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Exergoeconomic and exergoenvironmental evaluation of a solar-energy-integrated vacuum membrane distillation system for seawater desalination

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ABSTRACT

In this paper, exergoeconomic and exergoenvironmental analyses of a solar vacuum membrane distillation (VMD) desalination system were performed to evaluate the cost of exergy destruction and the environmental impact of each component of the desalination system. The analysis permits the identification and evaluation of inefficiencies in the plant as well as the determination of the most environmental friendly process components and opportunities for design improvements. The results showed that the solar collector has the largest irreversibility and cost of exergy destruction. Therefore, it is a very important component for improving solar VMD plant performance. In addition, it will be profitable to reduce exergy losses in the membrane module even at the expense of increased investment costs since the dominant factor in the total cost rate for this component is the cost of exergy destruction. Whereas, it would be advantageous to reduce capital costs in the condenser since it has a relatively high exergoeconomic performance. On the other hand, exergoeconomic factor and exergy efficiency for the heat exchanger are found to be 49.02% and 96.59%, respectively, indicating that the exergy and exergoeconomic performance of this component is satisfactory. Finally, the results revealed that the largest potential for reducing the overall environmental impact of the solar VMD system is associated with the solar collector, the membrane module, the condenser, and the heat exchanger.

Keywords: Seawater desalination; Vacuum membrane distillation; Solar energy; Exergoeconomic; Exergoenvironmental analysis; Efficiency

1. Introduction

Membrane distillation (MD) is a thermally driven membrane-based separation process, considered as one of the technologies that are emerging as an alternative desalination processes. The driving force in MD is the partial pressure difference between each side of the membrane pores. The temperature difference leads to a vapor pressure difference across the membrane. Due to the hydrophobic nature of the membrane, only vapor can pass across the membrane and not liquid solution being distilled [1,2].

Vacuum membrane distillation (VMD) is one of the possible configurations of MD, where vacuum is applied at the distilled side in order to create the driving force for the water vapor and volatile transfer from the feed to the permeate side. In VMD, the permeate side maintained at lower pressure by mechanical pumping to increase the permeate flux at the expense of higher energy requirements [3]. One of the possible solutions to improve energy efficiency in VMD is the coupling of this technology with solar energy since MD requires relatively low temperatures to generate the thermal driving force across the membrane [4,5].

Exergy-based methods (exergetic, exergoeconomic, and exergoenvironmental analyses) are powerful tools for developing, evaluating, and improving the design and

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operation of energy conversion systems. The fundamental idea behind the exergy-based methodology is that in energy conversion systems, exergy represents the only rational basis for assigning costs and environmental impacts to the energy carriers and the inefficiencies within the system. Balances and relations between monetary cost and environmental impact reveal appropriate compromises between economic and environmental recommendations and considerations [6–8].

Exergoeconomic analysis combines economic and thermodynamic analysis by applying the cost concept to exergy in order to provide information crucial to the design of a cost-effective system, not possible through conventional energy analysis and economic evaluations. It plays an important role in finding ways of improving the performance of energy systems because it considers not only the inefficiencies but also the costs associated with these inefficiencies and compares the latter with the investment expenditures to reduce inefficiencies [9,10].

In the literature, the exergoeconomic analysis has been applied to different systems by various researchers. The first application of exergoeconomic has been done for the water desalination process. In the late 1950s, Evans [11] studied desalination processes and making exergy analysis, which led them to the idea of exergy costing and its applications to engineering economics, for which they coined the word "Thermoeconomics". The concept of their procedure was to trace the flow of money, fuel cost, and operation and amortized capital cost through a plant, associating the utility of each stream with its exergy [12–14].

In the late 1960s, El-Sayed connected with Evans and Tribus in their research on desalination and they published one of the important papers in the subject in 1970, in which the mathematical foundation for thermal system optimization was given [15]. Another study on their idea was performed by Reistad [16], who applied the method of El-Sayed and Evans to a simple power plant, comparing that approach with conventional optimization procedures. Also in the 1960 s, Gaggioli [17] studied the optimal design of power plant steam piping and its insulation in his Ph.D. thesis. He proposed costing steam exergy at a value to that of power produced, penalizing exergy destructions and losses for the electricity, which, therefore, would not be produced [17].

Many years later, Frangopoulos, in 1983, and Von Spasovsky, in 1986, applied and formalized Evans and El-Sayed's optimization method, in their Ph.D. theses. In 1984, Tsatsaronis [18] introduced the term exergoeconomic as a more precise word for the concept of thermoeconomics on account of which he directly pointed at the thermodynamic value – exergy which is combined with economic principles. Since the expression, thermoeconomics was used in such general terms expressing the interaction between any thermodynamic value and economy. Tsatsaronis and Winhold [19] proposed that all those methods for calculating the costs based on exergy should be known as exergoeconomic.

Tsatsaronis and Winhold [19] introduced a "Fuel-Product", concept, which later became the base to define the exergy efficiency, one of the most important criteria for evaluating components of energy systems. Rosen [20] claimed that the existing understanding and developed tools related to exergy and economic connection have been a significant success. He also pointed out the need for further development and simplifications in order to apply this theory in practical situations.

