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Energy, exergy, exergoeconomic, and environmental (4E) and carbon footprint analysis of coupling the various energy recovery devices with seawater and brackish water reverse osmosis desalination

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ABSTRACT

Energy accounts for a large portion of the cost of reverse osmosis units, so the use of energy recovery technologies in reverse osmosis units reduces the cost of operating and utilizing these units more widely. The energy recovery devices (ERDs) such as turbochargers, Pelton wheels, Francis turbines, and pressure exchangers are among the techniques used to reduce energy consumption in these units. In this paper, a 100 m^3/d reverse osmosis unit with seawater and brackish water feed is considered, and thermodynamic, energy, exergy, exergoeconomic, exergoenvironmental, and carbon footprint analysis is performed on the reverse osmosis unit along with the energy recovery unit. The results show that the specific energy consumption (SEC) has been decreased by using ERDs and will be equal to 3.1 kWh/m^3 in sea water reverse osmosis (SWRO) with Pelton wheels, 2.74 kWh/m^3 in SWRO with turbocharger, and 2.46 kWh/m^3 in SWRO with pressure exchanger. Because of the lower energy consumption in the brackish feedwater unit, the ERD's are not effective same as seawater type. Economic analysis also shows that the amount of saved cost from connecting a pressure exchanger to a seawater reverse osmosis unit would be \$0.27/m^3. This value is the highest profitable rate among all the ERD units studied in this paper.

Keywords: Reverse osmosis (RO); Energy recovery devices (ERDs); Desalination; Exergy; Exergoeconomic; Exergoenvironmental; Carbon footprint

1. Introduction

Despite conventional marine reserves rapidly depleting, more capacity is required to provide freshwater from alternative sources. Seawater and brackish water sources are the latest, innovative water supplies for human usage. However, seawater desalination is an energy-intensive operation. Whereas, conventional surface water treatment energy usage vary from 0.2 to 0.5 kWh/m^3 [1,2].

By 50% energy recovery in a sea water reverse osmosis (SWRO) unit, the estimated specific energy consumption (SEC) will be about 1.07 kWh/m^3 [1–4] and considerable additional energy is needed for successful operation of the SWRO unit. A SWRO unit without energy recovery device (ERD) has a SEC about 2.5–4.0 kWh/m^3 [2]. Also, a SWRO plant is included pre-treatment and post-treatment units that rise the SEC about 3.5–4.5 kWh/m^3 [5]. Seawater is not commonly used over traditional surface water due to the inherent high-energy requirement for SWRO desalination. Given its high-energy usage, the use of SWRO unit is necessary for specific regions of freshwater production, where/when seawater is the only usable source of water.

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The middle east and north Africa (MENA) countries usually use SWRO because of traditional water scarcity for water production. The need for desalination in these regions is increasing exponentially with the need for freshwater [6], and desalinated water is used not only for drinking but also for agriculture and industry [7]. There will be no future stabilization of the security of currently available water source in all other regions of the world [8,9]. Nevertheless, when using SWRO, high-energy consumption is an inherent problem associated with the high-pressure pump (HPP) of the desalination unit. This indicates that a larger amount of fossil energy sources and other carbon sources should be required to generate freshwater, which will have harmful environmental impacts [10].

High-power consumption in SWRO desalination plants can lead to increased fossil fuel consumption and ultimately to increased carbon dioxide levels in the air. This amount of pollution can also change the climate and is a harmful parameter for global warming [11,12]. Reducing carbon dioxide footprint in reverse osmosis units can therefore be an important step in the optimal design of these units [13].

While several research articles identify the SEC array of SWRO plants, a study has not been established that clearly explains the SEC values for various SWRO and BWRO plants which have a small capacity of freshwater production and are integrated with various ERDs. In a previous study, an SWRO unit's standard cost and SEC (not the whole plant) was defined in conjunction with feed forms, but the SWRO plant's SEC was not in-examined [2].

Another study worked on energy demand of SWRO unit with various sources of water [2], but for SWRO plants it given only an SEC array. SWRO's SEC was technically evaluated and proposed strategies to reduce it [14].

Although fundamental principles and implementation dimensions of reverse osmosis were elucidated by Greenlee et al. [15].

Precise SEC rates are not readily available in small reverse osmosis units. This amount and the economic calculations based on it will definitely impose high costs on the investor. The amount of actual economic optimization associated with the use of ERD units is a very important parameter that is missing. There is also no complete study of the impact of using energy recovery units on low-pressure brackish reverse osmosis systems. [16,17]. Therefore, using energy recovery units can achieve higher efficiency in reverse osmosis units. But for this purpose, a detailed technical and economic analysis should be provided regarding the use of different ERD units [18,19].

A comprehensive review of energy use in SWRO was carried out recently [13], but there is no clear work on the comparison of various ERDs performance. However, the comparisons of the energetic, exergetic, economic, and environmental performance of ERDs in a high-pressure unit as seawater reverse osmosis and a low-pressure unit as brackish water reverse osmosis (BWRO) with a small capacity of freshwater production are presented in this study. In this paper, the ERD units like Pelton wheel, turbocharger, and pressure exchanger are combined with seawater and BWRO desalination units. The energy, exergy, exergoeconomic, exergoenvironmental, and carbon footprint of the use of ERDs have been investigated clearly.

2. Description of SWRO and BWRO plants

The pre-treatment systems are used to remove large particles and solids before SWRO for causing fouling and/or scaling onto the surface of the RO membrane. Most chemical compounds and ions are soluble in seawater with TDS concentrations of approximately 30,000–40,000 mg/L [20,21].

To generate groundwater, TDS should also be added. For this separation, a semi-permeable membrane is used in SWRO that allows water molecules to permeate while blocking solids molecules. Nonetheless, a barrier to desalination is the osmotic pressure across the semi-permeable membrane. The SWRO unit also requires high stress to relieve seawater's osmotic pressure, for which a HPP is used. The freshwater is obtained after the RO unit while concentrates are released from the RO unit. A considerable amount of pressure remains in the concentrate stream. For starters, ERDs can recover the stress in the focus to increase energy efficiency [21,22]. To increase the pressure of the feed flow, the saved energy is used. This pressure increase is not enough in the pressure exchanger unit, however, and a booster pump (BP) is applied to the feed stream to pressurize it. Brackish water is made up of more total dissolved solids than surface water but has lower salinity than seawater, which usually comes from deep sources of water like well water. Typically, the TDS level of brackish water is defined in the range of 1,000–10,000 ppm. The unit is designed to handle the pressure that is higher than the RO surface water [21]. The base RO unit has been considered to produce 100 m^3 of desalinated water per day. The units are shown in Fig. 1. The stream No.1 is the feedwater of unit that has been pressurized by the HPP and stream No.2 has been entered to the membrane. The stream No.3 show the permeate water and No.4 show the concentrate stream. The stream No.5 is the outlet stream of the ERD unit which its pressure is close to the ambient pressure and its usable energy has been saved. The stream No.6 in Fig. 1c represents the flow of feedwater outlet from the turbocharger, part of which is supplied to the membrane by the HPP and the other part by the turbocharger. Fig. 1d shows the streams of the RO unit with PX. The stream No.6 is a part of the feedwater that enters the PX and the stream No.7 has received the energy that recovered by PX and its pressure is as high as the output of the HPP, but also due to the pressure drop of the path, a circulation pump has been used to have a pressure equal to the HPP output. The design characteristics of the SWRO and BWRO are presented in Table 1.

All the ERD types have been used in the seawater reverse osmosis but in the BWRO, the pressure exchanger cannot be used because the pressure of the process is so low. The properties of the seawater and brackish water as the feed of the unit are presented in Table 2.

The turbochargers have been used since the 1990s. Installation, commissioning, and efficiency of turbochargers are easier and higher than Pelton and Francis wheels. The turbocharger is specifically designed for reverse osmosis units. The turbocharger is installed in a location where the reverse osmosis effluent enters the turbine blades and rotates the propeller and its associated axle. The power received by the turbocharger shaft is transmitted to the pump shaft and supplies part of the required energy.

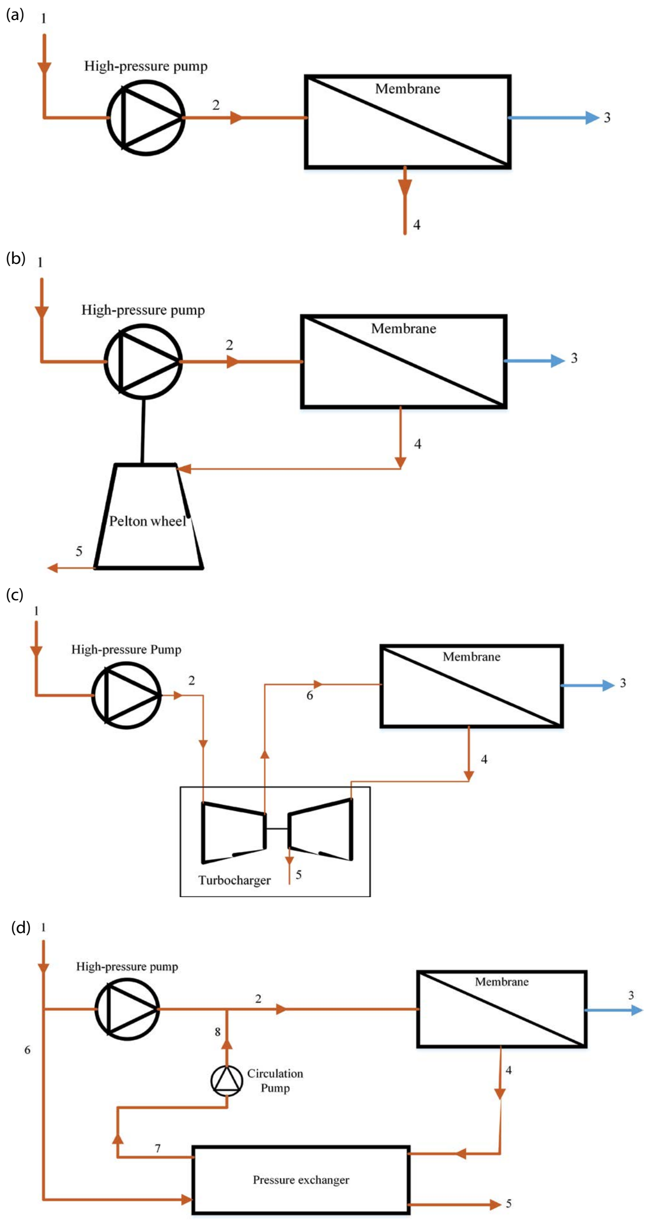

Fig. 1. (a–d) SWRO and BWRO units with various energy recovery devices.

