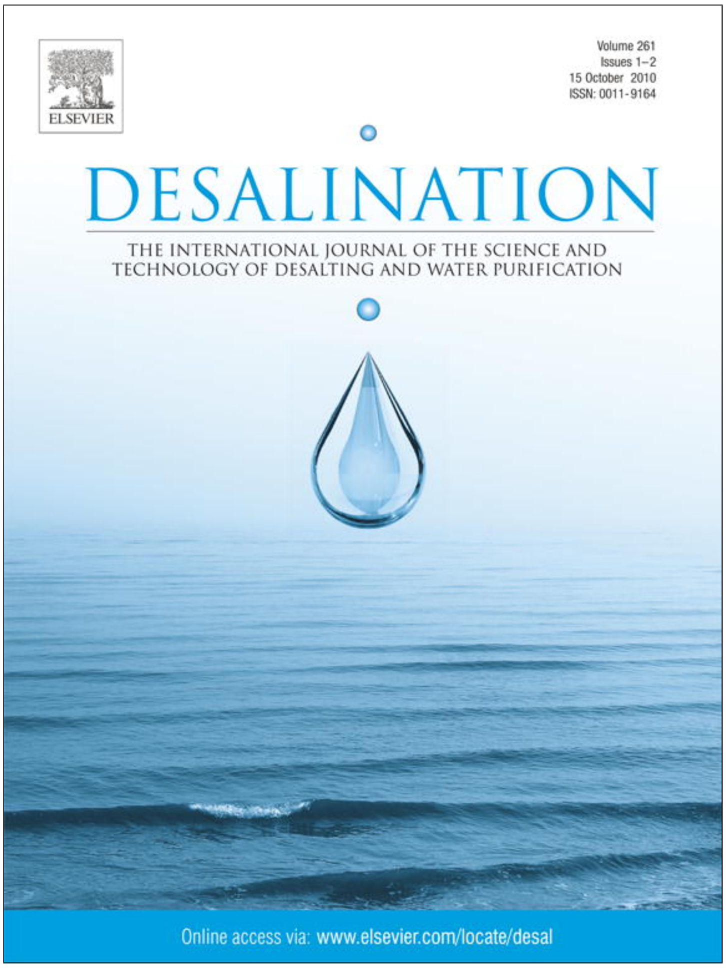
Volume 261
Issues 1–2
15 October 2010
ISSN: 0011-9164
ELSEVIER
DESALINATION
THE INTERNATIONAL JOURNAL OF THE SCIENCE AND TECHNOLOGY OF DESALTING AND WATER PURIFICATION
Online access via: www.elsevier.com/locate/desal

Desalination 261 (2010) 138–147

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Thermo-economic analysis of a combined solar organic Rankine cycle-reverse osmosis desalination process with different energy recovery configurations

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ARTICLE INFO

Article history:
Received 6 February 2010
Received in revised form 9 May 2010
Accepted 10 May 2010
Available online 17 June 2010

Keywords:
Thermo-economic
Reverse osmosis (RO)
Solar Rankine cycle
MatLab/SimuLink

ABSTRACT

Thermo-economy is a useful and powerful tool that combines thermodynamics and economics. It can evaluate how irreversibility and costs of any process affect the exergoeconomic cost of the product. In this work, a number of comparisons for solar thermal-powered different recovery units for reverse osmosis desalination system are performed using thermo-economic analysis. Three different configurations are used for this comparison (Basic, Pelton Wheel Turbine, and the Pressure Exchanger) with Sharm El-Shiekh RO desalination plant for a total productivity about 145.8 m^3/h (40.5 kg/s). As a result of this analysis, the unit product cost of Pelton Wheel Turbine (PWT) and Pressure Exchanger (PEX) configurations are 24% and 24.2% respectively less than that of the basic configuration. Thermo-economic analysis shows that the minimum investment and operating & maintenance costs are obtained by PEX configuration. Also, it achieves minimum exergy destruction against the two other configurations (Pelton Wheel and Basic systems). Therefore, the final conclusion of this work is that the PEX configuration is more economical than either stand alone or PWT configurations.

1. Introduction

The amount of fresh water resources in Mediterranean countries is continuously decreasing due to increasing demand and low rainfall. Moreover, strong variations of annual rainfall have been registered in the last few years. One result of this is that the management systems of the water resources have been improved. An economic analysis of industrial desalination processes shows that the most important factors influencing water cost include both energy cost and capital costs. Therefore, these two parameters should be specially improved in order to reduce the cost of the desalinated water. The energy costs of desalination may be reduced by means of the following two options: (1) the use of non-conventional energy sources and (2) the minimization of energy consumption and economic optimization [1]. The application of renewable energies such as solar energy to produce fresh water is receiving increased interest due to the need for solving the water shortage problems in various areas of the world at the same time as conventional energy sources used for obtaining water in different scenarios become depleted. The use of renewable energy sources in water desalination is of interest, especially for remote areas where a conventional energy supply is not easily available [2]. Over the past few decades, the reverse osmosis (RO) process of seawater desalination has gained much popularity. RO is a membrane process, and was developed in direct competition with distillation processes. Its main feature is that it requires no thermal energy but, rather, mechanical energy in the form of a high pressure pump. For these high pressure desalination systems, the addition of energy recovery devices allows a tremendous reduction in the overall energy requirement of the RO plant [3]. The energy to produce the required pressure for RO can be generated with renewable energy sources such as wind energy, solar thermo-electrical plants or photovoltaic solar electrical generation. Solar thermal energy coupled to a power cycle by using direct mechanical power can also be employed.

Solar organic Rankine cycle (ORC) considered remarkable to generate mechanical power for RO high pressure pump. Organic fluids (hydrocarbons, fluorocarbons, siloxanes…) can be used. The main advantage of organic working fluids in Rankine cycles is that they can be driven at lower temperatures than similar cycles using water and also in many cases superheating is not necessary. Also, the efficiency of the turbine unit is higher due to the higher molar mass of the organic fluid and the performance of the Rankine cycle slightly increases with superheating, then the top temperature required is not too high. Delgado-Torres et al. [3,4] gave a detailed analysis of low power (100 kW) solar driven Rankine cycles for medium range of operating temperatures (120 °C–400 °C, one-axis sun tracking collectors).

Although a large variety of different working fluids have been proposed in the literature for solar applications, Toluene is the working fluid used in most of the solar pilot facilities [3]. Therefore, it is selected to perform the analysis presented in this work. Direct solar

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doi:10.1016/j.desal.2010.05.017

vapor generation (DVG) within the absorber tube configuration of solar collector with ORC is analyzed and characterized with LS3 parabolic trough collector (PTC) models. The power output from the turbine is used to drive a (RO) unit with Pressure Exchanger (PEX) configuration. In Delgado-Torres's work, the organic Rankine cycle and the RO systems were not modeled by the same simulation platform and the cost analysis wasn't considered in that work. Voros [5] investigated the solar energy exploitation for assisting the operation of reverse osmosis seawater desalination plants. A hybrid solar-assisted steam cycle was designed in order to provide the required shaft work to drive the RO high pressure pump.