Rivero et al. [21] investigated the exergy improvement potential of components in the crude-oil refinery, as a measure of how much and how easily the system could be improved for optimization purposes. Valero et al. [22] published another key paper on thermoeconomics and presented the basic methodology related to exergy-based cost analysis and applications and with Lozano, he presented basics and several applications of the theory of exergetic cost, a major cornerstone approach to the field of thermoeconomics [23].

Since the 1980s, there have been numerous published papers all around the world on exergoeconomic cost analysis, application, and optimization of thermal systems. The major contributions were done in the 1990s, to achieve greater standardization and formalism in the area of thermoeconomic studies. The common idea was to propose a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that can be expressed by linear equations [24].

In general, the maturity of exergoeconomics is marked by the specific exergy costing (SPECO) method [25]; however, methodological and fundamental discussions have still been continued. One recent focus is the cost accounting associated with dissipative components, that is, those whose productive purpose is neither intuitive nor easy to define. Torres et al. [26] and Seyyedi et al. [27] discussed the mathematical basis and different criteria for cost assessment and formation process of the residues, and suggested that the costs entering a dissipative component should be charged to the productive component responsible for the residue. Piacentino and Cardona [28] introduced the scope-oriented thermoeconomics, which identified cost allocation criteria for dissipative components, based on a possible non-arbitrary concept of scope, and classified the system components by product maker/product taker but not by the classical dissipative/productive concepts. The subsequent optimization application, that is, Piacentino et al. [29] presented that the method enabled to disassemble the optimization process and to recognize the formation structure of optimality, that is, the specific influence of any thermodynamic and economic parameter in the path toward the optimal design. Banerjee et al. [30] proposed an extended thermoeconomics to allow for revenue-generating dissipative units and discussed the true cost of electricity for systems with such potential. Despite these, it seems that the choice of the best residue distribution among possible alternatives is still an open research line.

Efforts were also made to enhance the ability of exergoeconomics. Paulus and Tsatsaronis [31] formulated the auxiliary equations for specific exergy revenues based on SPECO, and presented "the highest price one would be willing to pay per unit of exergy is the value of the exergy". Cardona and Piacentino [32] extended exergoeconomics to analyze and design energy systems with continuously varying demands and environmental conditions. Moreover, an advanced exergoeconomic analysis, developed by the research group of Tsatsaronis [33–36], is capable of identifying the sources and availability of capital investments and exergy-destruction costs.

With these fundamental researches, exergoeconomic analysis had a wide application on the thermal power plant recently. Rashidi and Yoo [37] analyzed a power-cooling cogeneration system from an exergoeconomic point of view to obtain the unit cost of power-cooling generation and the most exergy destruction location of the system. Sahin et al. [38] carry out exergoeconomic analysis for a combined cycle power plant. Different weighting factors were applied to energy efficiency, exergy efficiency, levelized cost and investment cost in three different scenarios; namely, the conventional case, the environmental conscious case, and the economical conscious case. Thus, the optimization of the size and configuration is depended on the user priorities. Ahmadzadeh et al. [39] applied the SPECO approach to evaluate the cost of a solar-driven combined power and ejector refrigeration system. A genetic algorithm was used in their optimization process with the total cost rate as the objective function. Baghsheikhi and Sayyaadi [40] used a soft computing system to realize the real-time exergoeconomic optimization of a steam power plant, which was developed based on experts' knowledge and experiences regarding the exergoeconomic performance and features of the proposed power plant. It is proved to be an efficient method for real-time optimal response to the variation of operating condition. In the study by Wang et al. [41], the exergoeconomic analysis was conducted to an existing ultra-supercritical coal-fired power plant for giving a promising solution for future design by using total revenue requirement and the SPECO methods for economic analysis and exergy costing.

In analogy to the exergoeconomic analysis, the exergoenvironmental analysis was developed by Meyer et al. [42,43], and Buchgeister [44] on the same fundamental approach of the exergoeconomic methodology, replacing economics with the environmental impacts associated to an energy conversion system in order to find out to which extent each component is responsible for the overall environmental impact.

Exergoenvironmental analysis reveals the environmental impact associated with each relevant system components and the real sources of the impact by considering the exergy streams within the system and using a well-established tool, such as life cycle assessment (LCA), which is an internationally standardized method that considers the entire useful life cycle of the components or overall systems for their impact to the environment determined by the environmental models. The exergoenvironmental analysis does not only identify the components with the highest environmental impact but also reveals the possibilities and trends for improvement, in order to decrease the environmental impact of the overall system [45].