Table 1
Characteristics of SWRO and BWRO plants design

Characteristics	SWRO	BWRO
Membrane type	SW30XHR-440i	BW30HR-440i
Stages	1	1
Pressure vessel in each stage	1	1
Elements in each vessel	6	6
Recovery ratio (%)	40	60
Desalinated flow (m^3/d)	100	100

Table 2
Properties of the feed waters

Ions	Seawater	Brackish water
	Feed (mg/L)	Feed (mg/L)
$NH_4^+ + NH_3$	0	0.04
K	390	3.3
Na	10,968.55	188.18
Mg	1,310	6
Ca	410	84
Sr	13	0.7
Ba	0.05	0.07
CO_3	7.87	0.83
HCO_3	152	265
NO_3	0	4.3
Cl	19,700	290.2
F	1.4	0.14
SO_4	2,740	24
SiO_2	5	9
Boron	4.5	0
CO_2	1.91	8.2
TDS	35,723.62	4,402.7
pH	7.6	7.6

Positive displacement devices are divided into two categories. One device uses valves and pistons known as reciprocating or working exchanger to perform energy recovery in reverse osmosis, and the other using a cylindrical rotor known as rotary or pressure exchanger that recently it has entered the energy recovery market of reverse osmosis plants and performs energy recovery developments with high efficiency.

3. Methodology

3.1. Thermodynamic analysis

The thermodynamics relations are presented in Table 3. These relations are used to develop the simulated cycles in the MATLAB code. The properties of the seawater like enthalpy or entropy are calculated as the method that El-Emam and Dincer [23] have been introduced.

3.2. Exergy analysis

The first thermodynamic knowledge was established based on two main natural laws called first and second laws. The first law of thermodynamics simply refers to the energy conservation law. The law states that energy is a thermodynamic property that in each reaction, energy can be transformed in a different form, but the total amount of energy remains constant. The second law of thermodynamics indicated that energy has quality, and practical processes are going to reduce energy quality.

The proposed freshwater production unit is investigated in the perspective of exergy analysis and exergoeconomic analysis. This analysis has been explained as follows. This paper focuses on a portion of thermodynamics properties like energy, exergy, and entropy, and specifically highlights

Table 3
Thermodynamic relations for the cycle coding

Component	Equations	Inlet	Outlet
Reverse osmosis [24]	$\mathrm{RR} = \frac{\dot{m}_D}{\dot{m}_F}$ $\mathrm{RR} = \mathrm{RR}\vert T = 25 \times \frac{J_w}{J_w \vert T = 25}$ $\dot{m}_F = \dot{m}_D + \dot{m}_B$ $\dot{m}_F = \dot{m}_{\mathrm{cwd,MED}}$ $\dot{W}_{\mathrm{RO}} = \frac{\dot{m}_F \left(p_{\mathrm{Feed}} - p_2\right) \times 100}{\rho \times \eta_{\mathrm{pump}}}$ $J_w = \frac{D_w C_w V_w}{RTe\left[°\mathrm{K}\right]} \left\{\left(p_F - p_D\right) - \left(\pi_F - \pi_D\right)\right\}$ $\pi_i = \frac{385 \times \mathrm{sal}_i \times T_i}{0.14507(1{,}000 - 10\mathrm{sal}_i)}$ T: average temperature of RO R: universal gas constant e: membrane thickness V_w: water molar volume C_w: water concentration $D_w = \frac{k \times T\left[°\mathrm{K}\right]}{3\pi_F \mu_w d_s}$ $\mu_w = 4.23 \times 10^{-5} + \left[0.157\left(T_F + 64.993\right)^2 - 91.296\right]^{-1}$ $d_s = 0.076\mathrm{MW}_w$ d_s: stocks diameter MW: molecular weight $\mathrm{sal}_B = \frac{\mathrm{sal}_F}{1 - \mathrm{RR}}$ $h_4 = \frac{h_2 - \mathrm{RR} \times h_3}{1 - \mathrm{RR}}$	$\dot{m}_F$ T_2, p_2 p_{Feed} T RR $e = 2 \times 10^{-6}[\mathrm{m}]$ $V_w = 18\left[\mathrm{m}^3/\mathrm{mol}\right]$ $C_w = \rho$ MW_w k: Boltzmann $\eta_{\mathrm{RO-pump}}$	$\dot{m}_D, \dot{m}_B$ RR_{25} $\dot{W}_{\mathrm{RO}}$ p_3, T_3 p_4, T_4 x_4
Energy recovery devices [25]	$\mathrm{ES}_{\mathrm{ERD}}\left(\%\right) = \frac{\mathrm{ES}_{\mathrm{ERD}}}{W_{\mathrm{pump}}} \times 100$ $\mathrm{ES}_{\mathrm{ERD}} = \left(P_{\mathrm{ie}} - W_{\mathrm{pump}}\right) \times \eta_{\mathrm{mechanical}} \times \eta_{\mathrm{ERD}}$ $P_{\mathrm{ie}} = \frac{\mathrm{WP}_{\mathrm{on}}}{\eta_{\mathrm{pump}}}$ $\mathrm{WP}_{\mathrm{on}} = \mathrm{WP}_d - \mathrm{WP}_s$ $\mathrm{WP}_{\mathrm{each-stream}} = \frac{P \times Q}{36}$ $\eta_{\mathrm{ERD}} = \frac{\mathrm{WP}_{\mathrm{in}}}{P_{\mathrm{on}}} \times 100$ $\mathrm{WP}_{\mathrm{in}} = \mathrm{WP}_r - \mathrm{WP}_{\mathrm{fr}}$ $P_{\mathrm{on}} = \mathrm{ES}_{\mathrm{ERD}}$	–	$\mathrm{ES}_{\mathrm{ERD}}\left(\%\right)$ $\mathrm{ES}_{\mathrm{ERD}}$ η_{ERD} $\mathrm{WP}_{\mathrm{each-stream}}$

the division of these three domains. Eqs. (1) and (2) will be calculated the physical and chemical exergy [26].

$$\mathrm{ex}^{\mathrm{PH}} = \left(h - h_0\right) - T_0\left(s - s_0\right) \quad (1)$$

$$\mathrm{ex}^{\mathrm{CH}} = \sum x_k e\bar{x}_k^{\mathrm{CH}} + \bar{R}T_0 \sum x_k \ln\left(x_k\right) \quad (2)$$

The total exergy can be defined as the sum of the physical and chemical exergy [26].

The exergy of each stream can be obtained as follow [26]:

$$\dot{\mathrm{E}}\mathrm{x}_k = \dot{m}_k \times \mathrm{ex}_k \quad (3)$$

The exergy destruction rate can be calculated as Eq. (4) [26]:

$$\dot{\mathrm{E}}\mathrm{x}_{D,k} = \dot{\mathrm{E}}\mathrm{x}_{F,k} - \dot{\mathrm{E}}\mathrm{x}_{P,k} \quad (4)$$

Eq. (5) show the calculation of exergetic efficiency for each component [26]:

$$\Psi_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \quad (5)$$

3.3. Economic analysis

Thermodynamic calculations determine the efficiency of each equipment. This section examines the costs associated with each equipment and its economic performance. Table 4 presents some relations for calculating the initial capital investment cost of each equipment.

The operating and maintenance (O&M) costs related to SWIP, HPP, Pelton turbine, turbocharger, and pressure exchanger are considered to be 4% of the total initial purchased cost (PEC). The cost of operating and maintenance of membranes is 1% of the total initial cost and the cost of membrane replacement is 8% of the total initial cost.

Also, since the pressure exchanger and HPP have similar performance, their initial cost is considered equal. The cost of operating and maintenance of other equipment and buildings is 6% of the total initial cost.

The inlet parameters of the economic analysis are presented in Table 5.

In this segment, economic analyses of the reverse osmosis units are carried out on the basis of the definition of ACS (annualized system cost). Annualized capital cost $C_{a\mathrm{cap}}$, annualized replacement cost $C_{a\mathrm{rep}}$, annualized maintenance cost $C_{a\mathrm{main}}$, and annualized operating cost $C_{a\mathrm{ope}}$ are the principal sections of ACS [Eq. (6)]. The lifetime of the reverse osmosis units (n) is expected to be 20 y.

$$\mathrm{ACS} = C_{a\mathrm{cap}}\left(\mathrm{Instruments}\right) + C_{a\mathrm{rep}}\left(\mathrm{Instruments}\right) + C_{a\mathrm{main}}\left(\mathrm{Instruments}\right) + C_{a\mathrm{ope}}\left(\mathrm{Labor\ cost} + \mathrm{Fuel\ cost} + \mathrm{Insurance\ cost}\right) \quad (6)$$

All the required purchased equipment costs, replacement costs, and power costs are described in Table 6.

This should be remembered that the levelized cost of the product (LCOP) is not a benchmark for comparison with the cost of the commodity on the market, because

Table 4
Cost function of RO unit equipment

Component or power	Cost function	Reference
SWIP	$\mathrm{PC}_{\mathrm{SWIP}} = 996 \times \dot{V}_t$	[23,27,28]
Power of SWIP pump	$\dot{C}_{e,\mathrm{SWIP}} = P_{\mathrm{SWIP}} \times \dot{V}_t \times f_1 \times \frac{c_e}{\eta_{\mathrm{SWIP}}}$	[23,27,28]
Chemical treatment in SWIP	$\dot{C}_{\mathrm{op,ch}} = c_{\mathrm{ch}} \times \dot{V}_t \times f_1$	[23,27,28]
High-pressure pump	$\log_{10}\left(\mathrm{PC}_{\mathrm{HPP}}\right) = 3.3892 + 0.0536 \times \log_{10}\left(\dot{W}_{\mathrm{HPP}}\right) + 0.1538 \times \left[\log_{10}\left(\dot{W}_{\mathrm{HPP}}\right)\right]^2$	[23,27,28]
Power of high-pressure pump	$\dot{C}_{e,\mathrm{HPP}} = P_{\mathrm{HPP}} \times \dot{V}_{\mathrm{RO}} \times f_1 \times \frac{c_e}{\eta_{\mathrm{HPP}}}$	[23,27,28]
Membrane	$\mathrm{PC}_{\mathrm{RO}} = N \times \mathrm{PC}_m$	[23,27,28]
Pelton turbine	$\log_{10}\left(\mathrm{PC}_{\mathrm{PT}}\right) = 2.2476 + 1.4965 \times \log_{10}\left(\dot{W}_{\mathrm{PT}}\right) - 0.1618 \times \left[\log_{10}\left(\dot{W}_{\mathrm{PT}}\right)\right]^2$	[23,27,28]
Turbocharger	$\log_{10}\left(\mathrm{PC}_{\mathrm{Tbch}}\right) = 2.2476 + 1.3223 \times \log_{10}\left(\dot{W}_{\mathrm{Tbch}}\right) - 0.1884 \times \left[\log_{10}\left(\dot{W}_{\mathrm{Tbch}}\right)\right]^2$	[28]
Pressure Exchanger	$\log_{10}\left(\mathrm{PC}_{\mathrm{PX}}\right) = 3.3892 + 0.0536 \times \log_{10}\left(\dot{W}_{\mathrm{PX}}\right) + 0.1538 \times \left[\log_{10}\left(\dot{W}_{\mathrm{PX}}\right)\right]^2$	[28]

LCOP is measured based on all costs in the existence of the project. Some other economic parameters can help to analysis the RO units completely which are described in Table 7.

3.4. Exergoeconomic

The cost of the exergy casualties of each of the components of the unit can be estimated and evaluated in exergoeconomic analysis. Using the results, the role of component efficiency and cost overruns on the finished product cost can be estimated. The exergoeconomic analysis of SWRO systems are illustrated by Jamil et al. [31] and the effect of ERDs in the cost of SWRO plant has been conducted previously, but some new parameters as exergoeconomic factor and relative cost difference are expressed in this regard. The purchase equipment cost (PEC) of the equipment should be calculated by using equations presented in Table 4.

