

Combined solar organic Rankine cycle with reverse osmosis desalination process: Energy, exergy, and cost evaluations

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ABSTRACT

Organic Rankine cycles (ORC) have unique properties that are well suited to solar power generation. In this work design and performance calculations are performed using *MatLab/SimuLink* computational environment. The cycle consists of thermal solar collectors (Flat Plate Solar Collector (FPC), or Parabolic Trough Collector (PTC), or Compound Parabolic Concentrator (CPC)) for heat input, expansion turbine for work output, condenser unit for heat rejection, pump unit, and Reverse Osmosis (RO) unit. Reverse osmosis unit specifications used in this work is based on Sharm El-Shiekh RO desalination plant. Different working fluids such as: butane, isobutane, propane, R134a, R152a, R245ca, and R245fa are examined for FPC. R113, R123, hexane, and pentane are investigated for CPC. Dodecane, nonane, octane, and toluene are allocated for PTC. The proposed process units are modeled and show a good validity with literatures. Exergy and cost analysis are performed for saturation and superheated operating conditions. Exergy efficiency, total exergy destruction, thermal efficiency, and specific capital cost are evaluated for direct vapor generation (DVG) process. Toluene and Water achieved minimum results for total solar collector area, specific total cost and the rate of exergy destruction.

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1. Introduction

Water scarcity, which occurs not only in arid regions, may be characterized as a mismatch between water supply and water demand: Pollution and exploitation of groundwater aquifers and surface water have led to a decrease of quantity and/or quality of available natural water resources in many regions. The ongoing growth of population, industry and agriculture further increases water demand. In addition, higher living standards, especially in industrial countries, result in higher per capita water consumption and in intensified water scarcity [1]. Also, exploitation of natural fresh water resources combined with higher water demand has led to an increased demand for alternative fresh water resources.

Desalination provides such an alternative source, offering water otherwise not accessible for irrigational, industrial and municipal use. Desalination of saline (sea/brackish) water is one of the most promising techniques to overcome water shortages in a considerable number of countries. Throughout the world a trend to intensified use of desalination as a means to reduce current or future water scarcity can be observed. Many desalination techniques have been proposed for utilities and industrial applications. This

includes the thermal desalination processes such as multi-stage flash (MSF), multi-effect distillation (MED) and vapor compression (VC), and membrane desalination processes as reverse osmosis (RO) and reverse electro-dialysis (EDR) [2]. Reverse osmosis and multi-stage flash are the most widely used techniques. A great share of the world's desalination capacity is installed in the Middle East region. Although (RO) technique is rapidly gaining market share, thermal processes still dominate the Middle Eastern market [1]. At the same time, Middle East countries have a great potential of solar energy.

Egypt is considered one of the high insolation countries of the world (about 6–8 kWh/m²/day). The sunshine hours are estimated to be 3600 h/year [3]. Therefore utilization of solar energy in Middle East countries as an alternative renewable energy should be strongly taken into consideration, especially, when new communities are established in the desert and remote areas [4]. Therefore, it is possible to use this energy to produce fresh water from the sea or underground saline water (i.e., solar desalination). Desalination processes require significant quantities of energy to achieve separation of salts from seawater. The installed capacity of desalinated water systems in year 2000 is about 22 million m³/day, which is expected to increase drastically in the next decades. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of

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fossil fuels [5]. Renewable energy systems produce energy from sources that are freely available in nature. Their main characteristic is that they are friendly to the environment, i.e. they do not produce harmful effluents.

Production of fresh water using desalination technologies driven by renewable energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and conventional energy sources like heat and electricity grid. Solar energy can directly or indirectly be utilized for desalination. Collection systems that use solar energy to produce distillate directly in the solar collector are called direct collection systems whereas systems that combine solar energy collection systems with conventional desalination systems are called indirect systems. In indirect systems, solar energy is used either to generate the heat required for desalination and/or to generate electricity to provide the required power for conventional desalination plants. For power input to drive and operate the (RO) modules, solar Rankine cycle could be used [6]. The organic Rankine cycle (ORC) exhibits great flexibility, high safety and low maintenance requirements in recovering low grade of input heat. ORC's are particularly viable for small scale, unsupervised power generation systems which utilize waste heat from prime movers such as micro-turbines or reciprocating engines, also from industrial processes or by product in landfills.