Recently, combinations of exergy, economic, and environmental assessment have received increasing attention around the world as an acceptable method for analyzing and designing energy conversion systems. In this respect, this work aims to perform an exergoeconomic and exergoenvironmental analysis of a solar VMD plant for seawater desalination from SPECO-based exergoeconomic and environmental impact assessments of each component of the desalination plant in order to evaluate the cost-effectiveness and identify the environmentally most relevant system components of this process as well as provide information about possibilities for improving the system performance and reducing the overall environmental impact. The exergoeconomic and exergoenvironmental calculations are done by developing a computer program using MATLAB software for three major reasons. First, the productive structure derived from the application of SPECO can be helpful in understanding the fuel and product definitions of components, facilitates modeling the real components and reflects the interactions of exergy exchanges among components; Second, the SPECO method provides general criteria for developing auxiliary costing equations associated with any system, especially when the exergoeconomic and exergoenvironmental analyses are considered with chemical, physical, thermal and mechanical exergy separately; Third, a general matrix is formulated for the SPECO approach that extends the application of the exergetic cost theory matrix formulation to calculation of average costs. The matrix formulation for the system of linear equations was presented in conjunction with exergy-based approaches, this type of expressions are the most convenient formation for computer programming [46].

2. System description

The main components of the proposed solar VMD desalination plant are as follows (Fig. 1):

- a solar collectors field (7 rows and 5 collectors in series, with a total area of 70 m^2),
- a hollow fiber membrane module (PVDF) with an internal diameter of 1.4 mm and providing a total membrane area of 4 m^2,
- plate heat exchanger with 27 titanium plates of 26 kW power and offering an exchange area of 1.08 m^2,
- a tubular condenser in titanium 60 kW power,
- a mixing tank (volume: 80 L), which mixes the concentrate exiting from the membrane module and the supplement out of seawater,
- vacuum pump,
- circulating pumps.

The seawater to be distilled, which supplies the membrane module, is heated in a plate heat exchanger by a hot fluid that has been heated in the solar collector field. The concentrated retentate flow exiting the membrane module is mixed with additional preheated seawater. The steam produced is condensed in the condenser. The latent heat recovered from condensing steam is used to preheat the auxiliary seawater. The vacuum is ensured by a peristaltic pump mounted downstream of the condenser. The condenser cooling water flow rate is regulated so that condensation is complete [47]. A more detailed description of the solar VMD plant design and the dimensions of its components can be found in [48,49].

3. Methodology

The concept of exergoeconomic and exergoenvironmental analysis consists mainly of the following three steps:

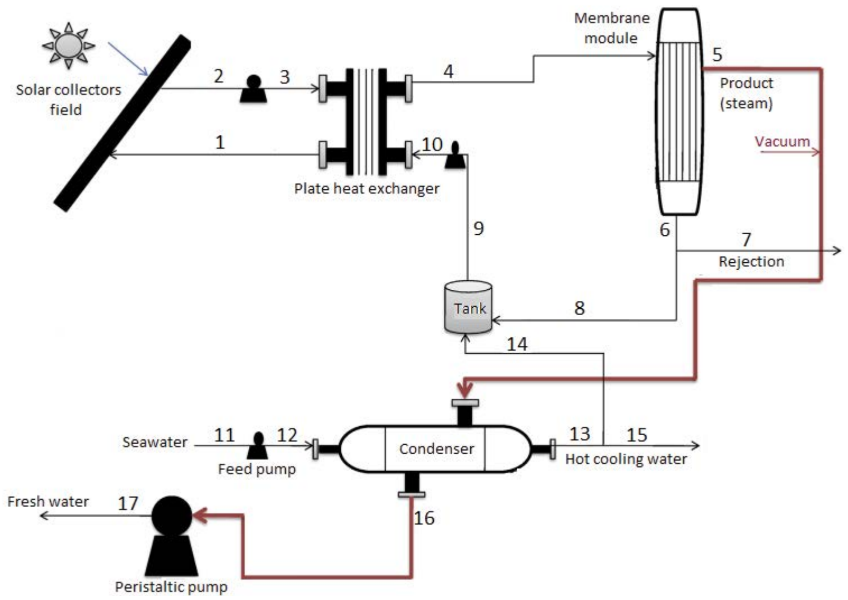

Fig. 1. Schematic of the solar vacuum membrane distillation plant [47].

- Exergy analysis of the investigated system;
- Total revenue requirement cost analysis and LCA assessment of each system component and system input flow;
- Assignment of costs (exergoeconomic analysis) and environmental impacts (exergoenvironmental analysis) to each exergy flow.

By applying both methods (exergoeconomic and exergoenvironmental) to the same process, it may be expected that in most cases the same process components are identified for improvement, but the results are not equivalent in general. The reason is the methodical difference between the two methods in the calculation of the construction-related effort (and economic or resource investment, respectively) [50].

3.1. Exergy analysis

The exergetic analysis is recognized as the most effective method for evaluating (a) the quality of energy carriers and energy-conversion processes, and (b) the rational use of energy. An exergetic analysis identifies the location, magnitude, and sources of thermodynamic inefficiencies in an energy conversion system. This information is used for improving the thermodynamic performance and for comparing various systems [2]. In addition, an exergetic analysis forms the basis for the exergoeconomic and exergoenvironmental analyses.

The detailed exergy analysis of the studied solar VMD system has been performed in a previous work by Miladi et al. [51] using the following assumptions:

- The product (steam) passing through the membrane module is assumed to be completely condensed.
- The rejection rate is 5%.
- The salinity of feedwater is constant.
- The heat exchanger is supposed to be adiabatic to the environment.
- The kinetic and potential part of the exergy is assumed negligible.