Then, the cost rate of the equipment can be determined by Eq. (9) [32].

$$\dot{Z}_k = \frac{\Phi_k \times \text{PEC}_k \times \text{CRF}}{3,600 \times N} \quad (7)$$

where Φ_k is the maintenance factor and it can be assumed about 1.06 [26,32] the plant's life in years has been shown by N, which is considered 20 y [26].

The other parameter is capital recovery factor. The CRF can be evaluated by Eq. (8) [26].

$$\text{CRF} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (8)$$

By calculating the cost of each component, the exergoeconomic balance equation can be written as Eqs. (9) and (10). The cost of each streams specific exergy rate can be obtained by the solve of the matrix that created by this balance equation in each component [26].

The cost rate of each streams will be obtained as shown in Eq. (11).

Table 5
Inlet parameters of the economic analysis

Parameter	SWRO	BWRO
Efficiency of high-pressure pump, η_{HPP}	50%	70%
Efficiency of Pelton turbine unit, η_{PT}	80%	80%
Efficiency of turbocharger unit, η_{Tbch}	90%	90%
Efficiency of pressure exchanger unit, η_{PX}	96%	96%
Plant load factor, f_1	100%	100%
Membrane recovery ratio, r_r	0.30	0.50
Cost of chemical treatment, C_{ch}	0.018 $/m³	0
Cost of cartridge filter replacement	0.01$/m³	0
Inlet water volume flow rate, $\dot{V}_t$	300 m³/d	200 m³/d
Cost of consumed power, C_e	0.03 $/kWh	0.03 $/kWh

Table 6
ACS parameters in the economic analysis

Parameter	Equation	Reference
Annualized capital cost	$C_{acap} = C_{cap} \cdot \text{CRF}(i,n) = C_{cap} \cdot \frac{i(1+i)^n}{(1+i)^n - 1}$	[29]
Replacement cost	$C_{rep} = C_{cap}(\text{In base year}) \cdot (1+i)^n$	[29]
Annualized replacement cost	$C_{arep} = C_{rep} \cdot \text{SFF}(i,n) = C_{rep} \cdot \frac{j}{(1+i)^n - 1}$	[29]
Net present value (NPV)	$\text{NPV} = \frac{\text{ACS}}{\text{CRF}(i,n)} = \text{ACS} \cdot \frac{(1+i)^n - 1}{i(1+i)^n}$	[29]
Levelized cost of product (LCOP)	$\text{LCOP} = \frac{\text{ACS}}{\text{Annual product of the system}}$	[29]

Table 7
Other economic parameters

Definition	Parameter	Reference
Capital investment cost	CC = 1.1 (Total capital cost)	[30]
Operating flow cost	OFC = OMC + fuel cost + insurance cost + labor cost	[30]
Total volume of freshwater product	VOP	[30]
Total freshwater price	SOPC = (VOP) × (COP)	[30]
Total benefit of unit	AB = SOPC – OFC	[30]
Net annual benefit	NAB = (AB) (1 – Tax%), Tax = 0.1 (AB)	[30]
Rate of return	ROR = NAB/CC	[30]
Period of return	POR = CC/NAB	[30]

$$\dot{C}_{P,k} = \dot{C}_{F,k} - \dot{C}_{L,k} + \dot{Z}_k \quad (9)$$

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (10)$$

$$\dot{C}_i = c_i \cdot \dot{E}_i \quad (11)$$

where $\dot{C}_P$ is the cost rate of component product streams, $\dot{C}_F$ is the cost rate of component fuel streams, and $\dot{Z}_k$ is capital investment and operating and maintenance cost rate of the component.

The cost associated with exergy destruction rate of each component can be calculated by Eq. (12) [26].

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

The exergoeconomic factor can be obtained as follows:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k}\dot{E}_{D,k}} \quad (13)$$

Also, the relative cost difference of each component calculated as follows:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1-\psi_k}{\psi_k} + \frac{\dot{Z}_k}{c_{f,k}\dot{E}_{P,k}} \quad (14)$$

3.5. Exergoenvironmental and footprint

In recent decades, the researchers and industries have considered environmental matters significantly. The power production or consumption systems have a remarkable amount of impacts on the environment. In this article, life cycle assessment (LCA) was regarded as a tool for researching the unit's environmental aspects. Such study takes into account the impacts of each unit component through its development, activity, and degradation. Combining LCA with the analyzes of exergy brings out useful data and information, named exergoenvironmental research. For each source, Eq. (15) indicates the relationship between the exergy and the environmental impact.

$$\dot{B}_i = b_i \dot{E}_i \quad (15)$$

where $\dot{B}_i$ is the environmental impact rate in pts/s, b_i is the environmental impact per exergy unit in pts/kJ, and $\dot{E}_i$ is the exergy rate of the *i*th stream in kW. The environmental indicator unit 99 is referred to as the eco-indicator point (pt) or milli-point (mpts). The scale is set in such a way that the 1 Pt magnitude is indicative of one thousandth of the annual carbon load of a typical European inhabitant. Similar to exergoeconomic section, another balance equation can be written for the exergoenvironmental analysis as given by Eq. (16).

$$\sum \dot{B}_{\text{in},k} - \sum \dot{B}_{\text{out},k} + \dot{Y}_k = 0 \quad (16)$$

where $\dot{Y}_k$ is the environmental impact rate of *k*th component in pts/s and it can be determined from Eco Indicator 99 [33] for obtaining $\dot{Y}_k$, Eq. (17) can be used [34]:

$$\dot{Y}_k = \frac{Y_k}{3,600t \cdot n} \quad (17)$$

Environmental impact rate of RO in Mpts/hm^3 distillate using interpolation data gathered by Raluy et al. [35]:

$$\dot{Y}_{\text{RO}} = 0.0195 \times \frac{\rho \times \dot{W}_{\text{RO}}}{3,600 \times \dot{m}_{\text{RO-distillate}}} + 0.00595 \quad (18)$$

The environmental impacts associated with the exergy destruction can be calculated by Eq. (19) [34]:

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \quad (19)$$

Also, Eq. (22) has been developed to calculate the exergoenvironmental factor:

$$\text{fb}_k = \frac{\dot{Y}_k}{\dot{Y}_k + b_{f,k}\dot{E}_{D,k}} \quad (20)$$

The basic calculations for estimating ecological footprint are conceptually simple: first, per capita consumption of major consumables (e.g., energy, food, production, and consumption of forest products) is estimated by dividing total consumption by population. Many of the data needed for preliminary surveys are readily available in national statistical tables [36–41].

The footprint of energy has been defined as the ratio of the annual consumption to the average product of consumption of the energy [36–41].

$$\text{aai} = \frac{\text{annual consumption of an item}}{\text{average annual yield}} \tag{21}$$

The other footprints are the carbon footprint that has been defined as the carbon dioxide production from electricity consumption in the reverse osmosis plant [38–41]. The carbon footprint of the SWRO and BWRO powering is described in Table 8 per m^3 of desalinated water.

The flowchart of the calculations in this manuscript has been drawn as Fig. 2.

4. Results and discussion

4.1. Thermodynamic and energy

The rate of energy recovery varies from 50% to 90% depending on the type of energy recovery device. This paper investigates the effect of Pelton wheel, turbocharger, and pressure exchanger on the energy consumption of seawater and BWRO unit. The simulation of the base SWRO and BWRO units are done in the ROSA commercial software and the results are presented in Table 9. The other units that combine RO with ERDs are simulated in the MATLAB. It should be noted that the streams number are used from Fig. 1.

An important output of ROSA software is the analysis of each stream composition. The compositions of each stream (specially the salinity of streams) have shown in Table 10.

The analyses of different ions of feed streams, brine discharge, and freshwater are presented in Table 10. The results show that by using the desalination unit, the salinity content in seawater is reduced by about 0.5% in desalinated water. The amount of salinity present in the brine discharge stream from the reverse osmosis unit increases by approximately 67%.

As can be seen from Fig. 3, the amount of SEC in the reverse osmosis unit of seawater and brackish water without energy recovery unit is 4.4 and 0.72 kWh/m^3, respectively. By adding Pelton wheels to the SWRO unit, the recovered energy in the seawater reverse osmosis unit will be 5.5 kW which reduces the SEC of the unit to 3.1 kWh/m^3. Also, in the brackish water unit the recovered energy is equal to 0.53 kW and the SEC is reduced to 0.59 kWh/m^3. Using turbocharger in SWRO unit will result in energy recovery of about 6.82 kW and the specific energy consumed in this unit will be 2.74 kWh/m^3, which reduces energy consumption by 38% compared to reverse osmosis without ERD.

Table 8
Carbon footprint for powering a reverse osmosis desalination plant (in g of carbon dioxide equivalent per m^3 of feedwater)

Energy source	SWRO	BWRO
Coal	3,580	364.9
Oil	2,729	278.1
Natural gas	2,121	216.2
Biomass	300	30.6
Solar PV	248	25.3
Geothermal	233	23.7
Wind	109	11.1
Hydroelectric	89	9.1
Nuclear	49	5.0

4.2. Economic

The costs and benefits analysis results are presented in Fig. 4. The initial cost associated with purchasing equipment, the cost of replacement, and the operating costs of each reverse osmosis units are very important parameters that are offered to attract an investor. The highest initial cost associated with purchasing equipment must be paid for a seawater reverse osmosis unit with a pressure exchanger. The unit costs are about 33% more than the seawater reverse osmosis unit. The cost of purchasing equipment in BWRO units is less than half that of seawater reverse osmosis units. Comparison of the replacement cost in SWRO units shows that in all units is approximately doubled by adding energy recovery units. This is because of the cost of adding a valuable equipment as ERDs to the plant. The comparison of the operating costs shows that by coupling ERDs to SWRO and BWRO units in all five scenarios, operating flow costs are reduced. The results of the ACS parameter show that the sum of the annual costs of reverse osmosis unit without ERD and the SWRO unit with turbocharger is equal. The next parameter is the net annual benefit of each unit. The net benefit of SWRO units with energy recovery compared to non-energy recovery units will increase from 70% to 100%. But this increase is not seen in BWRO units, and the net yearly benefit is almost constant with and without the energy recovery unit.

The levelized cost of freshwater production, the rate of return on capital, and the period of return on each of the reverse osmosis units are shown in Fig. 5. It is clear that the coupling of the SWRO unit with turbocharger has the maximum rate of return and the minimum period of return. The turbocharger imposes lower PECs to the unit than the pressure exchanger but the efficiency of it is close to the pressure exchanger. But in BWRO units, the use of ERDs has no economic justification. This is due to the low efficiency of the equipment at low pressure and low flow rates of BWRO units.

4.3. Exergy

The rate of exergy destruction is one of the most important parameters to determine the efficiency of an equipment in unit. If the exergy destruction rates in seawater reverse osmosis units are compared, it is clear from the results of Table 11 that with the use of turbocharger and pressure exchanger in SWRO units, the total exergy destruction rate is reduced highly. The highest exergy destruction occurs at the HPP. Comparison of exergy destruction in energy recovery units show that the pressure exchanger has the highest exergy destruction. This equipment accounts for about 41% of the total exergy destruction of the seawater reverse osmosis unit.