Although a small ORC is characterized by rather low efficiencies (8–12%), it is particularly easy to manufacture. Another important advantage of ORCs is that it can utilize waste heat from low-quality exhausts or steam, which makes it suitable for a very large range of applications which include those with low temperature waste heat sources [7]. Donghong Wei [8] presented a system performance analysis and optimization of an organic Rankine cycle (ORC) system using HFC-245fa (1,1,1,3,3-pentafluoropropane) as working fluid driven by exhaust heat. The thermodynamic performances of an ORC system under disturbances have been analyzed. Mago [9] presented an analysis of regenerative organic Rankine cycles using dry organic fluids, to convert waste energy to power from low-grade heat sources. The dry organic working fluids selected for that investigation were R113, R245ca, R123, and Isobutane, with boiling points ranging from -12°C to 48°C . The evaluation was performed using a combined first and second law analysis by varying certain system operating parameters at various reference temperatures and pressures. Yamamoto [10] developed a numerical simulation model for ORC in order to estimate its optimum operating conditions. The results showed that HCFC-123 gives higher turbine power than water which is a conventional working fluid, where saturated vapor at the turbine inlet would give the best performance.

Torres et al. [11–14] gave an analysis of low power (100kW) solar driven Rankine cycles for medium range of operating temperatures. Toluene, octamethylcyclotetrasiloxane (D4) and hexamethyldisiloxane (MM) were considered as the working fluids for ORC. Direct solar vapor generation (DVG) configuration of solar with ORC was analyzed and characterized with LS3 and IND300 parabolic trough collector (PTC) models. The power output from the turbine is used to drive the (RO) unit. Bruno [15] modeled and optimized solar organic Rankine cycle (ORC) engines for reverse osmosis (RO) desalination. The proposed systems are intended to be potentially attractive for remote areas without (or with) access to the public electricity grid. Two case studies were examined from Almeria and Barcelona that can be considered representative of two different levels of solar radiation characteristic of the Mediterranean area of Spain. In these case studies the area of the solar field collectors was calculated, considering both brackish and seawater desalting applications for a handling capacity of $15\text{ m}^3/\text{day}$.

It is obvious from the literatures that 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. This application is, however, still not well developed and it has only been tested in pilot plants and at a few demonstration sites. In this work, a combined organic Rankine cycle (solar collector, turbine, recuperator, condenser, and pump), and reverse osmosis unit (RO) for seawater desalination is considered. The aim of this work may be concluded into the following:

- Investigating and analyzing the design of Rankine cycle with different types of solar collectors: flat plate collector (FPC), parabolic trough collector (PTC), and compound parabolic collector (CPC).
- Examining the behavior of the proposed cycles using different working fluids under specified fresh water production output.
- Performing energy and exergy analyses of the considered process under two different operating conditions of the turbine inlet vapor (saturation and superheated).
- Determining the specific total cost for ORC-RO combined process for different working fluids and different operating conditions.
- The above investigations are performed using the same platform of MatLab/SimuLink computational environment.

2. Organic Rankine cycle

In the solar power generation, a low-grade solar thermal energy is converted to high grade mechanical or electrical energy for use in many applications. Two major techniques are used to employ solar energy for power production, photovoltaic and thermodynamic power cycles [16]. The use of the photovoltaic is still expensive and has low efficiency compared with the use of thermodynamic power cycles working at medium and high temperatures. The general method of converting thermal energy into mechanical energy in this case is to apply several processes on the working fluid of the power cycle. Power generation based on solar thermal medium temperature collectors are mature enough to cover power demand around tens of MW based on Rankine cycle. The use of solar thermal energy by means of a thermodynamic power cycle has interesting potentials of higher efficiency and lower costs than photovoltaic systems [16]. Solar thermal collectors are able to generate shaft power by means of a Rankine, Brayton cycle or by other specially designed expansion system [17]. Rankine cycle is used in conventional solar electricity generation systems which uses medium temperature solar collectors like the parabolic trough collectors. Also, Rankine cycle is used in high temperature solar systems like the heliostats and parabolic dish technologies. The use of solar-powered heat engines offers interesting potentials for small to medium size communities in developing and isolated areas. Direct applications are: electricity production, water pumping, reverse osmosis (RO) desalination, vapor compression chillers, etc [17]. With regard to seawater desalination, few works for the designs of solar heat engine-driven RO have been published and only some of them have been implemented [18–20]. Fig. 1 shows a schematic diagram of solar Rankine cycle for DVG.