Properties and exergy flow rates at various locations throughout the solar VMD plant are given in Table 1 [51].

In this study, the recovery unit is neglected in the calculation of exergy analysis. Therefore, the causes of exergy destruction in the solar VMD plant include flat-plate collector (FPC), heat exchanger, membrane module, condenser, storage tank, and pumps.

Using the exergy rates associated with fuel and product, $\dot{E}_F$ and $\dot{E}_P$, the exergetic balances for the *k*th component and the overall system are, respectively:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \tag{1}$$

$$\dot{E}_{F,\text{tot}} = \dot{E}_{P,\text{tot}} + \sum_n \dot{E}_{D,k} + \dot{E}_{l,\text{tot}} \tag{2}$$

$\dot{E}_{D,k}$ is the exergy destroyed due to the irreversibility within the *k*th component, $\dot{E}_{l,\text{tot}}$ is the exergy loss from the system to its surroundings.

The exergetic efficiencies for the *k*th component and the overall system are, respectively:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{3}$$

$$\varepsilon_{\text{tot}} = \frac{\dot{E}_{P,\text{tot}}}{\dot{E}_{F,\text{tot}}} \tag{4}$$

A useful variable calculated from the exergetic analysis is the exergy destruction ratio calculated as:

Table 1
Data of temperature, pressure, mass flow rate, salinity and exergy at each stream [51]

Stream	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Salinity (g/kg)	Exergy flow rate (kW)
1	75.89	215	0.35	0	5.716
2	91.14	152	0.35	0	9.094
3	91.14	217	0.35	0	9.117
4	80.84	196	0.62	42.43	10.361
5	77.54	7	0.02	0	1.681
6	74.34	119	0.60	43.84	7.924
7	74.34	119	0.03	43.84	0.396
8	74.34	119	0.57	43.84	7.528
9	72.20	121	0.62	42.43	7.475
10	72.20	208	0.62	42.43	7.528
11	29	101.325	0.50	35	0
12	29	235	0.50	35	0.065
13	49.06	225	0.50	35	1.329
14	49.06	225	0.05	35	0.134
15	49.06	225	0.45	35	1.196
16	39	7	0.02	0	0.064
17	29	101.325	0.02	0	0.066

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}} \quad (5)$$

The exergy destruction ratio is a measure of the contribution of the exergy destruction within each component to the reduction of the overall exergetic efficiency.

3.2. Exergoeconomic analysis

Exergoeconomics is an exergy-based method that identifies and calculates the location, magnitude, causes, and costs of thermodynamic inefficiencies in an energy-conversion system. The real inefficiencies in such a system are the exergy destruction and the exergy loss [2]. A complete exergoeconomic analysis consists of (a) an exergetic analysis, (b) an economic analysis, and (c) exergy costing that leads to the exergoeconomic evaluation.

The exergoeconomic model of an energy conversion system consists of cost balances and auxiliary costing equations. The cost balances are formulated for each system component:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \quad (6)$$

or

$$c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k \quad (7)$$

Here $\dot{C}_{P,k}$, and $\dot{C}_{F,k}$ are the cost rates associated with fuel and product, whereas $c_{P,k}$, and $c_{F,k}$ are the corresponding costs per unit of exergy.

$\dot{Z}_k$ is the sum of cost rates associated with the capital investment (CI) as well as operating and maintenance (OM) expenditures for the *k*th component:

$$\dot{Z}_k = \dot{Z}_k^{\text{CI}} + \dot{Z}_k^{\text{OM}} \quad (8)$$

In the present paper, the contribution of $\dot{Z}_k^{\text{OM}}$ is assumed to remain constant when design changes are made, and, therefore, the changes in the value of $\dot{Z}_k$ are associated only with changes in the capital investment cost $\dot{Z}_k^{\text{CI}}$ as below:

$$\dot{Z}_k = \dot{Z}_k^{\text{CI}} \times \text{CRF} \times \frac{\pi}{t} \quad (9)$$

with:

$$\text{CRF} = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \quad (10)$$

where t is the number of hours per year, φ is the maintenance factor, i is the interest rate and N is the component lifetime. Values for these are assumed to be 7,446 h; 1.06; 8%; and 20 y, respectively.

The analytical expressions for the capital cost of the system components are provided in Table 2. In this study, the chemical engineering plant cost index is applied for adapting all costs to the reference year (2019) by the following equation:

$$\text{Cost at the reference year} = \frac{\text{Original cost} \times \text{Cost index for the reference year}}{\text{Cost index for the year when the original cost was obtained}} \quad (11)$$

Therefore, the calculated equipment cost considers the influence of inflation and price escalation.