Table 9
Thermodynamic properties of the SWRO and BWRO with ERDs

Stream	SWRO								BWRO							
	P (bar)	T (°C)	Mass flow (kg/s)	h (kJ/kg)	s (kJ/kg °C)	Physical exergy (MW)	Chemical exergy (MW)	Total exergy (MW)	P (bar)	T (°C)	Mass flow (kg/s)	h (kJ/kg)	s (kJ/kg °C)	Physical exergy (MW)	Chemical exergy (MW)	Total exergy (MW)
1	1.01	25	2.89	98.25	0.34	2.92	0.98	3.9	1.01	25	2.89	104.77	0.37	0.91	0.27	1.18
2	49	25.6	2.89	104.45	0.35	16.4	0.98	17.38	6.58	25	2.89	107.37	0.37	2.62	0.27	2.89
3	1.01	25.6	1.15	107.02	0.37	0.28	0	0.28	1.01	25	1.15	107.02	0.37	0.8	0	0.8
4	49	25.6	1.73	103	0.34	11.44	1.2	12.64	6.58	25	1.73	107.15	0.37	0.88	0.28	1.16
Stream	SWRO with Pelton wheel								BWRO with Pelton wheel							
1	1.01	25	2.89	98.25	0.34	2.92	0.98	3.9	1.01	25	2.89	104.77	0.37	0.91	0.27	1.18
2	49	25.6	2.89	104.45	0.35	16.4	0.98	17.38	6.58	25	2.89	107.37	0.37	2.62	0.27	2.89
3	1.01	25.6	1.15	107.02	0.37	0.28	0	0.28	1.01	25	1.15	107.02	0.37	0.8	0	0.8
4	49	25.6	1.73	103	0.34	11.44	1.2	12.64	6.58	25	1.73	107.15	0.37	0.88	0.28	1.16
5	1.01	25	1.73	96.86	0.33	3.41	1.2	4.61	1.01	25	1.73	104.55	0.37	0.48	0.28	0.76
Stream	SWRO with turbocharger								BWRO with turbocharger							
1	1.01	25	2.89	98.25	0.34	2.92	0.98	3.9	1.01	25	2.89	104.77	0.37	0.91	0.27	1.18
2	25.7	25.3	2.89	101.61	0.35	9.86	0.98	10.84	3.26	25	2.89	104.98	0.37	1.83	0.27	2.1
3	1.01	25.6	1.15	107.02	0.37	0.28	0	0.28	1.01	25	1.15	107.02	0.37	0.8	0	0.8
4	49	25.6	1.73	103	0.34	11.44	1.2	12.64	6.58	25	1.73	107.15	0.37	0.88	0.28	1.16
5	1.01	25	1.73	96.86	0.33	3.41	1.2	4.61	1.01	25	1.73	104.55	0.37	0.48	0.28	0.76
6	49	25.6	2.89	104.45	0.35	16.4	1.2	17.6	6.58	25	2.89	107.37	0.37	2.9	0.28	3.18
Stream	SWRO with pressure exchanger															
1	1.01	25	1.21	98.25	0.34	2.92	0.98	3.9								
2	49	25.6	1.21	104.45	0.35	6.85	0.98	7.83								
3	1.01	25.6	1.15	107.02	0.37	0.28	0	0.28								
4	49	25.6	1.73	103	0.34	11.44	1.2	12.64								
5	1.01	25	1.73	96.86	0.33	3.41	1.2	4.61								
6	1.01	25	1.68	98.25	0.34	1.7	1.2	2.9								
7	47.2	25.6	1.68	104.29	0.35	9.26	1.2	10.46								
8	49	25.6	1.68	104.45	0.35	9.55	1.2	10.75								

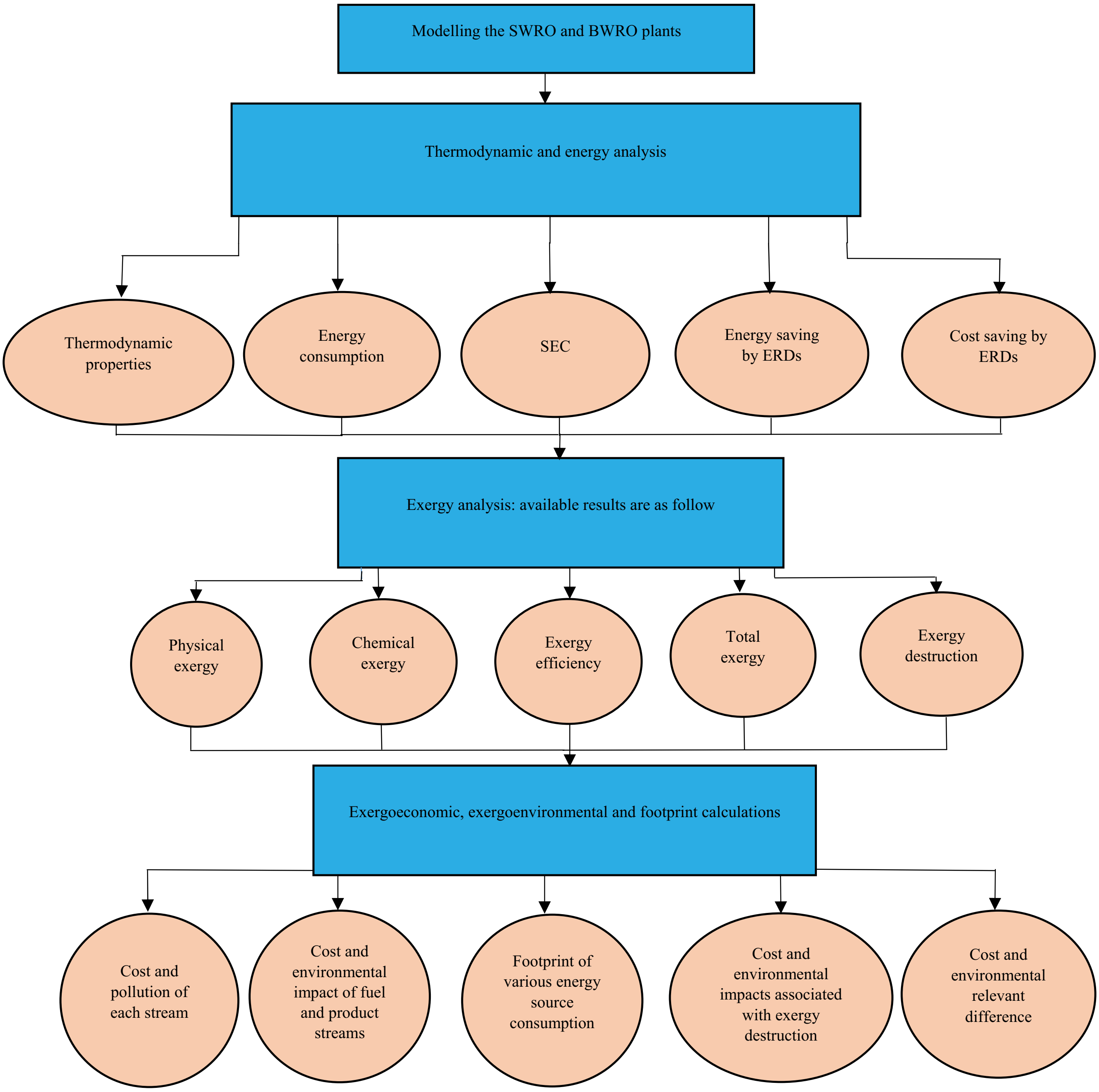

Fig. 2. Flowchart of the calculation path.

It is also evident in BWRO units that the amount of exergy destruction at the HPP is higher than other equipment. In BWRO units, on average, more than 75% of exergy destruction occurs by HPPs.

Fig. 6 shows the amount of exergy efficiency in different equipment. This figure shows that the exergy efficiency of the membrane in reverse osmosis units is almost constant and the exergy efficiency of the pump will be increased by adding energy recovery units. The pressure exchanger, Pelton wheel, and circulation pump also have the highest exergy efficiency rate among all equipment.

4.4. Exergoeconomic and exergoenvironmental

Table 12 shows the cost and pollutant values for each of the streams obtained by exergoeconomic and exergo environmental methods. These results can show how the energy recovery units influence the cost and contamination of the reverse osmosis unit.

The results show that the cost of power consumption at the SWRO unit pump is 0.88 × 10^{-3} (S/s), which is reduced by 30% by adding the Pelton wheel. Also, this cost reduces by up to 70% when the SWRO plant has been coupled to a turbocharger and reduces its associated

Table 10
Composition of each stream

Ions	SWRO			BWRO		
	Feed (mg/L)	Brine discharge (mg/L)	Desalinated water (mg/L)	Feed (mg/L)	Brine discharge (mg/L)	Desalinated water (mg/L)
$NH_4^+ + NH_3$	0	0	0	0.04	0.09	0
K	390	649.09	1.49	3.3	7.89	0.24
Na	10,968.55	18,258.94	36.58	1,577.16	3,890.45	35.06
Mg	1,310	2,182.95	1	6	14.88	0.08
Ca	410	683.22	0.31	84.68	210.09	1.08
Sr	13	21.66	0.01	0.7	1.74	0.01
Ba	0.05	0.08	0	0.07	0.17	0
CO_3	7.87	15.58	0	1.85	10.56	0
HCO_3	152	248.11	0.78	265	636.73	9.19
NO_3	0	0	0	4.3	10.2	0.37
Cl	19,700	32,797.48	60.24	2,426.5	5,990.25	50.8
F	1.4	2.33	0.01	0.14	0.34	0.01
SO_4	2,740	4,566.71	0.84	24	59.76	0.16
SiO_2	5	8.32	0.03	9	22.43	0.04
Boron	4.5	7.12	0.58	0	0	0
CO_2	1.91	3.3	2.25	6.43	9.66	7.14
TDS	35,723.62	59,475.15	178.36	4,402.75	10,855.6	153.04
pH	7.6	7.6	5.71	7.6	7.71	6.28

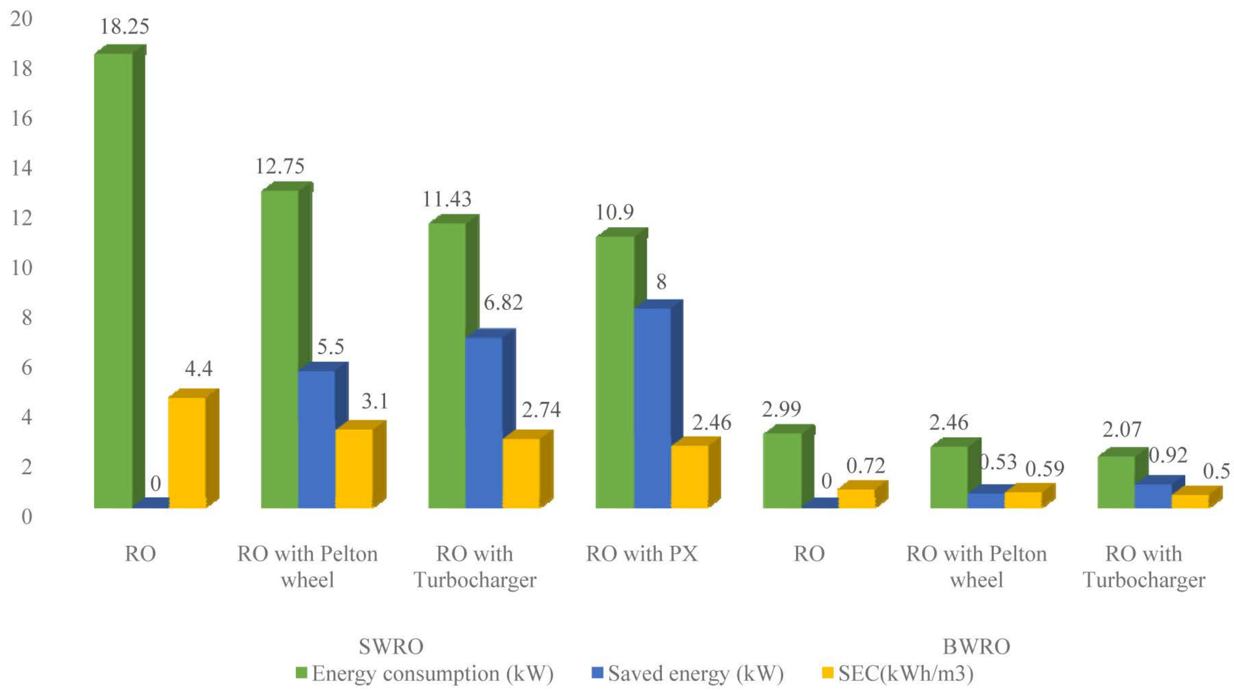

Fig. 3. Energy consumption, specific energy consumption (SEC), and saved energy in various SWRO and BWRO plants.