3. Working fluids

The selection of the most suitable working fluid that can be used with the solar operated Rankine cycle depends on many criteria the most important of which is the maximum temperature of the cycle. Other criteria include the following [21]:

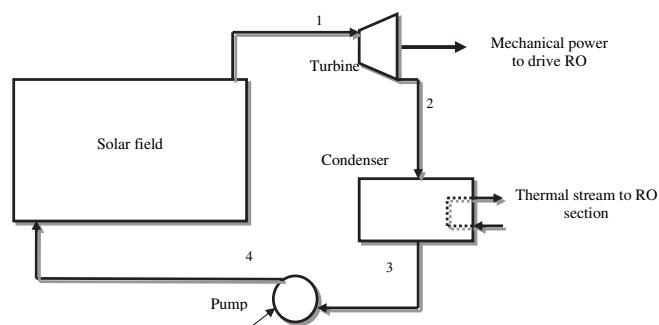


Fig. 1. A schematic diagram of solar Rankine cycle components for DVG.

- High molecular weight to reduce the turbine nozzle velocity.
- Reasonable pressure corresponding to boiling temperature of the fluid (high pressure requires careful sealing to avoid leakage).
- Dry expansion, i.e., positive slope of the vapor saturation curve on T – S diagram, to assure that all expansion states in the turbine exist on the superheat region.
- A critical temperature well above the maximum operating temperature of the cycle.
- Inexpensive, non-corrosive, non-flammable, and non-toxic fluid.
- Reasonable pressure at condensing temperature (usually around 30–40 °C).

In many solar operated Rankine systems the maximum temperature does not exceed 400 °C and thus water loses its advantages as a working fluid. Many organic fluids were found to satisfy the criteria stated above. Literatures [9,11,15,22] show that the selection of organic fluids is variable, wide and based on different criteria. Some literatures built their choices based on molecular weight and P – T behavior [11]. Others selected the organic fluid based on boiling point and melting point [22]; while others made their selection based on the thermal efficiency [9,15]. It is not recommended to use thermal efficiency as the only reference for comparison or selection of the organic fluids because systems with high thermal efficiency may also have high irreversibility and are not thermo-economically constructive. In this work, the selection of the organic fluids is based on the combination of all the above criteria. Based on critical temperature which it should be well above the collector operating temperature, butane, isobutane, propane, R134a, R152a, R245ca, and R245fa are selected to operate ORC with FPC. Fluids like R113, R123, hexane, and pentane are chosen for CPC type. Dodecane, nonane, octane, and toluene are suitable for PTC collectors. Table 1 shows a list of the considered working fluids grouped according to collector's operating temperature.

The fluids selected for FPC (Table 1) are regrouped again based on the operating temperature of the FPC collector. R152a, R134a and Propane are not recommended to be in use with FPC because these fluids have a critical temperature not well above the collector design temperature (80–100 °C). At the same time, these fluids present an isentropic action (not dry and/or positive slope) on the T – S diagram. However, the remaining fluids (Butane, Isobutane, R245ca, and R245fa) considered suitable for FPC according to the critical temperature range (130–170 °C) and the positive slope on T – S . But according to the molecular weight, R245ca presents the highest value about (134 kg/mol) followed by butane and isobutane.

For condenser pressure, lowering the pressure will increase the cycle efficiency and also the cycle net work. To take advantage of the increased efficiencies at low pressure, the condensers usually

Table 1
Properties list of the selected working fluids.