In Voros work, solar energy was in share with conventional cycle and not stands alone. Moreover, Voros [5] work established for RO unit with only Pelton Wheel Turbine (PWT) device. Nafey et al. [6] investigated the operation of RO system with different operating conditions and different configurations of solar Rankine cycle. In Nafey's work, energy, exergy, and cost analysis was performed only for RO basic configuration (PWT and Pressure Exchanger (PEX) were not considered). Nafey et al. work [6] recommended that Toluene with parabolic trough collector under super heat operation considered the most economic to drive RO desalination process.

Mark Wilf [7] considered the configuration and operating parameters of RO desalination systems. In this work, a combined solar ORC (solar collector, turbine, recuperator, condenser, and pump), with a RO unit and different energy recovery configurations are considered. Using a thermo-economic analysis, a comparison for the considered configurations of energy recovery units (PWT, and PEX) with RO desalination system is executed. The analysis and investigations are performed using the developed Solar Desalination Systems (SDS) package [8] under same platform of MatLab/SimuLink [9] computational environments. SDS package is a powerful tool box dealing with different configurations, techniques and types of solar desalination systems and it is also improved to calculate different kind of analysis such as energy, exergy, cost and thermo-economic.

2. Overview on the SDS package

Using the developed Solar Desalination Systems (SDS) package, different types and configurations of solar thermal desalination plants can be designed and simulated. The process units are modeled then the design and performance calculations are performed using the developed SDS program under MatLab/SimuLink computational environment. Different types of calculations such as energy, exergy, and thermo-economics can be performed by the developed SDS package. Desalination plant components (units), such as heat exchangers, flash chambers, evaporators, pumps, pipes, etc. are stored as blocks in a visual library. Using this visual library, different configurations can be constructed by just clicking the mouse over the required units (blocks). To construct such a configuration, the designer needs to drag the required units from the visual library and drop it in the panel. Then these blocks (units) are visually arranged similar to the real plant (for more details, see reference [8]).

3. The process configurations

Based on previous studies by the authors [6], Toluene is selected for ORC process with PTC under superheat operating conditions. It is required to desalinate and produce a total capacity of 145.8 m^3/h from RO module (Sharm El-Shiekh desalination plant). The developed SDS program is used to assemble and design the required solar ORC–RO units. By connecting between these units, the cycle becomes ready for energy, exergy, and thermo-economic calculations. The design parameters for the reverse osmosis (RO) plant are listed in Table 1. For design calculation and based on the RO mathematical model and plant specifications [6]; the product and plant recovery ratio considered known. However, specific power consumption, mass flow rate, the required feed pressure, the product salinity, the rejected brine mass flow rate, salt rejection percentage, and the high pressure pump and auxiliary power needed are calculated. The element area for RO module is fixed as 35.3 m^2 while using FTSW30HR-380. The RO high pressure pump (HPP), and PWT efficiencies were fixed at 80% and 96% value was fixed for PEX. The input feed seawater temperature is assigned by the output preheated stream from the ORC condenser unit. The assumptions and specified parameters for the proposed cycle model may be listed as following:

Table 1
Specifications of Sharm El-Shiekh RO desalination plant [10].

Variable	Value
Feed flow rate, m^3/h	468
Feed salinity, TDS, ppm	45,000
Recovery ratio	0.30
# of stages	1
Fouling factor	0.85
Feed pressure, bar	68
# of elements/vessel	42/7

- Rankine cycle gross work will be assigned by RO unit.
- The analysis performed at the design point, in which a direct normal irradiance of 850 W/m^2, and this considered a typical peak along summer time for Egypt and Mediterranean countries.
- Turbine, generator, and Rankine pump efficiencies would be fixed as 85%, 95%, and 75% respectively.
- Top temperature (superheat) from solar collector field is fixed as 340 °C.
- Condensation and inlet seawater temperatures would be fixed at 35 °C and 20 °C respectively.
- Recuperator effectiveness will set as 0.8.
- The design limits for Parabolic trough collector are considered based on the analysis introduced in Delgado-Torres and García-Rodríguez work [3,4].
- Table 2 shows the specifications and design parameters of solar ORC.

3.1. ORC–RO (Basic configuration)

Fig. 1 shows the process schematic diagram of the solar ORC with the basic configuration of RO desalination system. The process consists of solar field (superheat), expansion turbine for power generation, recuperator unit for regeneration, condenser unit for heat rejection and preheating processes, and pump unit. The condenser outlet stream (preheated seawater) is pumped into the RO module for desalination process by a high pressure pump.

3.2. ORC–RO (PWT configuration)

Fig. 1 shows a schematic diagram of a combined RO desalination process with different energy recovery units. Fig. 1-a shows the basic RO process with the high pressure pump unit (HPP). Fig. 1-b illustrates the combined RO process with a Pelton Wheel Turbine (PWT) unit. The rejected brine from RO unit with its high pressure will drive the PWT and that can provide sufficient operational flexibility as a power recovery device. The value of 80% for PWT efficiency is considered in this work. The advantage of the Pelton wheel is that the flat efficiency curve in a wide range of concentrate flows, and concentrate exits the Pelton wheel at atmospheric pressure.

3.3. ORC–RO (PEX configuration)

Fig. 1-c shows the process schematic diagram of the RO process with a pressure exchanger unit (RO-PEX). A higher efficiency positive displacement power recovery devices (pressure exchangers), that in

Table 2
Specifications of solar ORC for RO desalination process.

Operating conditions	Specified	Calculated
Ambient temperature, °C	✓ 25.4	✗
Solar radiation, W/m^2	✓ 850	✗
Solar collector (PTC)		
Outlet temperature (dry saturated), °C	✓ 300	✗
Superheat temperature, °C	✓ 340	✗
Saturated pressure, bar	✗	✓
Area, m^2	✗	✓
Thermal efficiency, %	✗	✓
Exergy destruction rate, kW	✗	✓
Turbine unit		
Mass flow rate through the cycle,	✗	✓
Outlet turbine temperature, °C	✗	✓
Exergy destruction rate, kW	✗	✓
Power developed, kW	✗	✓
Turbine efficiency, %	✓ 85	✗
Recuperator unit		
Effectiveness, %	✓ 80	✗
Preheated temperature to the solar collector, °C	✗	✓
Area, m^2	✗	✓
Thermal power, kW	✗	✓
Exergy destruction, kW	✗	✓
Condenser unit		
Condensation temperature, °C	✓ 35	✗
Seawater temperature, °C	✓ 20	✗
Preheated seawater temperature, °C	✗	✓
Thermal power rejected, kW	✗	✓
Area, m^2	✗	✓
Exergy destruction rate, kW	✗	✓
Pump unit		
Efficiency, %	✓ 75	✗
High pressure, bar	✗	✓
Power developed, kW	✗	✓
Outlet temperature to recuperator unit, °C	✗	✓
Exergy destruction rate, kW	✗	✓

the past were only used in small RO seawater units, are also slowly gaining acceptance in large desalination plants. Hydraulic efficiency of such types of equipment is in the range of 94–96% [7]. In this work, the values of 80% and 96% are considered for booster pump and PEX unit respectively. Some of these devices utilize pistons; other transfer energy through a direct contact between concentrate and the feed stream. According to the Fig. 1-c, feed (F) is split into two streams. One stream (F1), which has a flow rate equivalent to the permeate flow (P), is pumped to the feed pressure by the main high pressure pump (HPP). The second stream (F2), which flow rate is equivalent to the concentrate flow, flows through pressure exchanger and exchanges pressure with the concentrate stream (C).