Table 2
Capital cost expression for system components [52–54]

Component	Capital cost ($)	Observation
Membrane module	$Z_m^{CI} = 300 \times A_m$	$A_m = 4$ m^2 (PVDF membranes)
Heat exchange	$Z_{HX}^{CI} = 130 \times (A_{HX}/0.093)^{0.78}$	$A_{HX} = 1.08$ m^2
Condenser	$Z_{cd}^{CI} = 1{,}773 \times \dot{m}_{cd}$	$\dot{m}_{cd} = 0.02$ kg/s
Solar collector	$Z_{SC}^{CI} = 235 \times A_{SC}$	$A_{SC} = 70$ m^2
Storage tank	$Z_{ST}^{CI} = 4{,}042 \times (V_{ST})^{0.506}$	$V_{ST} = 80$ L
Pumps	$Z_p^{CI} = 3{,}540 \times (W_p)^{0.71}$	$W_p = \dot{m}_p v_p \Delta P/\eta_p$ (Feed pump and circulators)
		$W_p = \frac{1.97 \times 10^3}{\eta_p} \text{TQ}_p \ln \frac{P_{atm}}{P_p}$ (Vacuum pump)

Cost rate balances for each component of the system are listed in Table 3 along with auxiliary equations. Auxiliary equations are written assuming the same unit cost of incoming and outgoing fuel exergy streams.

An important outcome of the exergoeconomic analysis is the cost rate associated with the exergy destruction within the component defined as follows:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \quad (12)$$

The exergoeconomic relevance of a given component is determined by the total cost rate $\dot{Z}_{TOT,k}$, which is the sum of the cost of exergy destruction $\dot{C}_{D,k}$ and the component-related cost $\dot{Z}_k$:

$$\dot{Z}_{TOT,k} = \dot{Z}_k + \dot{C}_{D,k} \quad (13)$$

The total cost rate provides the component with the highest priority in terms of exergoeconomic viewpoint.

Moreover, relative cost difference r_k can also be used as a useful thermoeconomic evaluation, where it shows the relative increase in the average cost per exergy unit is between the fuel and product of the component and is defined as follows:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad (14)$$

Furthermore, an exergoeconomic factor f_k is also used to determine the contribution of non-exergy related costs to the total cost of a component. It is defined as follows:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k - \dot{C}_{D,k}} \quad (15)$$

When a component has a low exergoeconomic factor value, cost savings in the entire system might be achieved by improving the component efficiency even if the capital investment for that component will increase. On the other hand, a high value might suggest a decrease in the investment costs at the expense of its exergetic efficiency.

Table 3
Cost rate balances and auxiliary equations for components

Component	Cost rate balance	Auxiliary equation
Membrane module	$(\dot{C}_5 + \dot{C}_6) - \dot{C}_4 = \dot{Z}_M$	$\frac{\dot{C}_4}{E_4} = \frac{\dot{C}_6}{E_6}$
Heat exchanger	$(\dot{C}_1 - \dot{C}_3) + (\dot{C}_4 - \dot{C}_{10}) = \dot{Z}_{HX}$	$\frac{\dot{C}_4}{E_4} = \frac{\dot{C}_{10}}{E_{10}}$
Condenser	$(\dot{C}_{13} - \dot{C}_{12}) + (\dot{C}_{16} - \dot{C}_5) = \dot{Z}_{CD}$	$\frac{\dot{C}_5}{E_5} = \frac{\dot{C}_{16}}{E_{16}}$
Solar collector	$\dot{C}_2 - \dot{C}_1 = \dot{Z}_{SC} + \dot{C}_s$	$\frac{\dot{C}_s}{E_s} = 0$
Storage tank	$\dot{C}_9 - (\dot{C}_8 + \dot{C}_{14}) = \dot{Z}_{ST}$	$\frac{\dot{C}_9}{E_9} = \frac{\dot{C}_{14}}{E_{14}}$
Circulating pump1	$C_{10} - C_9 = C_{WP1} + \dot{Z}_{P1}$	$\frac{\dot{C}_{10}}{E_{10}} = \frac{\dot{C}_9}{E_9}$
Circulating pump2	$C_3 - C_2 = C_{WP2} + \dot{Z}_{P2}$	$\frac{\dot{C}_3}{E_3} = \frac{\dot{C}_2}{E_2}$
Feed pump	$C_{12} - C_{11} = C_{WP1} + \dot{Z}_{P3}$	$\dot{C}_{11} = 0$ $(E_{11} = 0)$
Peristaltic pump	$C_{17} - C_{16} = C_{WP1} + \dot{Z}_{P4}$	$\frac{\dot{C}_{17}}{E_{17}} = \frac{\dot{C}_{16}}{E_{16}}$

3.3. Exergoenvironmental analysis

The exergoenvironmental analysis is considered to be one of the most promising tools to assess energy-conversion processes from an environmental point of view [55]. An exergoenvironmental analysis consists of three steps: The first step is an exergetic analysis of the overall energy-conversion system. In the second step, an LCA of each relevant system component and all relevant input streams to the overall system is carried out. In the last step, the environmental impact obtained from the LCA is assigned to the exergy streams in the system.

The exergoenvironmental model of an energy conversion system consists of environmental-impact balances and auxiliary environmental-impact equations. The environmental-impact balances are written for each system component:

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \tag{16}$$

or

$$b_{P,k}\dot{E}_{P,k} = b_{F,k}\dot{E}_{F,k} + \dot{Y}_k \tag{17}$$

Here $\dot{B}_{P,k}$, and $\dot{B}_{F,k}$ are the environmental-impact rates associated with product and fuel, respectively, $b_{P,k}$, and $c_{F,k}$ are the corresponding environmental-impacts per unit of exergy for product and fuel.