Working fluid (WF)	Formula	Molecular weight, kg/mol	$T_{critical}$, °C	$P_{critical}$, bar	Collector type
Butane	C ₄ H ₁₀	58.122	151.9	37.96	FPC
Isobutane	C ₄ H ₁₀	58.122	134.66	36.23	FPC
Propane	C ₃ H ₈	44.1	95	39.75	FPC
R134a	C ₂ H ₂ F ₄	102.03	101	40.54	FPC
R152a	C ₂ H ₄ F ₂	66.05	113.261	45.1675	FPC
R245ca	C ₃ H ₃ F ₅	134.04	170	36.36	FPC
R245fa	C ₃ H ₃ F ₅	134.048	153	35.7	FPC
Pentane	C ₅ H ₁₂	72.1488	196.6	33.7	CPC
R113	C ₂ Cl ₃ F ₃	187.37	213	32.42	CPC
R123	C ₂ HCl ₂ F ₃	152.93	182	35.63	CPC
Hexane	C ₆ H ₁₄	86.175	231	29.71	CPC
Dodecane	C ₁₂ H ₂₆	170.334	382	17.94	PTC
Nonane	C ₉ H ₂₀	128.25	321	22.7	PTC
Octane	C ₈ H ₁₈	114.22	296	24.92	PTC
Toluene	C ₇ H ₈	92.1384	318	41.26	PTC

operate well below or near the atmospheric pressure. However, there is a lower limit on the condenser pressure that can be used. It can't be lower than the saturation pressure of cooling water temperature (range of 30–35 ~ 40 °C i.e., $P_{cond} = 0.032$ – 0.06 bar). But lowering the condenser pressure is not without any side effects; it creates the possibility of air leakage into the condenser and will increase the moisture content at the final stages of the turbine.

Therefore, R245ca recorded a suitable condenser pressure (about 1.51 bar) at temperature about 35 °C while Isobutane achieves condenser pressure about 4.72 bar at the same condenser temperature. Also, R245ca, gives lower saturation pressure at 100 °C (about 7.8 bar) and that considered an advantage when used in DVG process inside the absorber tubes of a FPC. Therefore, R245ca is suitable for FPC based on the molecular weight, critical temperature, and condenser pressure point of view. But R245ca shows a little bit isentropic behavior on T – S diagram. On the other hand, Butane shows dry (sharp positive slope than R245ca) behavior on T – S diagram. At the same time R245ca is considered more toxic than Butane. For these reasons Butane is considered for FPC. Fig. 2(a) shows a schematic diagram of the considered working fluids on T – S . Fig. 3(a) shows the saturation pressures for different collector types with different working fluids at the saturation temperature in the range of 35–100 °C.

For the CPC collector, Pentane, Hexane, R113, and R123 are examined as working fluids. R113 has a highest molecular weight against the remaining (187.3 kg/mol) followed by R123, Hexane, Pentane respectively. However, regarding the condenser pressure, Hexane recorded the minimum value (0.3064 bar) at saturation temperature equal to 35 °C, followed by R113 with 0.654 bar. Pentane gives higher values little bit more than R113 and Hexane with a value of 1.011 bar. However, R123 gives the highest value for condenser pressure about 1.34 bar. Therefore, Hexane is recommended for the operation of CPC with ORC. Also it is highly recommended to choose an organic fluid with high critical temperature to achieve highest cycle efficiency [6] and that's another advantage for Hexane against the remaining fluids for CPC operation. Fig. 2(b) shows a schematic diagram of the selected working fluids on T – S . Fig. 3(b) shows the saturation pressures for CPC collector with different working fluids at the saturation temperature in the range of 35–100 °C.

Dodecane, Toluene, Nonane, and Octane are evaluated for PTC operation. They have high critical temperature well above the accepted temperature range for PTC to operate ORC. Dodecane gives the highest molecular weight against the others with a value equal to 170.3 kg/mol, followed by Nonane, Octane, and Toluene