The pressure of stream F2 at the exit from the pressure exchanger is a function of concentrate pressure and efficiency of the pressure exchanger device. The pressure of stream F2 is lower by 3–5 bars than the pressure of stream F1 at the discharge of the HPP [7]. The pressure of stream F2 is increased to the pressure of stream F1by a Booster Pump (BP). Both streams (F1+F2) are combined at the entrance to the membrane feed manifold. The pressure exchangers are positive displacement devices and therefore have high transfer efficiency. Splitting the feed stream, as in the case of operating a PEX, leads to a significant reduction of the energy demand for the far smaller high pressure pump. Additionally, due to the high efficiency of the PEX, an amount of about 36.8% of the input energy can be recovered from the energy contained in the concentrate that leaves the modules with 37.4% of the initial value [11]. Nowadays PEX configuration has been used in over 400 seawater reverse osmosis plants worldwide [12].

4. Exergy, costs and thermo-economic analyses

Thermo-economic is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but crucial to the design and operation of a cost effective system [13]. Thermo-economic balance for any unit is performed based on exergy and cost balances. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as following [13];

$$\sum_{\text{out}} \dot{C} = \sum_{\text{in}} \dot{C} + Z^{\text{IC\&OM}} \tag{1}$$

where $\dot{C}$ the cost rate according to inlet and outlet streams, and $Z^{\text{IC\&OM}}$ is the capital investment and operating & maintenance costs. In exergy costing a cost is associated with each exergy stream. Thus, for inlet and outlet streams of matter with associated rates of exergy transfer $E_{i,o}$, power W, and the exergy transfer rate associated with heat transfer E_q it can be written as follows;

$$\dot{C}_{i,o} = c_{i,o} \dot{E}_{i,o} \tag{2}$$

$$\dot{C}_w = c_w \dot{W} \tag{3}$$

$$\dot{C}_q = c_q \dot{E}_q \tag{4}$$

where $c_{i,o,w,q}$ denote average costs per unit of exergy in \$/kJ for inlet (i), outlet (o), power (w), and energy (q) respectively.

4.1. Exergy analysis

Unlike energy, which is conserved in any process according to the first law of thermodynamics, exergy is destroyed due to irreversibility taking place in any process, which manifests itself in entropy creation or entropy increase. The availability equation for an open system in a uniform-state, uniform-flow process can be developed with the first and second law of thermodynamics. The general form of the availability is defined by the following equation [14].

$$A_2 - A_1 = A_q + A_w + A_{f_i} - A_{f_o} - I \tag{5}$$

Where $A_2 - A_1 = 0$ is the non-flow availability change in steady state condition, $A_q = \sum_j \left(1 - \frac{T_{amb}}{T_j}\right) Q_j$ is the availability transfer due to the heat transfer between the control of volume j and its surroundings, $A_w = -W_{cv} + P_0\,(V_2 - V_1)$ is equal to the negative value of the work produced by the control volume but in most cases the control volume has a constant volume, therefore A_w can be further simplified. And $I = T_{amb} \times S_{gen}$ is the availability destruction in the process. The flow availability expressed as $A_{f_{i,o}} = \sum_{i,o} m_{i,o} a_{f_{i,o}}$. So the general form in steady state condition would become;

$$A_q + A_w + A_{f_i} - A_{f_o} = I. \tag{6}$$

By simplifying A_{f_i} and A_{f_e}, the following equation can be used;

$$A_{f_i} - A_{f_o} = m_{i,o}((h_i - h_o) - T_{\text{amb}}(s_i - s_o)). \tag{7}$$

Based on the above general equations of exergy destruction; analysis will be set unit by unit for the entire considered process. Total exergy destruction rate in kW for the combined solar ORC with a RO desalination process can be found by the summing of all irreversibility as following:

$$I_{\text{total}} = \left(I_{\text{collector}} + I_{\text{turbine}} + I_{\text{rec}} + I_{\text{condenser}} + I_{\text{pump}} + I_{\text{ro}}\right). \tag{8}$$

The exergy destruction for solar collector is calculated based on the following equation;

$$I_{\text{collector}} = A_{\text{col}} \times G_b \times \left(1 - \frac{T_{\text{amb}}}{T_{\text{sun}}}\right) + \dot{m}_{\text{col}}[h_i - h_o - T_{\text{amb}}(s_i - s_o)]_{\text{col}}. \tag{9}$$