$\dot{Y}_k$ is the component-related environmental impact associated with the life cycle of the kth component environmental impact that occurs during the construction phase. It is calculated by using data available in standard database [56].

When auxiliary equations need to be formulated, to make the number of the unknowns equal to the number of equations, the same principles are valid as for the exergoeconomic analysis. The environmental impact of the exergy destruction is calculated as follows:

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \tag{18}$$

The total environmental impact associated with the kth component $\dot{B}_{\text{TOT},k}$, which is the sum of the component-related environmental impact and the impact of exergy destruction, identifies the environmental relevance of the kth component within the system being studied:

$$\dot{B}_{\text{TOT},k} = Y_k + \dot{B}_{D,k} \tag{19}$$

The relative difference $r_{b,k}$ between the average specific environmental impact of the product $b_{P,k}$ and the fuel $b_{F,k}$ is given by:

$$r_k = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \tag{20}$$

Finally, the sources for the formation of environmental impact in a component are compared with the aid of the exergoenvironmental factor $f_{b,k}$, which expresses the relative contribution of the component-related environmental impact $\dot{Y}_k$ to the sum of environmental impacts associated with the kth component:

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \tag{21}$$

4. Results and discussion

4.1. Exergy analysis

Applying the exergy rate balance equation to each component of the solar VMD system allows the component exergy destruction rates and the exergetic efficiency to be calculated, as shown in Table 4. The relative irreversibility of each component is represented in Fig. 2. It can be seen that the irreversibilities produced in the collector account for the highest exergy destruction rates relative to the other components (about 64% of total exergy input rate). The cause of exergy destruction in the collector is that solar energy with high quality heats a fluid with low temperature. In this process, the irreversibility created due to heat transfer between two large temperature differences that solar energy with high quality is converted to heat in the absorber with low quality. Hence, effort should be made to reduce this exergy loss. Potential improvement of the solar collector field might be achieved by maximizing the collector's optical efficiency as well as minimizing the overall heat losses of the collector area. Several studies have investigated the thermal behavior of solar collectors and have addressed the issues integrated with their performance by introducing the enhancement techniques [57–62]. In some of the works, the researchers have proposed methods to increase the thermal performance of a specific type of thermal collectors such as FPCs [18,19], or evacuated tube collectors [23], while the others have proposed particular methods to increase the efficiency of thermal collectors such as using nano working fluids [24–26] or phase change material [18]. Different studies have been carried out to improve the solar collectors' efficiency by employing various flow arrangements and design modifications [57–65]. Very recent works have studied the analysis of the solar FPC using nanofluids [66–68]. Shamshirgaran et al. [69] investigated the effect of using nanofluid and

Table 4
Exergy performance data for the solar VMD system

Equipment	E_d (kW)	η_{ex} (%)
Membrane module	0.756	92.70
Heat exchanger	0.568	96.59
Condenser	0.353	79.78
Solar collector	3.378	5.03
Storage tank	0.187	97.56
Circulating pump1	0.0176	90.80
Circulating pump2	0.0076	78.80
Feed pump	0.0216	93.50
Peristaltic pump	0.0006	99.60
System	3.586	2.3

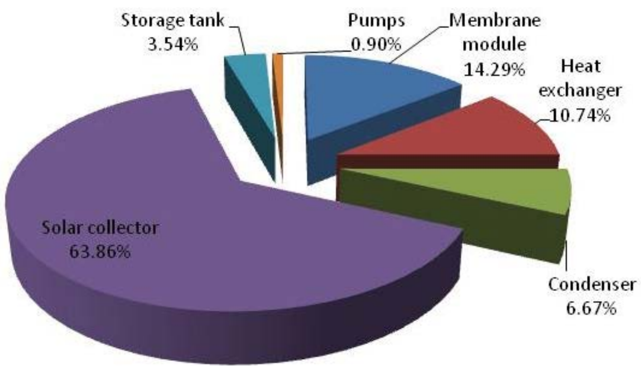

Fig. 2. Relati1ve irreversibilities of each component.

selective absorber on the improvement of work extraction by a solar FPC. The obtained results showed that an increase of 7.5% in optical efficiency, would lead to an improvement of 10.5% and near 8% on the collector exergy efficiency and energy efficiency, respectively. Moreover, the results demonstrated that exploiting nanofluid rather than pure water could enhance the maximum power generation by the collector since the exergy efficiency boosted by almost 4.1% at 4% volume concentration. Other methods proposed in the literature to augment the thermal performance of FPCs are the use of expanded surfaces through porous media [70,71], expanded metal mesh on the absorber plate [72,73], wire coils and twisted tapes [74–78], metal foams [79], compound honeycomb absorbers [80–82], corrugated surfaces [83–85], and finned absorbers [86–88], which cause enhancing heat transfer by narrowing the thickness of the thermal boundary layers and boosting the turbulence and swirling flow [61,89]. A comprehensive review of the recent advancements in thermal performance enhancements of solar collectors is provided by Gorjian et al. [90].