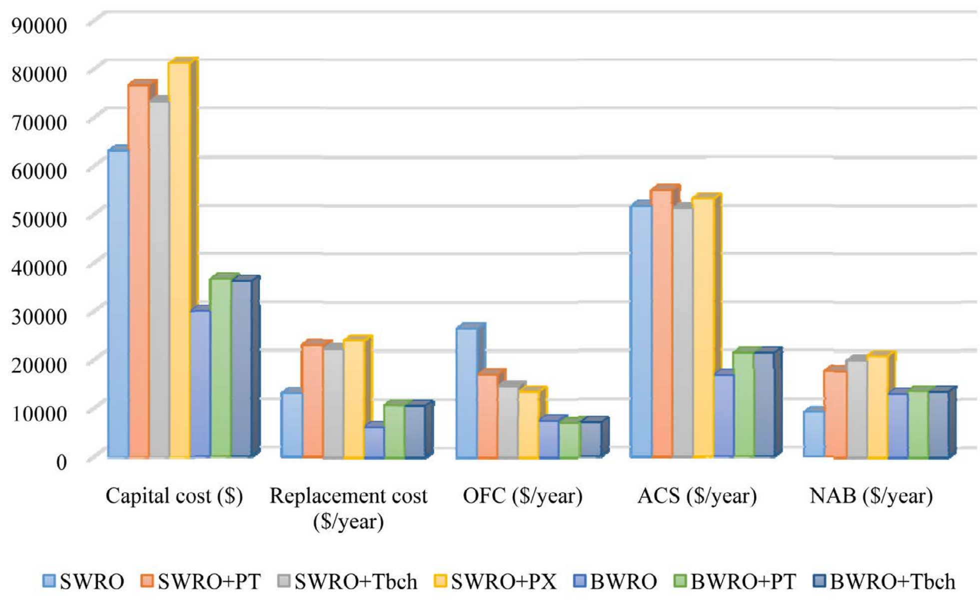

Fig. 4. Costs and benefits analysis of SWRO and BWRO units.

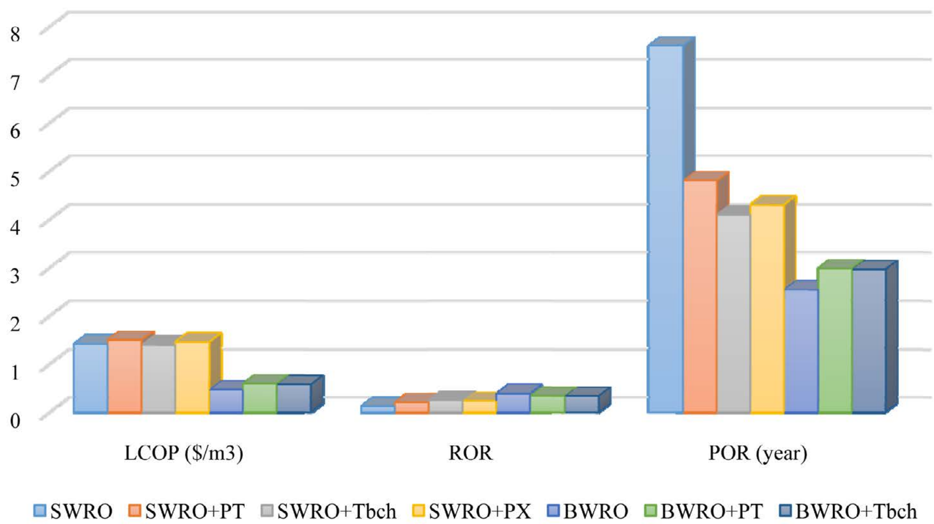

Fig. 5. LCOP, ROR, and POR results in SWRO and BWRO units.

Table 11
Exergy destruction rate of each component

Component	SWRO				BWRO		
	RO	RO with Pelton wheel	RO with turbocharger	RO with PX	RO	RO with Pelton wheel	RO with turbocharger
High-pressure pump	31.74	31.44	15.26	11.14	6.32	5.99	5.23
Membrane	4.46	4.46	4.68	5.66	1.33	1.33	1.34
ERD	0.00	8.04	9.02	9.70	0.00	1.67	1.87
Circulation pump	0.00	0.00	0.00	0.29	0.00	0.00	0.00

Table 12
Cost and environmental impact of each stream associated with exergy rate (×10^{-3})

Stream	SWRO				BWRO			
	C ($/kJ)	$\dot{C}$ ($/s)	b (mpts/kJ)	$\dot{B}$ (mpts/s)	C ($/kJ)	$\dot{C}$ ($/s)	b (mpts/kJ)	$\dot{B}$ (mpts/s)
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.05	0.84	5.50	95.60	0.05	0.15	16.00	46.20
3	0.03	0.01	0.00	0.00	0.01	0.01	0.00	0.00
4	0.04	0.56	7.10	89.70	0.05	0.06	39.00	45.20
W_{Pump}	0.05	0.88	5.50	100.00	0.10	0.19	26.90	50.00
Stream	SWRO with Pelton wheel				BWRO with Pelton wheel			
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.03	0.58	3.80	66.00	0.05	0.15	12.00	34.70
3	0.03	0.01	0.00	0.00	0.01	0.01	0.00	0.00
4	0.04	0.56	5.20	65.70	0.05	0.06	65.00	75.40
5	0.04	0.21	6.00	27.70	0.05	0.04	65.00	49.40
W_{Pump}	0.03	0.61	3.80	69.40	0.09	0.13	22.60	33.90
$W_{\text{Energy recovery device}}$	0.03	0.26	3.80	29.80	0.09	0.03	22.60	8.16
Stream	SWRO with turbocharger				BWRO with turbocharger			
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.02	0.23	2.10	22.80	0.07	0.15	14.70	30.80
3	0.03	0.01	0.00	0.00	0.01	0.01	0.00	0.00
4	0.05	0.59	4.80	60.70	0.02	0.02	17.30	20.10
5	0.05	0.22	4.80	22.10	0.02	0.01	17.30	13.10
6	0.05	0.83	4.80	84.50	0.02	0.06	17.30	55.00
W_{Pump}	0.03	0.26	3.50	29.10	0.08	0.12	21.80	31.10
$W_{\text{Energy recovery device}}$	0.03	0.31	3.50	34.80	0.08	0.04	21.80	9.44
Stream	SWRO with pressure exchanger							
1	0.00	0.00	0.00	0.00				
2	0.02	0.16	2.50	19.60				
3	0.03	0.01	0.00	0.00				
4	0.14	1.72	7.10	89.70				
5	0.04	0.21	7.10	32.70				
6	0.00	0.00	0.00	0.00				
7	0.14	1.42	342.00	3,580.00				
8	0.21	2.29	342.00	3,670.00				
W_{Pump}	0.03	0.22	3.40	24.50				
$W_{\text{Energy recovery device}}$	0.03	0.33	3.40	37.50				

environmental impacts by up to 71.5%. By using the pressure exchanger, the cost of pump power consumption, and its environmental impacts can be reduced by up to 75% and 73%, respectively. The cost of recovered power is maximum in the integration of SWRO unit with Pelton wheel. In the BWRO unit, the cost of pump power consumption has been reduced by 78% than SWRO unit, with the integration of the Pelton wheel and turbocharger down to 33% and 37.5%, respectively.

The relative cost difference and relative environmental impacts differences give a good idea of the cost and pollutants of each equipment relative to their exergetic efficiency. However, the results of these specifications can also be seen in Fig. 7. The results show that in exergoeconomic factor, the highest rate is related to HPP and in exergoenvironmental factor, the highest rate is related to reverse osmosis membranes. The reason for the high exergoeconomic factor in the pump is the high purchase price of this equipment and the low fuel streams price. The reason for the high exergoenvironmental factor in the membrane is that the rate of environmental destruction caused by this equipment is low.

The results of the relative cost difference indicate that the use of a pressure exchanger will be more cost-effective. However, the results, in this case, do not have a particular maximum or minimum point and each unit has different

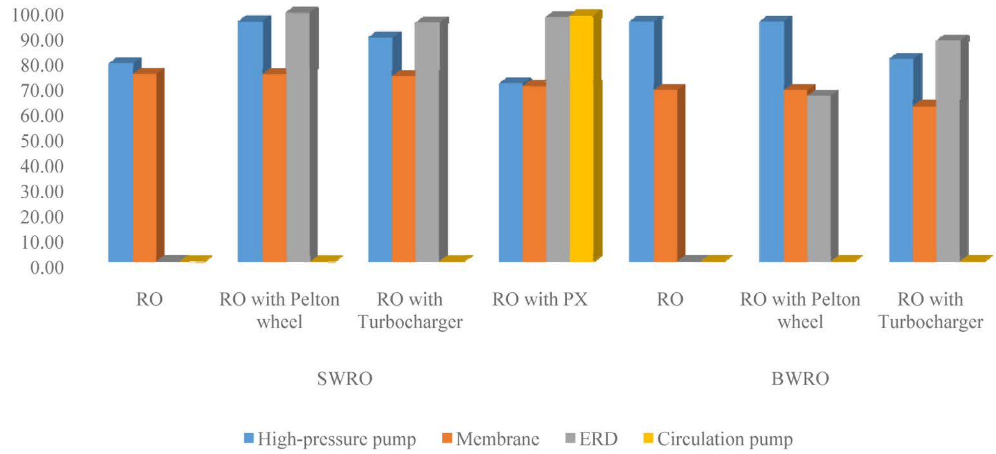

Fig. 6. Exergy efficiency of each components.