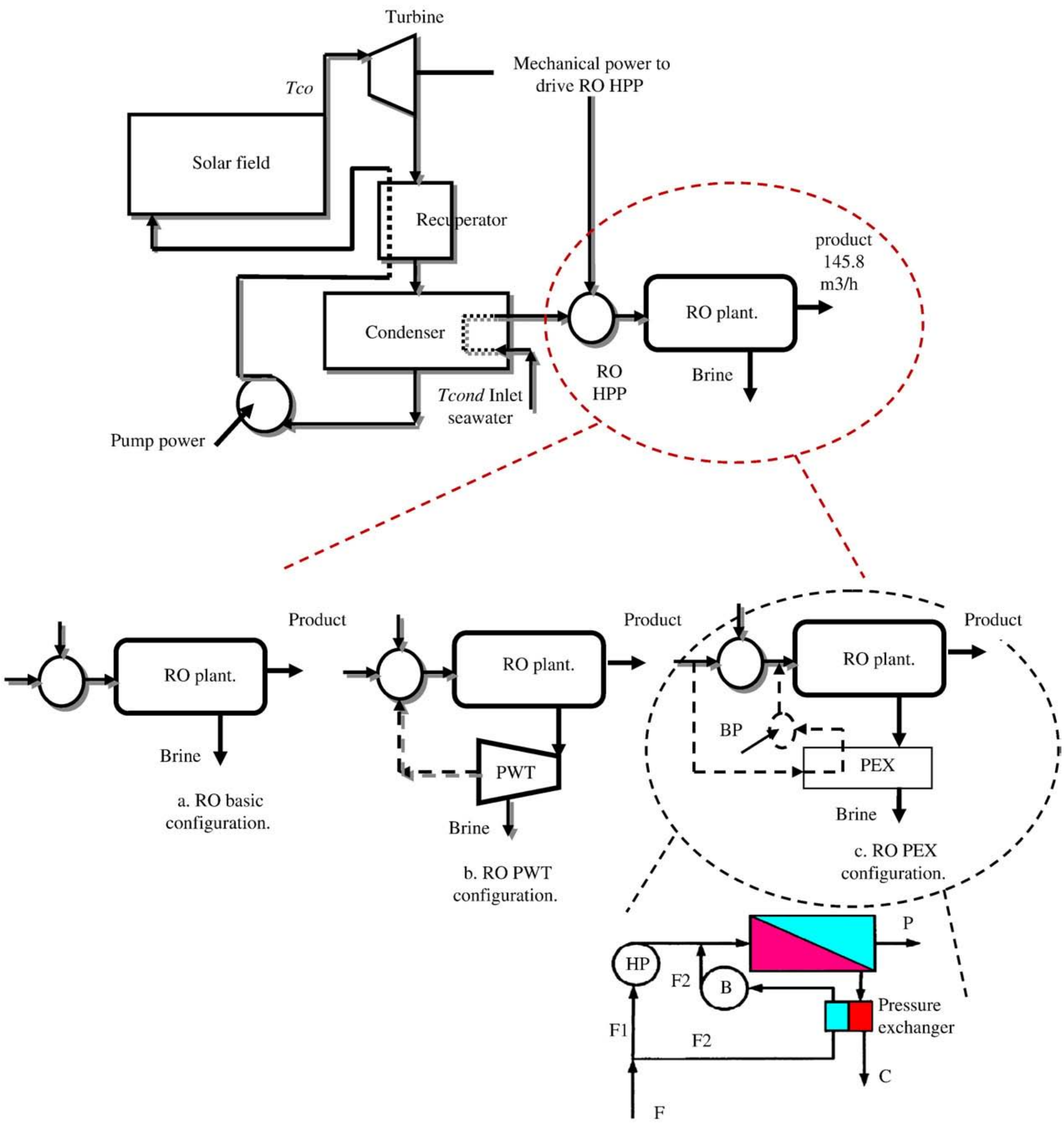


Fig. 1. A schematic diagram of the RO process with different energy recovery units.

Bejan [15] has recommended $T_{sun} = 6000$ K and this is used in this study.

$$I_{turbine} = \dot{m}_{turbine}[h_i - h_o - T_{amb}(s_i - s_o)]_{turbine} - W_t \tag{10}$$

$$I_{rec} = \dot{m}_{rec}[h_i - h_o - T_{amb}(s_i - s_o)]_{Hot} + \dot{m}_{rec}[h_i - h_o - T_{amb}(s_i - s_o)]_{Cold} \tag{11}$$

$$I_{condenser} = \dot{m}_{cond}[h_i - h_o - T_{amb}(s_i - s_o)]_{cond} + \dot{m}_{cw}\left[h_{cw_i} - h_{cw_o} - T_{amb}\left(s_{cw_i} - s_{cw_o}\right)\right]_{cw} \tag{12}$$

$$I_{pump} = \dot{m}_{pump}[h_i - h_o - T_{amb}(s_i - s_o)]_{pump} + W_p \tag{13}$$

$$I_{RO} = W_{HPP} - \dot{m}_b \times \left(h_f - h_b\right) + \dot{m}_p \times \left(h_f - h_p\right) \tag{14}$$

where h_f, h_b, and h_p is calculated based on seawater specific heat capacity, salinity X, and feed seawater temperature for each stream [17] where;

$$h_{f,p,b} = h_o + \left(A \times T + {}^{B}/_{2} \times T^2 + {}^{C}/_{3} \times T^3 + {}^{D}/_{4} \times T^4\right)$$

Where; $h_o = 9.6296 \times X - 0.4312402 \times X^2$

And;

$$A = 4206.8 - 6.6197 \times X + 1.2288 \times 10^{-2} \times X^2$$

$$B = -1.1262 + 5.4178 \times 10^{-2} \times X - 2.2719 \times 10^{-4} \times X^2$$

$$C = 1.2026 - 5.3566 \times 10^{-4} \times X + 1.8906 \times 10^{-6} \times X^2$$

$$D = 6.8774 \times 10^{-7} + 1.517 \times 10^{-6} \times X - 4.4268 \times 10^{-9} \times X^2.$$

Exergy efficiency can be measured as a relationship between ingoing and outgoing exergy flows [12] or the ratio of net exergy output to the actual exergy input for any given system when achieving the required task.

$$\eta_{ex} = \frac{E_p}{E_q + W_p + E_f} \tag{15}$$

4.2. Cost analyses

Cost analysis is introduced based on two major parts. First of them is the solar organic Rankine cycle, and the second is the RO desalination plant.

4.2.1. Cost analysis of solar organic Rankine cycle

For this part, investment and operating & maintenance costs analyses are performed for each component, solar field, steam turbine, recuperator, condenser, and pump unit. For this purpose; the amortization factor is estimated based on the following relation [16];

$$A_f = \frac{i.(1+i)^{LTp}}{(1+i)^{LTp-1}} \tag{16}$$

where i is the interest rate and set as 5%, LT_p is the plant lifetime and set as 20 years. Table 3 illustrates the indirect capital cost ICC, and operating and maintenance O&M costs for solar Rankine cycle components.

4.2.2. Cost analysis of RO unit

For this part, cost analyses are estimated based on direct capital costs (DCC), indirect capital costs (ICC), and the total capital costs (TCC). Table 4 illustrates the costs for RO desalination plant.

4.3. Thermo-economic analyses

Based on thermo-economic fundamentals as presented in Eq. (1); the thermo-economic balance equations for each component in the combined processes (ORC/RO) should be presented as following;

For Rankine cycle pump unit;

$$C_{pump-rec} = C_w + C_{cond-pump} + Z^{IC\&OM}_{pump}. \tag{17}$$

For solar collector; the relation should become;

$$C_{col-st} = C_q + C_{rec-col} + Z^{IC\&OM}_{pump}. \tag{18}$$

And for steam turbine unit;

$$C_{st-rec} + C_{w-HPP} = C_{col-st} + Z^{IC\&OM}_{st}. \tag{19}$$

For recuperator unit, the relation becomes as following;

$$C_{rec-cond} + C_{rec-col} = C_{st-rec} + C_{pump-rec} + Z^{IC\&OM}_{rec}. \tag{20}$$

For condenser unit;

$$C_{cond-pump} + C_{cond-HPP} = C_{cw} + C_{rec-cond} + Z^{IC\&OM}_{cond}. \tag{21}$$

For high pressure pump of RO unit;

$$C_{HPP} = C_{cond-HPP} + C_{w-st} + Z^{IC\&OM}_{HPP}. \tag{22}$$

For RO module;

$$C_p + C_{brine} = C_{feed} + Z^{IC\&OM}_{RO}. \tag{23}$$

For Pelton wheel recovery turbine;

$$C_{w-HPP} + C_{brine-blowdown} = C_{brine-RO-PWT} + Z^{IC\&OM}_{PWT}. \tag{24}$$

For pressure exchanger unit;

$$C_{feed-RO} + C_{brine-blowdown} = C_{feed} + C_{brine-RO-PEX} + Z^{IC\&OM}_{PEX}. \tag{25}$$

By solving the above equations together, the following equation could maintain the overall thermo-economic balance of the system.

$$C_{brine-blowdown} + C_{product} = C_{cw-cond} + C_{q-col} + C_{w-pump} + Z^{IC\&OM}_{total} \tag{26}$$

where

$$Z^{IC\&OM}_{total} = Z^{IC\&OM}_{pump} + Z^{IC\&OM}_{col} + Z^{IC\&OM}_{st} + Z^{IC\&OM}_{rec} + \cdots Z^{IC\&OM}_{cond} + Z^{IC\&OM}_{HPP} + Z^{IC\&OM}_{PEX,PWT}. \tag{27}$$

Assuming that for any flow from the environment, external valuation of the unit exergoeconomic cost is performed. In this work, this involves seawater, and solar radiation (free) and external consumption. Also, for any flow without later usefulness (losses), zero unit exergoeconomic cost is assigned and this involves brine blow down. Therefore, the overall equation will become as follows;

$$C_p = C_{w-pump} + Z^{IC\&OM}_{total} \tag{28}$$

$$c_p = \frac{c_{cw} + c_{w-pump} + Z^{IC\&OM}_{total}}{E_p} \$/\mathrm{GJ} \tag{29}$$

where E_p is the exergy of the product stream from RO desalination plant.