The next largest exergy destruction rate appeared to be in the membrane module representing 14.3% of the total exergy destruction rate. Then the membrane module is followed by the heat exchanger and condenser, accounting for 10.74% and 6.67%, respectively. The storage tank was responsible for 3.54% of the total exergy destroyed. The pumps are the lowest contributors to exergy destruction with about 1% of the total exergy input rate.

The exergy efficiency of the whole solar VMD system is found to be very low (2.3%) indicating that the system is highly inefficient. Therefore, a lot of opportunities exist to improve the performance of the system. The overall exergy efficiency can be improved by reducing the exergy destruction rate of the FPC, the hollow fiber module, and the heat exchanger as these components are the main source of the irreversibilities of the system. This will also diminish the overall exergy destruction rate of the system and will lead to an increase in the exergy efficiency of these components, as well as the whole system.

4.2. Exergoeconomic analysis

By solving the system cost balance and auxiliary equations, the cost of unknown streams of the system is obtained. The values of important exergy and exergoeconomic parameters of the system are summarized in Table 5. According to exergoeconomic evaluation guidelines, the components that have the highest priority are the ones that have the highest sum of total capital investment and exergy destruction cost rate ($\dot{Z}_k + \dot{C}_{D,k}$). In Table 5, the components of the studied solar VMD desalination system have been arranged according to the descending value of the sum $\dot{Z}_k + \dot{C}_{D,k}$.

The results showed that, like exergy analysis, the solar collector has the highest value of $\dot{Z}_k + \dot{C}_{D,k}$ due to higher purchase cost. Hence, a decrease in the capital cost of this component is merited. The exergoeconomic factor of the solar collector f_k is 100% because the incoming solar energy to the collector surface is free and the destroyed exergy cost is equal to zero. This means that the total cost is due to the investment cost. The membrane module has the second-largest $\dot{Z}_k + \dot{C}_{D,k}$ among the other components similar to the exergy analysis study, but a low value of f_k (31.85%). This suggests that the cost rate of exergy destruction dominates. Therefore, component efficiency should be improved by increasing the capital investment. In addition, a relatively high value of f_k in the condenser (61.78%) suggests a reduction in the investment cost of this component. In the case of the heat exchanger, the exergy destruction and investment cost are almost equal, thus the current investment cost for this component is found to be reasonable. Nevertheless, the system performance may be improved by increasing the investment cost of the heat exchanger.

The next most important component in the exergoeconomic analysis is the storage tank because of its value of the cost rate $\dot{Z}_k + \dot{C}_{D,k}$. For this component, the value of r_k is the lowest among all the components. Therefore, the relative contribution of this component in the system's total cost is low. On the other hand, the exergoeconomic factor for the storage tank is found to be 7.50%. The very low value of f_k for this component suggests that an increase in capital cost of this component is merited. For the pumps, changes in the exergoeconomic parameters do not affect notably the exergoeconomic performance of the system, as the values of $\dot{Z}_k + \dot{C}_{D,k}$ associated with these components are the lowest in the cycle. Therefore, improving pumps' efficiency would be more cost-effective even if the capital investment of these components will increase. Finally, the overall value of f_k for the solar VMD system is determined

Table 5
Exergoeconomic parameters for each equipment

Equipment	$\dot{Z}$ ($/h)	$c_{F,k}$ ($/GJ)	$c_{P,k}$ ($/GJ)	$\dot{C}_D$ ($/h)	$\dot{C}_D + \dot{Z}$ ($/h)	r (%)	f (%)
Membrane module	0.0272	21.4	35.53	0.0582	0.0854	14.48	31.85
Heat exchanger	0.0300	15.25	24.19	0.0312	0.0612	25.35	49.02
Condenser	0.0409	19.89	34.43	0.0253	0.0662	35.32	61.78
Solar collector	0.1406	0	11.56	0	0.1406	–	100
Storage tank	0.0041	7.51	7.85	0.0506	0.0547	1.98	7.50
Circulating pump1	0.0015	0	7.34	0.00046	0.00196	–	76.53
Circulating pump2	0.0015	0	18.11	0.00049	0.00199	–	75.38
Feed pump	0.0083	0	35.47	0.00276	0.01106	–	75.05
Peristaltic pump	0.0031	0	430.5	0.00093	0.0248	–	76.92
System	0.2572	64.05	102	0.170	0.42714	59.25	60.21

to be 60.21%. This indicates that 39.79% of the total system cost is associated with the exergy destruction. Therefore, in general, an increase in the capital costs of the components improves the exergoeconomic performance of the system.

4.3. Exergoenvironmental analysis

The results of the exergoenvironmental analysis of the solar VMD system are shown in Table 6. As can be seen, the component-related environmental impacts determined in the LCA differ in relative magnitude from costs obtained in the exergoeconomic analysis. While in the economic analysis, the cost rates are relatively substantial, in the LCA, the component-related environmental impact rates are much lower in scale.