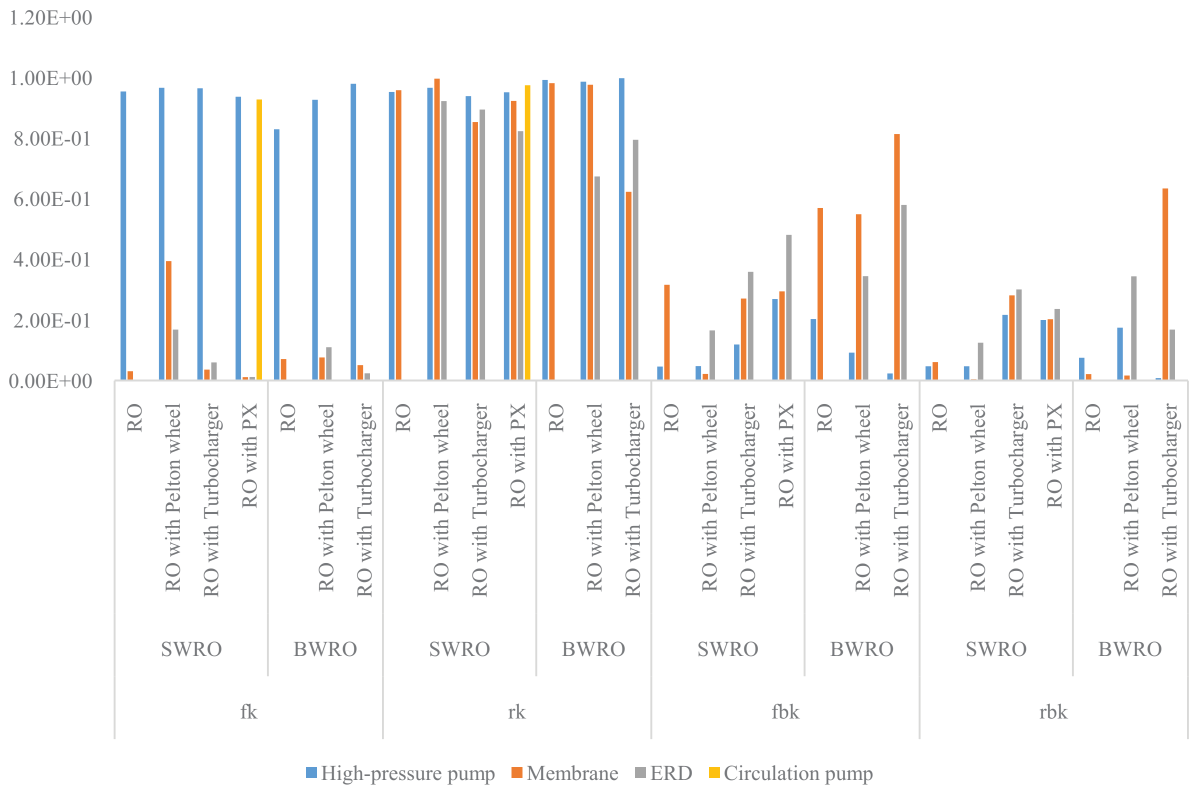

Fig. 7. Comparison of f_k, f_{bk}, r_k, and r_{bk} in the various reverse osmosis plants.

results. Also, for the difference of relative environmental impacts, the results indicate that membranes create higher relative environmental impacts difference in the reverse osmosis unit.

4.5. Footprint

To analyze the carbon dioxide footprint in seawater and BWRO units, one must calculate the amount of carbon dioxide released into the air based on the power used in the HPP. It is assumed that the power required by the reverse osmosis pump is provided by the combustion of fuels such as oil, natural gas, coal, and biomass or by renewable energy such as solar, wind, hydro, geothermal, and nuclear. Based on each of these energy sources, the carbon dioxide footprint is calculated and Fig. 8 presents the relative results. The results show that the carbon dioxide footprint is maximum when the power of seawater reverse osmosis provided

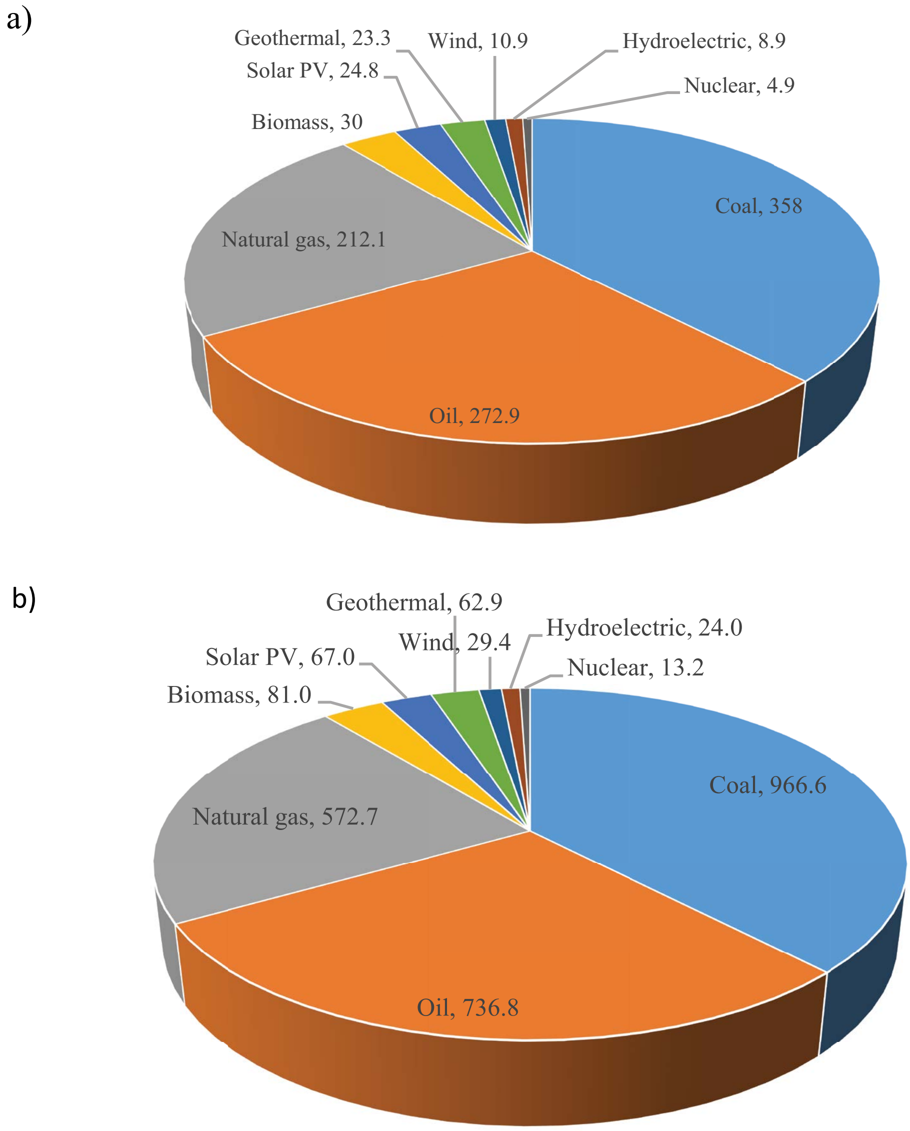

Fig. 8. Carbon footprint results in the different reverse osmosis units (g/d). (a) SWRO and (b) BWRO.

by combustion of coil. In the seawater reverse osmosis unit, the amount of carbon dioxide is about 41% lower when the natural gas has been used to provide the RO unit power.

In the BWRO unit, the results are similar to those of the seawater unit, and the use of coal increases the CO_2 emissions.

4.6. Sensitivity analysis

Given the low cost of production water and the power consumption by the plants in Iran, sensitivity analysis is one of the important issues that creates a great deal of confidence in the use of energy recovery units. In this analysis, the price of electricity varies between \$0.001 and \$0.009/kWh and the cost of freshwater produced varies between \$0.4 and \$2.5/m^3. The results for the annual net benefit in seawater and brackish units are presented in Figs. 9 and 10, respectively. The negative numbers in Figs. 9 and 10 indicate the economic loss to the unit. The results show that the net benefit in SWRO units is improved by using better technology of energy recovery units such as pressure exchanger and net annual benefit is approximately improved constantly in brackish units due to low power consumption. With the increase in the price of freshwater, the benefit obtained per unit has increased and with the increase in the price of power consumption, the benefit obtained decreases. It is clear from the figures that with a maximum input power price and a price of less than \$0.5/m^3 for freshwater produced, the unit will be unprofitable.

The results for the effect of power consumption cost and desalinated water price on the SWRO and BWRO units' period of return are presented in Figs. 11–14. The results of the period of return sensitivity analysis indicate that the higher efficiency of the energy recovery unit causes the lower effects of the sensitivity of the system to changes in electricity and freshwater prices.

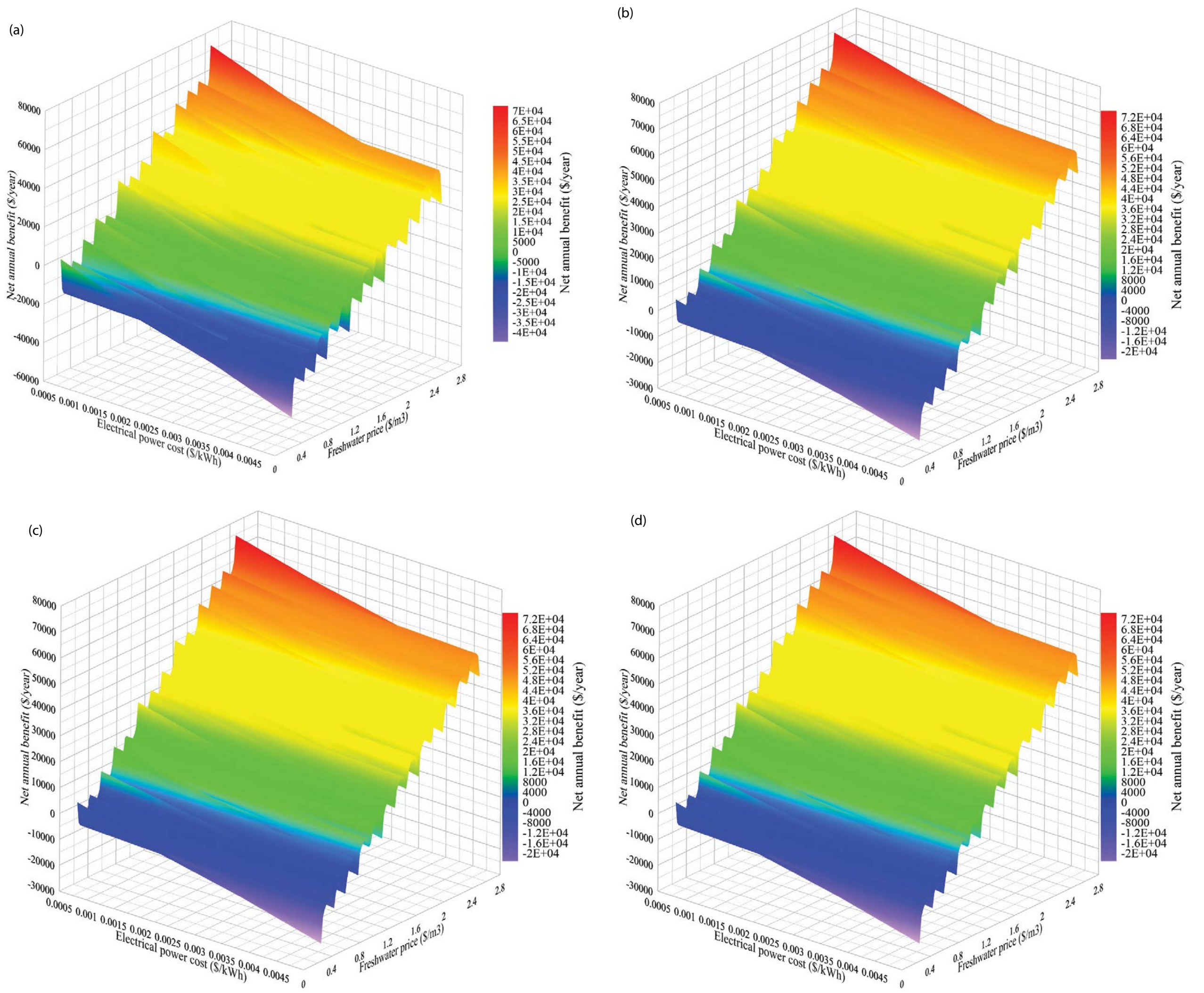

Fig. 9. Sensitivity analysis of the SWRO units net annual benefit, (a) SWRO, (b) SWRO + PT, (c) SWRO + Tbch, and (d) SWRO + PX.