5. Results and discussions

The general specifications and the specified design parameters of the combined processes for two energy recovery configurations for a RO desalination process are illustrated in Table 5.

Based on the mathematical model for the considered process (see reference [6] for more details) and the energy, cost, and thermo-economic analysis presented in Section 4, the developed SDS program [8] gives the results illustrated in Tables 6 and 7.

Table 3
ICC and O&M costs for solar organic Rankine cycle components.

Parameter	ICC, $	O&M, $	TCC, $/y	Z^{ICOM}, $/h	Ref
Solar field	$150 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TCC_{col}/8760$	[5]
Steam turbine	$4750 \times (W_t)^{0.75}$	$25\% \times ICC_{st}$	$A_f \times (ICC + O\&M)_{st}$	$TCC_{st}/8760$	[5]
Recuperator	$150 \times (A_{rec})^{0.8}$	$25\% \times ICC_{rec}$	$A_f \times (ICC + O\&Mre)_{rec}$	$TCC_{rec}/8760$	[5]
Condenser	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TCC_{cond}/8760$	[5]
Pump	$3500 \times (W_p)^{0.47}$	$25\% \times ICC_{pump}$	$A_f \times (ICC + O\&M)_{pump}$	$TCC_{pump}/8760$	[5]

Table 4
ICC and O&M costs for RO desalination plant [16].

DCC, $	ICC, $	TCC, $	ACC, $/y	O&M, $/y	$Z^{IC\&OM}$, $/h
$CC_{swip} = 996 \times M_f^{0.8}$ $CC_{hpp} = 393000 + 10710 \times \Delta P_f$ $CC_e = F_e \times P_p \times N_p + F_e \times PV_p \times n_v$ $CC_{equip} = CC_{swip} + CC_{hpp} + CC_e$ $CC_{site} = 10\% \times CC_{equip}$ $DCC = CC_{equip} + CC_{site}$	$ICC = 27\% \times DCC$	$TCC = ICC + DCC$	$ACC = TCC \times A_f$	$OC_{power} = LF \times 0.06 \times SPC \times M_p$ $OC_{labor} = LF \times 0.01 \times M_p$ $OC_{chm} = LF \times 0.04 \times M_p$ $OC_{insur} = 0.005 \times TCC \times A_f$ $OC_{memb} = P_p \times N_p / LT_m$ $OC_{ro} = OC_{power} + OC_{labor} + OC_{chm} + OC_{insur} + OC_{memb}$	$Z^{IC\&OM} = (ACC + OC_{ro})/8760$

5.1. Results of basic configuration

Table 6 shows that the required power for the HPP of the RO process is 1.123 MW. This power is obtained by a 5377 m^2 of solar collector area and a mass flow rate of 4.934 kg/s. Also, Table 6 shows that the irreversibility of the basic configuration is 6 MW. This amount is distributed on the process components as shown in Table 7. The solar collector field irreversibility rate considered the highest among the other units with percentage about 48.3% of the total irreversibilities, followed by the RO plant with 45.4%, steam turbine with 2.8%; condenser and recuperator units both give 1.2%, and the pump unit with a sharing percentage of about 0.4%. The overall exergy efficiency is 9.38% due to the outlet exergy streams (product stream) over inlet exergy streams (feed, pump power, and solar power to the system). The specific annual total costs (C_t, $/$m^3$) for this configuration is about 0.898$/$m^3$, with total investment and operation & maintenance costs ($Z^{IC+O\&M}$) about 131$/h. RO sector exhibits the largest percentage of ($Z^{IC+O\&M} = 131$/h) by 89.16% followed by steam turbine unit with 8.44$/h and a percentage of 6.44%. Solar field gives a percentage of 4.22%, recuperator unit with 0.018%, and condenser unit with 0.022%, and the pumping unit with a percentage of 0.111%. Thermo-economic unit product exergy cost is about 58.7$/GJ with a total water price (TWP) about 0.89$/$m^3$. The specific power consumption (SPC) is about 7.7 kWh/m^3 and this considered high regarding to the other configurations.

5.2. Results of PWT configuration

In this work the, PWT efficiency is set as 80% the same as the efficiency of HPP unit. The consumed power ($W_{HPP} - W_{PWT}$) would require about 3038 m^2 of solar collector field area with a percentage of decrease about 43.5% against the basic configuration. The consumed power of this configuration is decreased by 43.5% producing specific power consumption (SPC) about 4.35kWh/m^3. To maintain the same operating conditions for RO section (HPP pressure load should be = 68 bar for all configurations) the number of pressure vessels is then increased to become 44 instead of 42 as in basic plant. According to the less in total solar field area comparing with the basic one, the total irreversibility (3.763 MW) would decrease against the basic configuration (6 MW) with a percentage of 37.2%. RO section gives the highest exergy destruction of about 1.91 MW with a percentage of 50.7% followed by solar collector field with a percentage of 43.45%, steam turbine gives a percentage about 2.6%, recuperator and condenser units result together 2.84%, and the organic cycle pump unit gives 0.34%. This configuration exhibits larger exergy efficiency than of the basic one (11% against 9.3%) with a percentage of increases about 15%. The specific annual total costs for this configuration is about 0.683$/$m^3$, with total investment and operation & maintenance costs ($Z^{IC+O\&M}$) about 99.58$/h meaning by this a percentage of decreasing equal to 24% against the basic configuration. RO sector costs about 91.2% of all the total $Z^{IC+O\&M} = 99.58$/h, and this due to the additional costs of PWT drive, and the exceeding of permeators numbers. Steam turbine is followed by a cost of 5.5$/h with a sharing percentage about 5.5%. Solar collector field consumes about 3.215$/h with a percentage of 3.22%, followed by both recuperator and condenser units with a percentage 0.035%, and the organic Rankine cycle pump unit with a percentage of 0.11%. The plant total water price is about 0.0.69$/$m^3$, and the unit product cost becomes 59.2$/GJ. This configuration is favorable against the basic configuration due to many aspects such as total exergy efficiency, total irreversibility, total solar collector area, specific power consumption (SPC) and total water price (TWP).