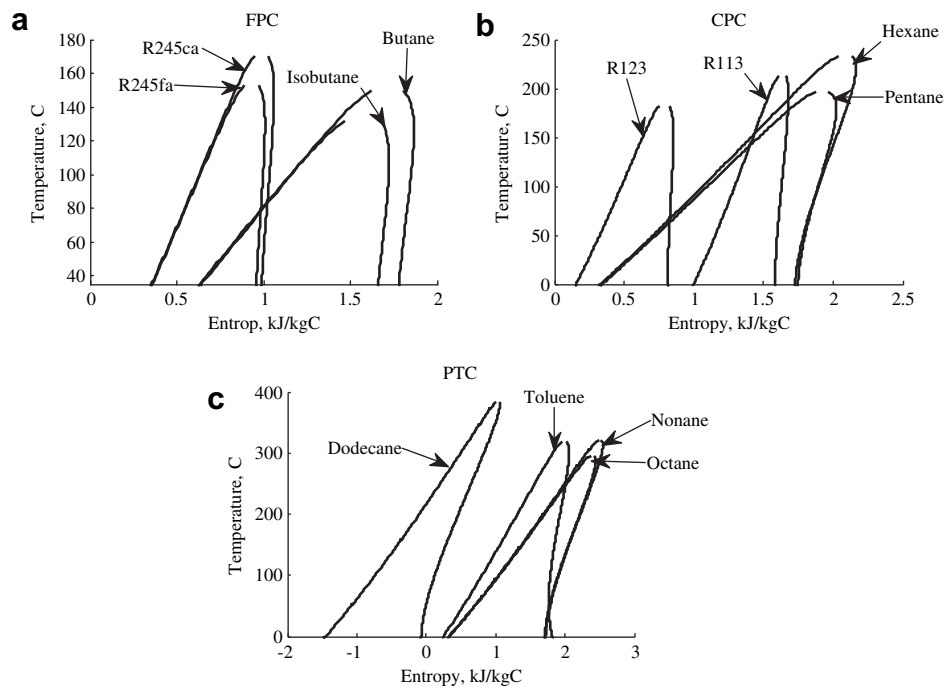


Fig. 2. The selected fluids behavior on T – S diagram for different solar collectors (FPC, CPC, and PTC).

respectively. However, Dodecane gives very low value for condenser pressure at 35 °C (about 0.00043 bar). At this pressure value, many aspects for safety are required and large condensers are needed. Nonane comes next with respect to the condenser pressure with 0.0106 bar. Octane achieves a suitable value for condenser pressure about 0.0336 bar but with lowest critical temperature (about 296 °C) value.

Dodecane and Octane are not suitable for solar ORC due to very low condenser pressure and low critical temperature respectively. Toluene gives a condenser pressure value about 0.0648 bar. And that mean it is suitable for this selection. Although Nonane is recommended by its molecular weight and critical temperature (little bit higher than Toluene), Toluene achieves the recommended condenser pressure value at the same saturation temperature. Also,