When evaluated from an exergoenvironmental point of view, the most important component would be the one with the highest sum of component-related environmental impact and environmental impact due to the exergy destruction rate ($Y_k + \dot{B}_{D,k}$). Moreover, the exergoenvironmental factor and relative difference of exergy-related environmental impacts are also calculated to provide the relationship between these two factors. The capital environmental impact, exergy destruction impact rate, and exergoenvironmental factor for each component of the solar VMD system is provided in Table 6. It can be observed that the major environmental impacts associated with exergy destruction ($\dot{B}_{D,k}$) occur in the membrane module, heat exchanger and condenser. This is due to high exergy destruction in these components. The results obtained from the LCA (Y_k) demonstrate that the system-related environmental impact associated with the solar FPC is the largest. The main factors, which contributed to this value, are the amount of material used in the construction stage. For other components, the contribution of Y_k is much smaller.

When the components are analyzed with respect to $Y_k + \dot{B}_{D,k}$, the solar collector, the membrane module, the condenser, and the heat exchanger are the most important components from an exergoenvironmental viewpoint. Therefore, careful attention should be paid to these components. The exergoenvironmental factor $f_{b,k}$ is calculated to identify the causes of the environmental impact associated with each component. For the components with a very low $f_{b,k}$ value, such as the membrane module, heat exchanger, storage tank, and pumps, it is apparent that the environmental performance is dominated by the environmental impact caused by exergy destruction $\dot{B}_{D,k}$. Therefore, the improvement of the environmental performance for these components should focus on reducing the thermodynamic inefficiencies. The collector with the exergoenvironmental factor of 100% expresses that all of its environmental impacts are related to the collector investment. Hence, the improvement of the environmental performance of this component should focus on reducing the component-related environmental impact Y_k by testing new materials of construction or other types of solar collectors. However material constraints for construction and operation play an important role.

5. Conclusions

In this study, exergoeconomic and exergoenvironmental analyses of a solar VMD desalination system have been conducted. The exergy destruction, exergetic efficiency, cost rate, and environmental impact per exergy unit, cost rate, and environmental impact per exergy unit of product and fuel, cost rate and environmental impact rate associated with the exergy destruction, exergoeconomic and exergoenvironmental factor for each component collector evaluated.

The results from the exergy analysis showed that the were is the most significant exergy destructor in the solar VMD plant because of the large temperature difference between solar heat and the coolant fluid in the collector field, which results in high irreversibilities. Therefore, careful design and selection of this component are required to improve the exergetic performance. The improved design includes, mainly, the higher optical efficiency of the solar collector and fewer heat losses from the receiver. Other main sources of exergy destruction occur in the membrane module, the heat exchanger, and the condenser. The lowest of the cost rate is for the pumps.

The results from the exergoeconomic analysis, in common with those from the exergy analysis, demonstrated that the solar collector has the greatest cost of exergy destruction compared with other components. In terms of fuel cost, since that of solar energy is assumed to be zero, the resulting cost of exergy destruction for the collector is accounted for zero. This suggests that it can be cost-effective to reduce

Table 6
Exergoenvironmental analysis results

Component	Y_k (mpts/h)	b_f (mpts/GJ)	B_D (mpts/h)	$Y + B_{D,k}$ (mpts/h)	r (%)	f (%)
Membrane module	0.0001	104.889	0.285	0.285	0.5313	0.042
Heat exchanger	0.0198	49.992	0.102	0.122	0.239	16.214
Condenser	0.0071	141.737	0.180	0.187	0.290	3.814
Solar collector	0.3460	0	0	0.346	–	100
Storage tank	0.0016	104.864	0.070	0.072	0.068	2.157
Circulating pump1	9.9×10^{-5}	147.777	0.009	0.009	–	1.054
Circulating pump2	9.9×10^{-5}	147.777	0.004	0.004	–	2.409
Feed pump	9.9×10^{-5}	147.777	0.0115	0.011	–	0.861
Peristaltic pump	9.9×10^{-5}	147.777	3.19×10^{-4}	4.19×10^{-4}	–	23.819

investment costs. After the solar collector, the highest sum of total capital investment rate and cost rate of exergy destruction is determined to be the membrane module followed by the condenser, and heat exchanger. These components are followed by the storage tank and the pumps, which have relatively insignificant cost rates compared with the rest of the system components.

The results from the exergoenvironmental analysis revealed that the largest potential for reducing the overall environmental impact of the solar VMD system is associated with the collector, the membrane module, the condenser and the heat exchanger. Improvement can be obtained primarily by reducing the thermodynamic inefficiencies or by reducing the consumption of materials during construction or operation of the component. Nevertheless, the material constraints for construction, capital investment and operation costs must be considered. The storage tank and the pumps' impacts are found to be exergoenvironmentally insignificant compared with the aforementioned components.

Finally, it should be noted that the suggestions for exergoeconomic and exergoenvironmental performance improvements for each component of the solar VMD desalination plant are made through considering the behavior of that component only. However, an improvement in the performance of one component could reduce the performance of other components or the system. Therefore, caution must be exercised in optimizing the system from an exergoeconomic and exergoenvironmental viewpoint, and some of the above-mentioned suggestions may be disregarded.

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