5.3. Results of PEX configuration

Table 6 shows that the PEX configuration consumes very low power compared against the past two configurations. The developed power by the Rankine cycle steam turbine is about 0.394 MW with a power decreasing percentage of about 65% against the basic configuration. This leads to specific power consumption of about 2.7 kWh/m^3 with mass flow rate and total solar field area of about 1.732 kg/s and 1887 m^2 respectively. To maintain the operating pressure over the HPP in RO section; the number of pressure vessels become 48 instead of 42 as in the basic and 44 as in PWT configurations. The reduction in the power is caused by splitting the sea water feed stream which in turn decreases the total solar collector field area. Therefore; the total irreversibility rates for this configuration is about 2.538 MW which representing a percentage of decrease of about 57.7% against the basic configuration. RO section irreversibility has a large sharing with a percentage of about 54.5%, and the steam turbine gives about 2.36%, recuperator and condenser units together give about 2.5%, and the Rankine cycle pump unit gives about 0.33%, and the solar field gives about 41.8%. The overall exergy efficiency is increased from 9.3% for the basic to become 11.6% for this configuration. Also the total inlet exergy rate is reduced from 6.59 MW in the basic to become 2.87 MW. This is due to the reduction of the solar collector area against the basic configuration. The specific annual total cost (C_t, $/$m^3$) for this configuration is about 0.68$/$m^3$, with total investment and operation & maintenance costs ($Z^{IC+O\&M}$) of about 99.26$/h which leads to 24.2% less than the basic configuration. The major costs belong to RO section which consumes about 93.94% followed by solar collector field with 2.06%, steam turbine gives about 3.8%, and recuperator, condenser, and pump units give about 0.023%. The expenditures of RO section exceeded due to the high prices of recovery units however the total plant expenditures for this configuration considered the lowest against the other configurations due to the high effect of solar collector cost. It is clear from Tables 6, 7 that PEX configuration appears lowest against the remaining configurations regarding to the solar collector area cost, collector area irreversibility, total power, specific power consumption, cycle flow rate, total water price, total capital costs, total investment and operating & maintenance costs. It is clear that solar collector field produces larger irreversibility only in case of the basic RO; however; $RO_{section}$/PWT–PEX produces larger exergy destruction due to the less in exergy inlet to the cycle. Moreover, larger costs are belonging to RO section followed by steam turbine, and solar field respectively. ORC pump produces the lowest cycle irreversibility rate in the range of 9–28 kW for the considered configurations followed by the recuperator and the condenser units respectively. From Table 7, it is obvious that and regardless the final thermo-economic product cost c_p, the unit cost stream from pump unit to recuperator unit c_{p-rec} is particularly high (about 2.07, 2.32, and 2.57$/GJ for basic, PWT, and PEX configurations respectively). The recuperator to solar collector stream cost $c_{rec-col}$ comes next and it decreases from the basic configuration down to PEX. Cooling sea water cost stream is decreased from the basic down to PEX. The most important parameter is thermo-economic unit product cost which is obviously less in basic followed by PWT, then the PEX configuration. That's because the increase of power cost stream and at the same time the decreasing of exergy of product stream as presented in Eq. (29). This effect is indirectly proportional of preheated inlet seawater stream from the condenser unit. The exergy of the inlet seawater stream for the basic configuration considered the highest comparing against PWT and PEX respectively. And that would follow a decreasing in product exergy stream, moreover; that would increase the unit product cost of PEX followed by PWT then the basic one. Although the operation & maintenance costs ($Z^{IC+O\&M}$) is notable less in PEX configuration but the effect of unit power cost c_w and product exergy E_p is highly effective.

Based on the overall thermo-economic equation ($c_p = \frac{c_{cw} + c_{w\text{-pump}} + Z^{IC\&OM}_{total}}{E_p}\,\$/\mathrm{GJ}$), it is obvious that the unit product cost is highly dependent on product exergy which is also depending on the product mass flow rate. By increasing of water demand, the product exergy would increase related to the increase of mass flow rate. Also the upper side in the overall thermo-economic equation ($C_{cw} + C_{w\text{-pump}} + Z^{IC\&OM}_{total}$) will increase but the effect of product exergy is massive and leads to a decrease in the overall thermo-economic product cost. The unit product cost for basic configuration is noticed less than PWT and PEX configurations respectively. Although the basic configuration considered not recommended based on the consumed power, total solar collector area, total water price, but the product exergy is the highest due to the effect of the temperature of the preheated seawater from condenser unit. The preheated seawater leads to an increase in product exergy which will decrease the thermo-economic unit product cost. Fig. 2 shows the effect of fresh water production rate (m^3/h) on thermo-economic product cost ($/GJ). Increasing the productivity would decrease thermo-economic unit product cost but also would harvest much larger solar collector area and power from turbine unit. Fig. 3 shows the behavior of increasing the power consumption related to the productivity demand. Fig. 4 represents data results for each stream in solar ORC/RO-PEX configuration.

Table 6
Energy and thermo-economic results for different configurations.

Energy							
Parameter:	A_{col}, m^2	W_t, MW	m_{ORC} kg/s	η_R, %	P_{ev}, bar	SPC, kWh/m^3	RO ΔP, bar
Basic	5377	1.123	4.934	32.64	32.78	7.704	68.66
PWT	3038	0.634	2.788	32.64	32.78	4.35	68.74
PEX	1887	0.394	1.732	32.64	32.78	2.704	68.74
Thermo-economic (exergy & cost)							
Parameter:	I_{cycle}, MW	η_{ex}, %	E_{xin}, MW	C_t, $/$m^3$	$Z^{IC+O\&M}$, $/h	c_p, $/GJ	TWP, $/$m^3$
Basic	6	9.38	6.593	0.898	131	58.7	0.89
PWT	3.763	11.06	4.231	0.683	99.37	59.2	0.69
PEX	2.538	11.61	2.871	0.572	83.45	66.6	0.59

6. Conclusion

In this work, comparisons for different configurations of reverse osmosis energy recovery units powered by solar organic Rankine cycle have been performed using the exergy and thermo-economic analysis. The comparison performed based on the same platform and working under the same operating conditions. SDS software package is used to perform such analysis. The numerical results reveal that by the presence of PEX recovery unit, the needed solar collector field area to generate a sufficient power will not exceed about 1887 m^2 with a percentage of decreasing in the range of 65% against the basic configuration and PWT comes next with a percentage of 43.5%. As a result of decreasing the solar collector field area, the cycle total irreversibility would decrease from 6 MW to 2.538 MW. Moreover, the cycle flow rate will decrease from 4.934 kg/s to 1.732–1.8 kg/s. The total investment and operation & maintenance costs ($Z^{IC+O\&M}$) is 131, 99.58, and 83$/h for basic, PWT, and PEX respectively. For the three configurations, RO section consumes the largest $Z^{IC+O\&M}$ with a range of 80–93% of total costs followed by steam turbine with 3.8–6.4%; and solar collector field in the range of 2–4% of total costs. Although PEX consumes lower $Z^{IC+O\&M}$ costs but it considered the highest in thermo-economic unit product cost against the other configurations. The thermo-economic product cost is massively affected by the exergy of the product stream which considered the lowest in value for RO-PEX compared against the other configurations (347 kW vs. 490 kW for PWT and 662 kW for Basic). And that would explain the highest value of thermo-economic product cost for RO-

Table 5
Specifications and design parameters of the considered processes.

