	103.99	Same as 1
	Weekly time to carry sea water, min $week^{-1}$	45	Assumed
	Calories required for seawater transport, kcal d^{-1}	13.39	(3,000 kcal d^{-1})(min $week^{-1}$)/(10,080 min $week^{-1}$)
	Work required for seawater transport, J $year^{-1}$	2.05E+07	(kcal d^{-1})(4,186 J $kcal^{-1}$)(365 d $year^{-1}$)
	Transformity, seJ J^{-1}	6.76E+06	[53]
5	Stainless steel		
	Total steel and iron in assets, kg	1,500	Assumed
	Useful life of aqueduct assets, year	15	Assumed
	Prorated steel and iron assets, kg $year^{-1}$	100	Total assets in kg $year^{-1}$
	Emergy per mass of steel, seJ kg^{-1}	1.80E+12	[42]
6	Aluminum		
	Total aluminum in assets, kg	100	Assumed
	Useful life of aqueduct assets, year	15	Assumed
	Prorated aluminum assets, kg $year^{-1}$	6.67	Total assets in kg $year^{-1}$
	Emergy per mass of aluminum, seJ kg^{-1}	1.25E+10	[54]
7	Glass		
	Average area of the glass used, m^2	1	[7]
	Thickness of the glass used, m	0.01	[7]
	Volume of the glass used, m^3	0.01	Area × thickness

(*Continued*)

Table 4 (*Continued*)

	Density of the glass, kg m^{-3}	2,200	
	Useful life of assets, year	15	Assumed
	Weight of the glass, kg	1.47	Volume × density
8	Concrete and cement		
	Weight of concrete used, kg	2,700	Volume of concrete × density of ready mix
	Useful life of aqueduct assets, year	15	Assumed
	Weight used per year, kg $year^{-1}$	180.00	Total assets in kg $year^{-1}$
	Emergy per unit, seJ kg^{-1}	1.23E+12	[54, p. 175]
9	PVC		
	Volume of PVC used, m^3	0.14	Measured
	Density of PVC pipes used, kg m^{-3}	1,800	
	Useful life of assets, year	15	Assumed
	Weight used per year, g	16.96	(Volume)(density)/(useful life)
	Emergy per unit, seJ g^{-1}	5.85E+09	[54]
10	Solar panel and batteries and heaters and other auxiliary equipment		
	Purchase price of the auxiliary equipment, $	2,000	Purchased value
	Replacement time, year	15	Assumed
	Annual cost, $ $year^{-1}$	133.33	Price of equipment/replacement time
	Emergy per dollar ratio, seJ $\$^{-1}$	5.40E+11	Projected from 1993 seJ $\$^{-1}$ ratio in [42] using 5.7% decrease/year
11	Land lease, $		
	Land required, m^2	5	Area required is taken five times the distiller area
	Land leasing rate, $ m^{-2} $year^{-1}$	10	From an average rate in NM
	Land	Land	Land
	Lease, $ $year^{-1}$	50	(Area)(leasing rate)
	Emergy per dollar ratio in 2,000, seJ $\$^{-1}$	5.40E+11	Projected from 1993 seJ $\$^{-1}$ ratio in [42] using 5.7% decrease/year)
12	Potable water produced, m^3		
	Total potable water produced, m^3 $year^{-1}$	4.38	(L $year^{-1}$)/1,000
	Total emergy yield, seJ $year^{-1}$	7.04E+14	Sum of items 1–11
	Emergy per volume of drinking water, seJ m^{-3}	1.61E+14	(seJ $year^{-1}$)(m^3 $year^{-1}$)
13	Potable water produced, J		
	Total drinking water produced, m^3 $year^{-1}$	4.38	Same as 12
	Total energy content of the water, J $year^{-1}$	2.16E+07	(m^3 $year^{-1}$)(4.94 J g^{-1})(1E6 g m^{-3})
	Total emergy yield, seJ $year^{-1}$	7.04E+14	Sum of items 1–11
	Transformity of potable water, seJ J^{-1}	3.26E+07	(seJ $year^{-1}$)(g $year^{-1}$)
14	Potable water produced, g		
	Total potable water produced, m^3 $year^{-1}$	4.38	Same as 12
	Mass of potable water produced, g $year^{-1}$	4.38E+06	(m^3 $year^{-1}$)(1E+6 g m^{-3})
	Total emergy yield, seJ $year^{-1}$	7.04E+14	Sum of items 1–11
	Emergy per mass of potable water, seJ g^{-1}	1.61E+08	(seJ $year^{-1}$)/(g $year^{-1}$)
15	Potable water produced without services		
	Emergy of potable water without services, seJ $year^{-1}$	4.27E+14	(Total emergy-services) = Y – S
	Energy of potable water, J $year^{-1}$	2.16E+07	Same as note 13
	Transformity without services, seJ J^{-1}	1.97E+07	(seJ $year^{-1}$)/(J $year^{-1}$)
16	Emergy investment ratio		
	P = items (5–10), seJ $year^{-1}$	4.02E+14	P = electricity, fuels, goods and materials
	S = items (3–4), seJ $year^{-1}$	2.78E+14	S = services-all money flows
	N, seJ $year^{-1}$	0	N = local non-renewable resources
	R, seJ $year^{-1}$	2.54E+13	R = renewable resources