The results of the sensitivity analysis as shown in Figs. 12 and 14 indicated that in order to have a period of return less than 5 y in BWRO units with ERDs, it should be reasonable for the power consumption cost to be between 0 and 0.01 ($/kWh), but the price of freshwater must be more than $0.5/m^3.

Also, in SWRO units integrated with ERDs, as shown in Figs. 11 and 13 to have a period of return less than 5 y, the cost of power consumption must be below $0.03/kWh and the price of freshwater produced must be above $1/m^3.

As shown in Fig. 12, the cost of power consumption has a low effect on the period of return in the BWRO units because of the low power consumption in these units. However, the results of Figs. 13 and 14 indicated that the desalinated water price has a major effect on the period of return in the SWRO and BWRO units.

5. Conclusion

In this paper, the energy recovery in RO units examined by using Pelton turbine, turbocharger, and pressure exchanger were calculated by examining a 100 m^3/d SWRO and BWRO desalination plants with the help of reverse osmosis units design software (ROSA) and MATLAB software code. The following is an overview of the results.

- The coupling of the pressure exchanger with the SWRO unit will result in the maximum energy recovery of about 8 kW and the minimum SEC about 2.46 kWh/m^3.
- The coupling of the SWRO unit with turbocharger has the maximum rate of return (about 40%) and the minimum period of return (about 4 y), but in BWRO units, the use of ERDs have no economic justification.
- Comparison of exergy destruction in energy recovery units shows that the pressure exchanger has the highest exergy destruction. This equipment accounts for about 41% of the total exergy destruction of the SWRO unit.
- The carbon dioxide footprint is maximum when the power of seawater reverse osmosis provided by combustion of coil. In the seawater reverse osmosis unit, the amount of carbon dioxide is about 41% lower when the

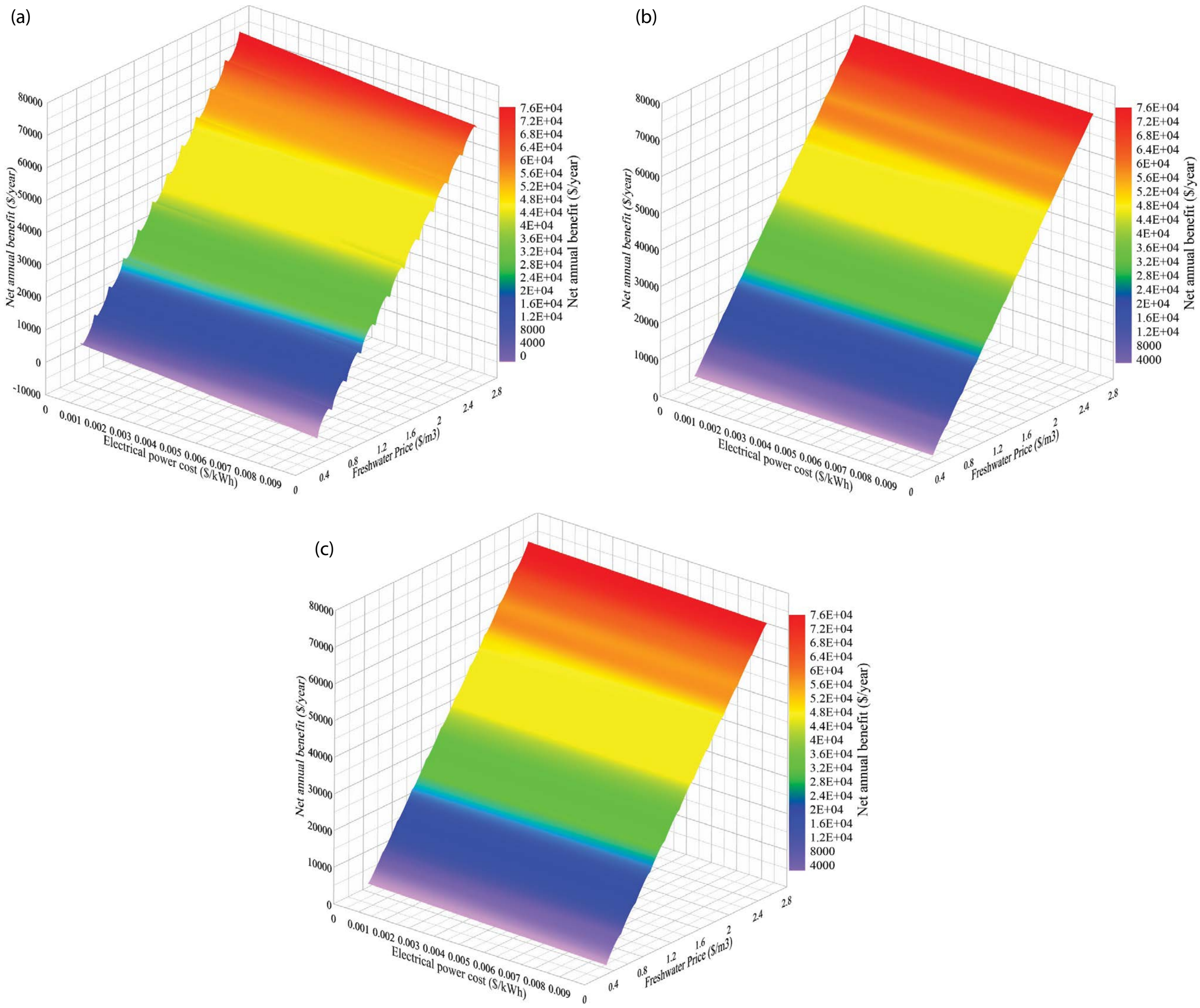

Fig. 10. Sensitivity analysis of the SWRO units net annual benefit, (a) BWRO, (b) BWRO + PT, and (c) BWRO + Tbch.

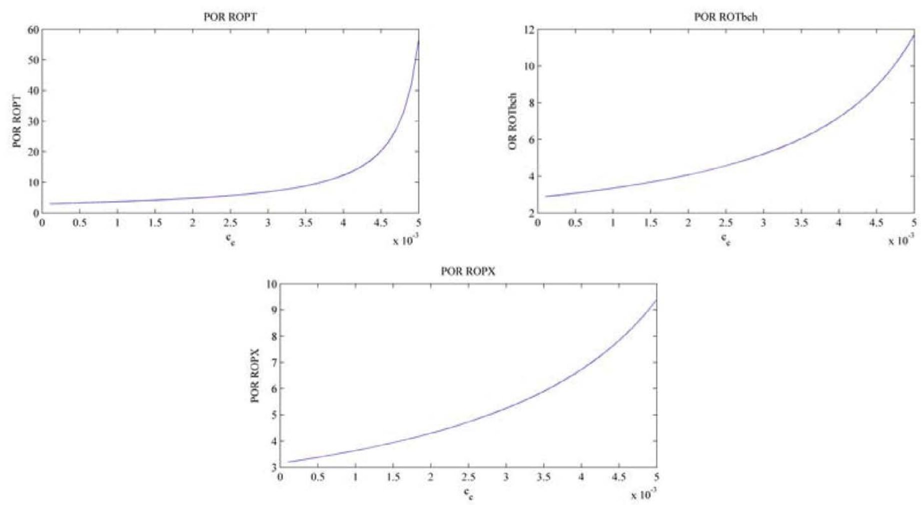

Fig. 11. Sensitivity analysis of the effect of power cost on the SWRO with ERD units' period of return.

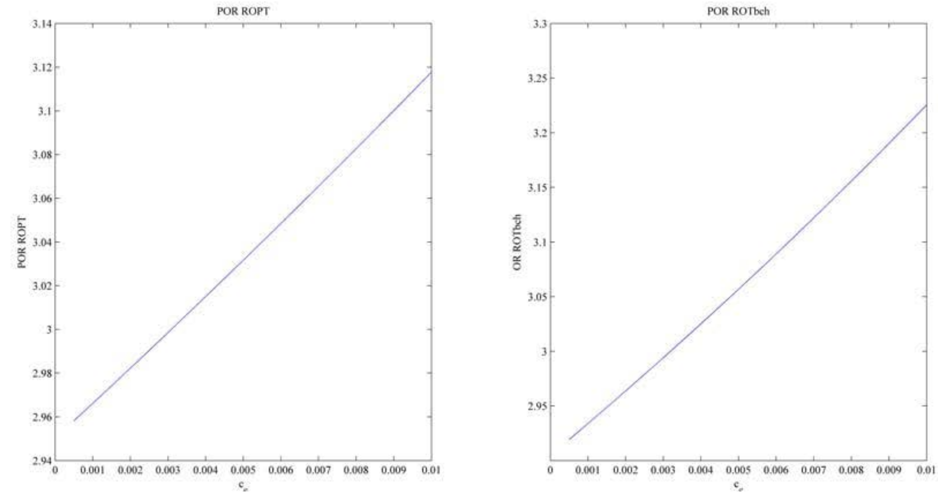

Fig. 12. Sensitivity analysis of the effect of power cost on the BWRO with ERD units' period of return.

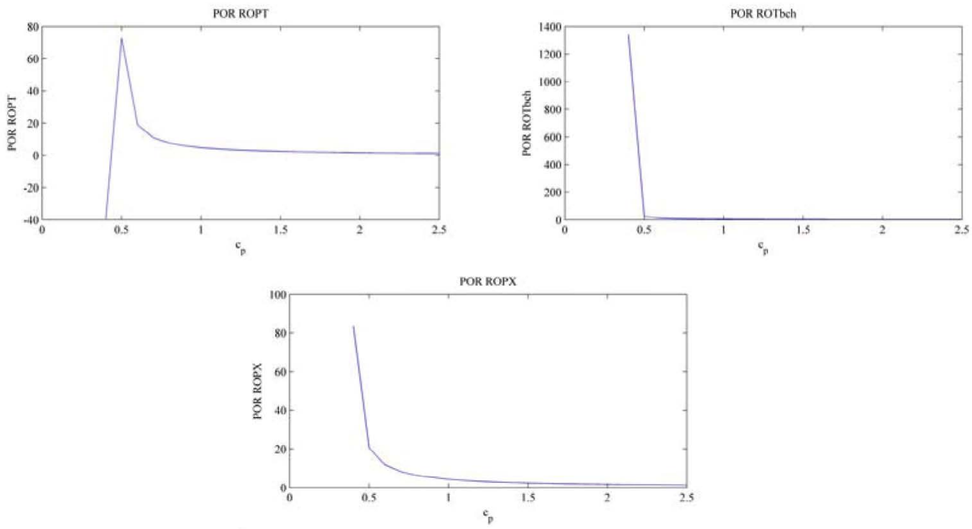

Fig. 13. Sensitivity analysis of the effect of desalinated water price on the SWRO units' period of return.