Parameter:		ORC/RO-Basic	ORC/RO-PWT	ORC/RO-PEX
Design point	G_b, W/m^2	850	850	850
	T_{amb}, °C	25	25	25
ORC	T_{co}/T_{sup}	300/340	300/340	300/340
	T_{cond}, °C	35	35	35
	η_t %	85	85	85
	η_p %	75	75	75
	η_g %	95	95	95
	ε_{rec} %	80	80	80
RO plant	m_p, kg/s	40.5	40.5	40.5
	X_f, ppm	45000	45000	45000
	RR	0.3	0.3	0.3
	n_e/n_v	7/43	7/44	7/48
	A_e, m^2	35.3	35.3	35.3
	η_{HPP} %	80	80	80
	η_{PWT} %	–	80	–
	η_{PEX} %	–	–	96
	FF %	85	85	85
Cost	LT_p, year	20	20	20
	LT_m, year	5	5	5
	LF %	90	90	90
	i %	5	5	5

Table 7
The comparison percentages for different configurations based on thermo-economic results.

Parameter:		Basic	PWT	PEX
Irreversibility, MW	I_{col}	2.89 (48.3%)	1.635 (43.45%)	1.061 (41.8%)
	I_{st}	0.173 (2.8%)	0.098 (2.6%)	0.06 (2.36%)
	I_{rec}	0.072 (1.2%)	0.04 (1.063%)	0.025 (0.985%)
	I_{cond}	0.111 (1.85%)	0.067 (1.78%)	0.043 (1.6%)
	I_{pump}	0.024 (0.4%)	0.013 (0.34%)	0.008 (0.335%)
	I_{ro}	2.725 (45.4%)	1.91 (50.7%)	1.384 (54.53%)
$Z^{IC+O\&M}$,$/h	Z_{col}	5.53 (4.22%)	3.215 (3.22%)	2.045 (2.06%)
	Z_{st}	8.442 (6.44%)	5.5 (5.5%)	3.85 (3.8%)
	Z_{rec}	0.024 (0.018%)	0.015 (0.015%)	0.01 (0.01%)
	Z_{cond}	0.03 (0.022%)	0.02 (0.02%)	0.013 (0.013%)
	Z_{pump}	0.146 (0.111%)	0.112 (0.11%)	0.09 (0.09%)
	Z_{ro}	116.8 (89.16%)	90.77 (91.2%)	77.48 (93.94%)
Thermo-economic streams, $/GJ	C_{col-st}	1.073	1.095	1.112
	C_{st-rec}	1.073	1.095	1.112
	$C_{rec-col}$	1.295	1.171	1.03
	$C_{rec-cond}$	1.073	1.095	1.112
	C_{cond-p}	1.073	1.095	1.112
	C_{p-rec}	2.07	2.32	2.573
	C_{cw}	0.043	0.032	0.027
	C_p	54.7	56.1	66.6
	C_w	3.326	3.672	3.996

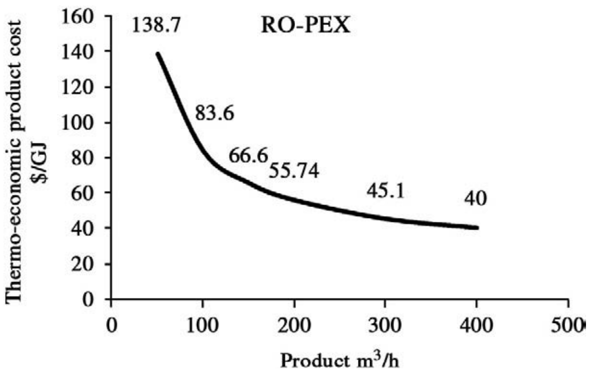


Fig. 2. Variation of thermo-economic product cost against the variation in productivity.

PEX against the other configurations. As a result, the unit product cost of PEX configuration is 29.2% higher than that of the basic. And that also refers to the direct effect of product stream and the indirect effect of seawater stream temperature. Therefore, the specific total cost would be dropped from 0.898$/m^3 in basic configuration to reach 0.683$/m^3 in PWT and 0.572$/m^3 in RO-PEX. Also the total water price would become 0.6$/m^3 in PEX instead of 0.89$/m^3 in basic. These results show that PWT comes next after PEX configuration which is considered more economical than either stand alone.

Nomenclature

A Availability
A_{col} Solar collector area, m^2
A_{cond} Condenser area, m^2
A_{rec} Recuperator area, m^2
ACC Annualized capital cost, $/year
A_f Amortization factor, y^{-1}, flow availability
A_q Heat transfer availability, kW
A_w Power availability, kW
Bp Booster pump
C Cost, $
CC Capital costs, $
C_p Specific heat capacity at constant pressure, kJ/kgK, thermo-economic unit product cost, $/GJ
C_t Specific annual total costs, $/m^3
C_w Thermo-economic power cost stream, $/GJ
$C_{pump-rec}$ Thermo-economic cost stream from pump to recuperator unit, $/GJ
C_{col-st} Thermo-economic cost stream from solar collector to steam turbine, $/GJ
C_{st-rec} Thermo-economic cost stream from steam turbine to recuperator unit, $/GJ
$C_{rec-cond}$ Thermo-economic cost stream from recuperator to condenser, $/GJ
$C_{cond-pump}$ Thermo-economic cost stream from condenser to pump, $/GJ
$C_{pump-rec}$ Thermo-economic cost stream from pump to recuperator unit, $/GJ
DCC Direct capital cost, $
E Exergy rate, kW
E_p Product exergy rate, kW
E_q Thermal exergy (solar radiation × Solar collector area) rate, kW
E_f Exergy of feed flow rate, kW
F_e Corrective factor = 1
FF Fouling factor
G_b Beam radiation, W/m^2
h Enthalpy, kJ/kg
HPP High pressure pump
I Irreversibility rate, kW
ICC Indirect capital costs, $
i Interest rate, %
LF Load factor
LT_p Plant life time, year
LT_m Membrane life time, year
$\dot{m}$ Mass flow rate, kg/s
N_p Number of permeator
n Number, #
n_e Element number
n_v Number of pressure vessels
OC Operating cost, $
O&M Operating and maintenance costs, $
ORC Organic Rankine cycle
P Permeator, or Pressure, bar
P_p Permeator price, $
P_v Pressure vessel price, $
PEX Pressure exchanger
PWT Pelton wheel turbine
ΔP Pressure difference, bar
Q Thermal power, kW
RO Reverse osmosis
RR Recovery ratio
S_{gen} Entropy generation, kJ/kgK
SPC Specific power consumption, kWh/m^3 = power (kW)/productivity (m^3/h)
T Temperature, °C
T_{co} Solar collector outlet temperature, °C
T_{sup} Super heat temperature, °C
T_{sun} Sun temperature, 6000 K
T_{amb} Ambient temperature, °C
TCC Total capital cost, $
TWP Total water price based on RO section only, $/m^3
W_t Turbine power, kW
W_p Pump power, kW
X Salinity, ppm
$Z^{IC\&OM}$ Total investment and operating and maintenance cost, $/h

Subscripts

amb Ambient
b, brine Brine
col Collector
Cold Cold side
co Collector outlet stream
chm Chemical
cond Condenser
cw Cooling water
e Element
equip Equipment
ex Exergy
f flow
g Generator
hpp High pressure pump
Hot Hot side
i Inlet
insur Insurance
memb Membrane
o Outlet
ORC Organic Rankine cycle
p Pump–Plant–Permeator–Product mass flow rate (kg/s)
q Heat transfer
ro Reverse osmosis
rec Recuperator
site Site costs
st Steam turbine
swip Sea water and intake price