(*Continued*)

Table 4 (*Continued*)

	EIR = 26.78 (P + S)/(N + R)	26.78	(P + S)/(N + R)
17	Emergy yield ratio		
	Yield (Y), seJ year^{-1}	7.04E+14	Y = total emergy of potable water
	EYR	1.04	(Y)/(P + S)
18	Percentage of renewable emergy		
	Yield (Y), seJ year^{-1}	7.04E+14	
	R	2.54E+13	
	% of renewable energy	3.60E+00	100 × (R/Y)
19	Ratio of emergy benefit to the purchaser		
	Em $ value of water, Em $ year^{-1}	1,304.53	(Y)/(seJ/2009$ ratio)
	Annual cost of desalinating, $ year^{-1}	257.79	Sum of all the operating costs in $ year^{-1}
	Emergy benefit to the purchaser, EM $ $$^{-1}$	5.06	Em $ $$^{-1}$
20	Em $ value of potable water per m^3		
	Em, $ m^{-3}	297.84	(Y)/[(seJ/2009$ ratio)(potable m^3 year^{-1})]
21	Transformity of potable water, seJ J^{-1}		
	Transformity of potable water, seJ J^{-1}	3.26E+07	See note 13
22	Emergy per m^3 of potable water		
	Emergy per m^3 of potable water, seJ m^{-3}	1.61E+14	(Y)/(m^3 produced year^{-1})

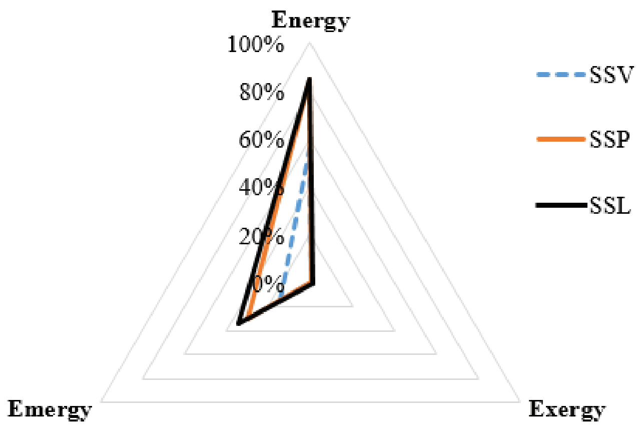

Fig. 6. Energy, exergy and emergy performance comparison for SSV, SSP and SSL configurations.

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 with 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 with 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 (×10^7) value; the higher will be the process efficiency in resource utilization. The SSL configuration seems to have higher transformity due to the use of SSL and higher thermodynamic efficiency from the source to the product. Considering the above metrics from Fig. 5, and the graphical presentation in Fig. 6, it can be concluded that the SSL configuration is more sustainable process with acceptable EBP, Em $ and transformity values compared with 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. Conclusion

Energy, exergy and emergy performance analysis of a low temperature desalination process utilizing SSV, SSPV and SSL was presented. It was observed that the overall exergy efficiency of the desalination process was very low. For the solar powered 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 SSL, the exergy efficiencies were 59.39%, 19.88% and 1.31% for HE, EC and CO, respectively, since the input heat source is already of very low quality. The overall exergy efficiency of the process was 0.78%. The greatest amount of exergy destruction occurred in the CO for this process.

Emergy accounting of the three different desalination configurations was performed by developing six performance indicators. 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 SSLs such as process waste heat can result in higher energy and exergy efficiencies and improve the emergy benefits of the low temperature desalination process. The results indicate that the efficient resource utilization is key to sustainable desalination and water supply development since the desalination processes are energy-, cost- and potentially chemical-intensive that can have detrimental effects on the environment and ecological systems.

Acknowledgments

This research was partially supported by the research grants from the New Mexico Water Resources Research Institute and the United States Environmental Protection Agency's P3 program under award SU836130.

Symbols

c_p — Specific heat of ideal gas at constant pressure, kJ kg^{-1} K^{-1}
E — Exergy, kJ
$\dot{E}$ — Exergy flow rate, kW
h — Specific enthalpy, kJ kg^{-1}
$\dot{m}$ — Mass flow rate, kg h^{-1}
P — Pressure, atm
Q — Heat energy, kJ
$\dot{Q}$ — Total heat transfer rate, kW
s — Specific entropy, kJ kg^{-1} K^{-1}
T — Absolute temperature, K
T_o — Reference temperature, K
w — Seawater concentration, kg kg^{-1}

Special characters

ψ — Exergetic efficiency, %
μ — Chemical exergy, kJ kg^{-1}
η — Thermal efficiency, %

Subscripts

D — Destruction
e — Exit, specific exergy
i — Inlet
in — Input, supply
o — Surroundings
s — Saline water stream, sun
th — Thermal
w — Withdrawal stream

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