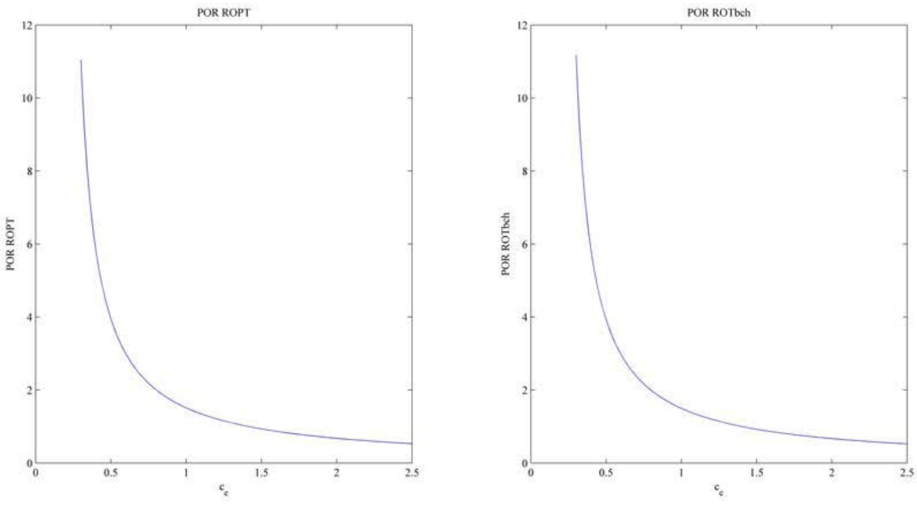

Fig. 14. Sensitivity analysis of the effect of desalinated water price on the BWRO units' period of return.

natural gas has been used to provide the RO unit power demand.

- The results of the period of return in sensitivity analysis indicate that the higher efficiency of the ERD cause the lower sensitivity of the period of return to change with power consumption and freshwater prices.

Symbols

A — Area
B — Brine
b — Environmental impact per exergy unit
$\dot{B}$ — Environmental impact rate
c — Cost per exergy unit
$\dot{C}$ — Cost rate
CRF — Capital recovery factor
ES — Energy saving
ex — Specific exergy
$\dot{E}x$ — Exergy rate
f — Exergoeconomic factor
fb — Exergoenvironmental factor
h — Enthalpy
i — Interest rate
J — Specific mass flow rate
$\dot{m}$ — Mass flow rate
MW — Molecular weight
mpts — Eco-indicator mili-points per time unit
P — Pressure
PEC — Purchase equipment cost
PT — Pelton turbine
PX — Pressure exchanger
r — Relative cost difference
Rb — Relative environmental impact difference
RR — Recovery ratio
S — Entropy
SEC — Specific energy consumption
SWRO — Seawater reverse osmosis
T — Temperature
Tbch — Turbocharger
W — Work
Y — Environmental impact of the component
$\dot{Y}$ — Environmental impact rate of the equipment
$\dot{Z}$ — Cost rate of the equipment

Greek letters

Γ — Ratio of the specific heats
Δ — Difference
ψ — Exergetic efficiency
H — Efficiency
P — Density
Π — Osmotic pressure

Subscripts

D — Destruction
F — Fuel
P — Product
Sw — Seawater

References

[1] M. Wakeel, B. Chen, T. Hayat, A. Alsaedi, B. Ahmad, Energy consumption for water use cycles in different countries: a review, Appl. Energy, 178 (2016) 868–885.
[2] N. Voutchkov, Energy use for membrane seawater desalination–current status and trends, Desalination, 431 (2018) 2–14.
[3] R.K. McGovern, On the potential of forward osmosis to energetically outperform reverse osmosis desalination, J. Membr. Sci., 469 (2014) 245–250.
[4] A. Shrivastava, S. Rosenberg, M. Peery, Energy efficiency breakdown of reverse osmosis and its implications on future innovation roadmap for desalination, Desalination, 368 (2015) 181–192.
[5] J. Kim, S. Hong, A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination, Desalination, 429 (2018) 142–154.
[6] N. Ghaffour, The challenge of capacity-building strategies and perspectives for desalination for sustainable water use in MENA, Desal. Water Treat., 5 (2009) 48–53.
[7] J.R. Werber, A. Deshmukh, M. Elimelech, The critical need for increased selectivity, not increased water permeability, for desalination membranes, Environ. Sci. Technol. Lett., 3 (2016) 112–120.
[8] P.C. Milly, K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438 (2005) 347–350.
[9] V. Ramanathan, Y. Feng, Air pollution, greenhouse gases and climate change: global and regional perspectives, Atmos. Environ., 43 (2009) 37–50.
[10] M.W. Shahzad, M. Burhan, L. Ang, K.C. Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination, 413 (2017) 52–64.
[11] J.T. Kim, J.-H. Choe, J.-S. Kim, D. Seo, Y.D. Kim, K.H. Chung, Graphene-based plasmonic waveguide devices for electronic-photonic integrated circuit, Opt. Laser Technol., 106 (2018) 76–86.
[12] S.G. Rothausen, D. Conway, Greenhouse-gas emissions from energy use in the water sector, Nat. Clim. Change, 1 (2011) 210–219.
[13] J. Kim, K. Park, D.R. Yang, S. Hong, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants, Appl. Energy, 254 (2019), doi: 10.1016/j.apenergy.2019.113652.
[14] M. Elimelech, W.A. Phillip, The future of seawater desalination: energy, technology, and the environment, Science, 333 (2011) 712–717.
[15] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res., 43 (2009) 2317–2348.
[16] N. Ghaffour, S. Lattemann, T. Missimer, K.C. Ng, S. Sinha, G. Amy, Renewable energy-driven innovative energy-efficient desalination technologies, Appl. Energy, 136 (2014) 1155–1165.
[17] A. Drak, M. Adato, Energy recovery consideration in brackish water desalination, Desalination, 339 (2014) 34–39.
[18] V.G. Gude, Energy storage for desalination processes powered by renewable energy and waste heat sources, Appl. Energy, 137 (2015) 877–898.
[19] C.F. Wan, T.-S. Chung, Energy recovery by pressure retarded osmosis (PRO) in SWRO–PRO integrated processes, Appl. Energy, 162 (2016) 687–698.
[20] R. Tariq, N.A. Sheikh, J. Xamán, A. Bassam, An innovative air saturator for humidification-dehumidification desalination application, Appl. Energy, 228 (2018) 789–807.
[21] N. Voutchkov, Desalination Engineering: Planning and Design, McGraw Hill Professional, 2012.
[22] J.L. Prante, J.A. Ruskowitz, A.E. Childress, A. Achilli, RO-PRO desalination: an integrated low-energy approach to seawater desalination, Appl. Energy, 120 (2014) 104–114.
[23] R.S. El-Emam, I. Dincer, Thermodynamic and thermoeconomic analyses of seawater reverse osmosis desalination plant with energy recovery, Energy, 64 (2014) 154–163.
[24] A. Al-Zahrani, J. Orfi, Z. Al-Suhaibani, B. Salim, H. Al-Ansary, Thermodynamic analysis of a reverse osmosis desalination unit with energy recovery system, Procedia Eng., 33 (2012) 404–414.
[25] A. Farooque, A. Jamaluddin, A.R. Al-Reweli, P. Jalaluddin, S. Al-Marwani, A. Al-Mobayed, A. Qasim, Comparative Study of Various Energy Recovery Devices Used in SWRO Process,

Saline Water Desalination Research Institute, Saline Water Conversion Corporation (SWCC), Al-Jubail, Saudi Arabia, 2004.
[26] A. Bejan, G. Tsatsaronis, M.J. Moran, Thermal Design and Optimization, Wiley, New York, NY, 1996.
[27] A. Malek, M. Hawlader, J. Ho, Design and economics of RO seawater desalination, Desalination, 105 (1996) 245–261.
[28] R. Turton, R.C. Bailie, W.B. Whiting, J.A. Shaeiwitz, Analysis, Synthesis and Design of Chemical Processes, Pearson Education, Upper Saddle River, NJ, 2008.
[29] S. Rahimi, M. Meratizaman, S. Monadizadeh, M. Amidpour, Techno-economic analysis of wind turbine–PEM (polymer electrolyte membrane) fuel cell hybrid system in standalone area, Energy, 67 (2014) 381–396.
[30] H.A. Reyhani, M. Meratizaman, A. Ebrahimi, O. Pourali, M. Amidpour, Thermodynamic and economic optimization of SOFC-GT and its cogeneration opportunities using generated syngas from heavy fuel oil gasification, Energy, 107 (2016) 141–164.
[31] M.A. Jamil, B.A. Qureshi, S.M. Zubair, Exergo-economic analysis of a seawater reverse osmosis desalination plant with various retrofit options, Desalination, 401 (2017) 88–98.
[32] I. Dincer, M.A. Rosen, P. Ahmadi, Optimization of Energy Systems, Wiley, New York, 2017.
[33] M. Goedkoop, R. Spriensma, S. Effting, M. Collignon, The Eco-indicator 99: A Damage Oriented Method for Life-cycle Impact Assessment: Manual for Designers, PRé, Product Ecology Consultants, 2000.
[34] E.J.C. Cavalcanti, Exergoeconomic and exergoenvironmental analyses of an integrated solar combined cycle system, Renewable Sustainable Energy Rev., 67 (2017) 507–519.
[35] G. Raluy, L. Serra, J. Uche, Life cycle assessment of MSF, MED and RO desalination technologies, Energy, 31 (2006) 2361–2372.
[36] B. Holmatov, A. Hoekstra, M. Krol, Land, water and carbon footprints of circular bioenergy production systems, Renewable Sustainable Energy Rev., 111 (2019) 224–235.
[37] A. Demirbas, Political, economic and environmental impacts of biofuels: a review, Appl. Energy 86 (2009) S108–S117.
[38] G.P. Hammond, B. Li, Environmental and resource burdens associated with world biofuel production out to 2050: footprint components from carbon emissions and land use to waste arisings and water consumption, Gcb Bioenergy, 8 (2016) 894–908.
[39] H. Alderson, G.R. Cranston, G.P. Hammond, Carbon and environmental footprinting of low carbon UK electricity futures to 2050, Energy, 48 (2012) 96–107.
[40] D. Gupta, S.K. Gaur, Carbon and biofuel footprinting of global production of biofuels, Biomass Biopolym. Based Mater. Bioenergy, (2019) 449–481, https://doi.org/10.1016/B978-0-08-102426-3.00019-9.
[41] R.W. Howarth, R. Santoro, A. Ingraffea, Methane and the greenhouse-gas footprint of natural gas from shale formations, Clim. Change, 106 (2011) 679, doi: 10.1007/s10584-011-0061-5.