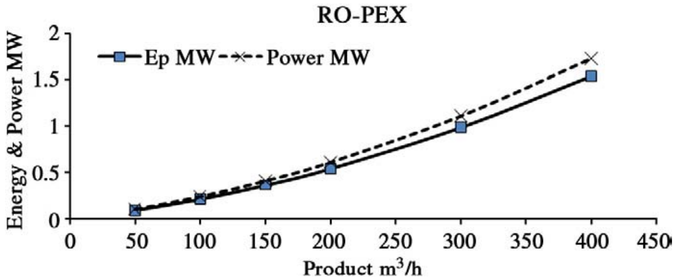


Fig. 3. Variation of product stream exergy rate (MW) and power consumed (MW) by the RO-PEX against the variation in fresh water production rate (m^3/h).

sup Super heat condition
t Turbine
w Work-power

Greek
η Thermal efficiency, %
ε_{rec} Recuperator effectiveness

Appendix A

Thermo-economic balance equations for each component in the cycle (ORC/RO) can be presented as following;

For Rankine cycle pump unit;

$$C_{pump-rec} = C_w + C_{cond-pump} + Z_{pump}^{IC\&OM} \quad (A.1)$$

So; the unit product cost for the pump becomes;

$$c_{pump-rec} = \frac{c_w E_w + c_{cond-pump} E_{cond-pump} + Z_{pump}^{IC\&OM}}{E_{pump-rec}} \quad (A.2)$$

For solar collector;

$$C_{col-st} = C_q + C_{rec-col} + Z_{col}^{IC\&OM} \quad (A.3)$$

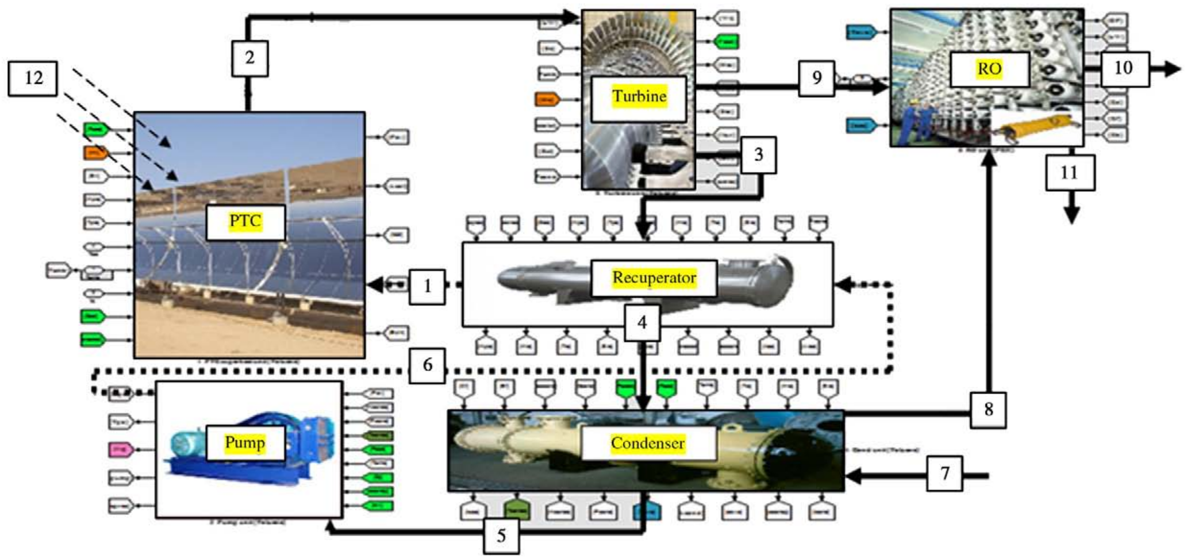
And the product cost rate from solar collector field to steam turbine;

$$c_{col-st} = \frac{c_{rec-col} E_{rec-col} + Z_{col}^{IC\&OM}}{E_{col-st}} \quad (A.4)$$

And for steam turbine unit;

$$C_{st-rec} + C_{w-HPP} = C_{col-st} + Z_{st}^{IC\&OM}. \quad (A.5)$$

Steam turbine would maintain one auxiliary equation for two streams outlet (power stream, and exhaust stream to recuperator unit). For



streams		1	2	3	4	5	6	7	8	9	10	11	12
p	bar	32.78	32.78	0.062	0.062	0.062	32.78	1	68	--	1	1	--
t	°C	143.1	340	198.4	70	35	38	20	22	--	22	22.2	5727
h	kJ/kg	330	987.6	774	571	121.6	126.8	84	91	--	91	91	--
m	kg/s	1.732	1.732	1.732	1.732	1.732	1.732	135	135	--	40.5	94.55	--
Ex	kW	43.75	573.6	125.5	7	3	37.2	0	1367	394	346.1	0	1568
c	$/GJ	1.03	1.112	1.112	1.112	1.112	2.573	0	0.027	3.99	66.6	0	0

- Solar field area=1887m²
- Recuperator area=3m²
- Condenser area=18m²

Fig. 4. Data streams for solar ORC with RO-PEX configuration (145 m^3/h).

this, the unit product power for steam turbine can be represented as follows;

$$c_w = \frac{c_{col-st}(E_{col-st} - E_{st-rec}) + Z^{IC\&OM}_{st}}{E_w}, c_{col-st} = c_{st-rec}. \quad (A.6)$$

For recuperator unit;

$$C_{rec-cond} + C_{rec-col} = C_{st-rec} + C_{pump-rec} + Z^{IC\&OM}_{rec}. \quad (A.7)$$

For recuperator unit with two streams input and two streams output, the relation needs two auxiliary equations to maintain the outlet streams.

$$c_{st-rec} = c_{rec-cond} \quad (A.8)$$

$$c_{pump-rec} = c_{rec-col} \quad (A.9)$$

$$c_{rec-col} = \frac{c_{st-rec}(E_{st-rec} - E_{rec-cond}) + c_{pump-rec}E_{pump-rec}E_{pump-rec} + Z^{IC\&OM}_{rec}}{E_{rec-col}} \quad (A.10)$$

For condenser unit;

$$C_{cond-pump} + C_{cond-HPP} = C_{cw} + C_{rec-cond} + Z^{IC\&OM}_{cond}. \quad (A.11)$$

Assuming that C_{cwi} the cooling water cost is zero, and $c_{cond-pump} = c_{rec-cond}$ so;

$$c_{cwo-RO} = \frac{c_{rec-cond}\left(E_{rec-cond} - E_{cond-pump}\right) + Z^{IC\&OM}_{cond}}{E_{cwo-RO}}. \quad (A.12)$$

For RO plant with basic or PWT, or PEX units;

$$C_{product} + C_{brine} = C_{cwo-HPP} + Z^{IC\&oM}_{RO}. \quad (A.13)$$

Assuming that C_{brine} is zero, so the relation takes the following form;

$$c_p = \frac{c_{cwo-RO}E_{cwo-RO} + c_w E_w + Z^{IC\&OM}_{RO}}{E_P}. \quad (A.14)$$

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