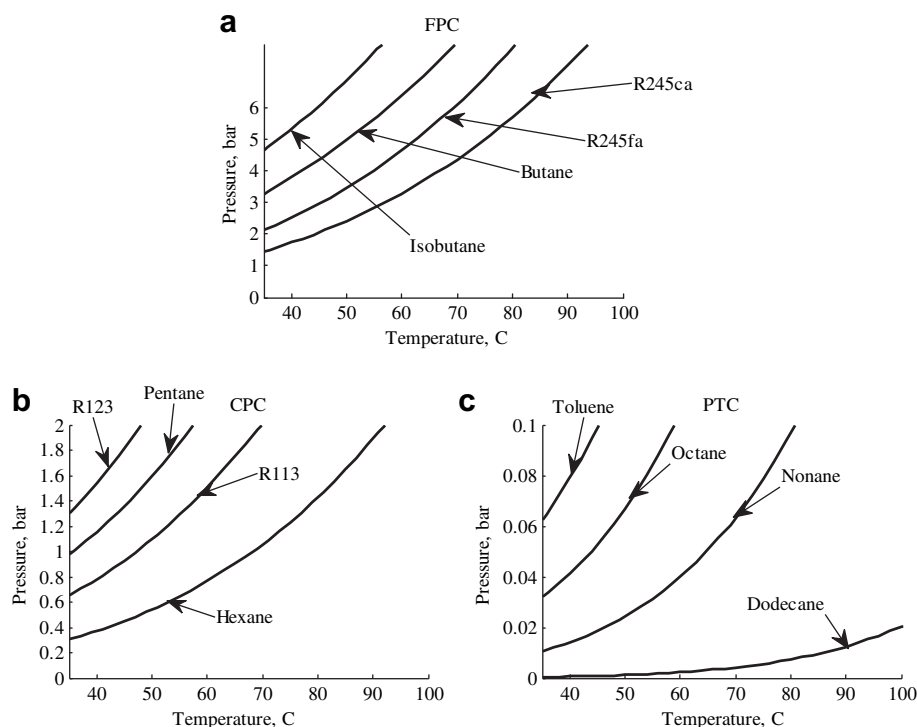


Fig. 3. Saturation pressures for different collectors with different working fluids at the saturation temperature at the range of 35–100 °C.

toluene achieves lower values of specific vapor volume ($0.00117 \text{ m}^3/\text{kg}$ vs $18.75 \text{ m}^3/\text{kg}$) [23], this leading to a low condenser area causes lower values in economic evaluation. Fig. 2 (c) shows a schematic diagram of the selected working fluids on T – S . Fig. 3(c) shows the saturation pressures for PTC collectors with different working fluids at the saturation temperature at the range of 35 – 100°C .

4. ORC mathematical model

The solar collector instantaneous efficiency can be determined from its characteristic curve using the solar irradiance, mean collector and ambient temperatures. The curve used for FPC, evacuated tube, and CPC are expressed by Eq. (1) and the parameters given in Table 2 [24–26]. The corresponding efficiency equation for the medium-high temperatures parabolic trough collectors (PTC) is given by Eq. (2) [27].

$$\eta_{\text{col}} = \eta_0 - a_1 \left(\frac{T_{\text{co}} - T_{\text{amb}}}{G_b} \right) - a_2 \left(\frac{T_{\text{co}} - T_{\text{amb}}}{G_b} \right)^2 G_b \quad (1)$$

$$\eta_{\text{col}} = \eta_0 - a_{11}(T_{\text{co}} - T_{\text{amb}}) - a_{21} \left(\frac{T_{\text{co}} - T_{\text{amb}}}{G_b} \right) - a_{31} \left(\frac{T_{\text{co}} - T_{\text{amb}}}{G_b} \right)^2 \quad (2)$$

The collector total area can be estimated based on the collector energy balance equation as a function of collector efficiencies as:

$$A_{\text{col}} = Q_u / \eta_{\text{col}} G_b \quad (3)$$

where Q_u is the collector useful thermal power and (G_b) is the normal beam solar radiation (W/m^2) hits the collector surface area, and A_{col} is the collector area. The collector useful energy equation may exist according to the following relation:

$$Q_u = m_{\text{col}} \times (h_1 - h_4)_{\text{DVG}} \quad (4)$$

The mathematical model of the solar organic Rankine cycle units in Fig. 1 are introduced as follows:

A. Turbine unit

The outlet enthalpy of the turbine kJ/kg :

$$h_2 = h_1 - \eta_t \times (h_1 - h_{2s}) \quad (5)$$

where η_t is the turbine efficiency and the subscript s tends to isentropic state. The cycle flow rate kg/s is presented as following:

$$m_{\text{ORC}} = \frac{W_t}{\eta_t \times \eta_g \times (h_1 - h_{2s})} \quad (6)$$

B. Condenser unit

Condenser heat rejection kW :

$$Q_{\text{cond}} = m_{\text{ORC}} \times (h_2 - h_3) = m_{\text{CW}} \times (h_{\text{CWO}} - h_{\text{CWi}}) \quad (7)$$

The condenser effectiveness $\varepsilon_{\text{cond}}$ based on hot side:

$$\varepsilon_{\text{cond}} = \frac{T_2 - T_a}{T_2 - T_{\text{CWi}}} \quad (8)$$

C. Pump unit

Pump work W_p in kW is calculated as:

$$W_p = \frac{m_{\text{ORC}} \times \Delta P}{\rho \times \eta_p} \quad (9)$$

where ΔP pressure difference between the condenser low pressure and the turbine high pressure, and ρ is the density of the working fluid, and η_p pump efficiency.

The pump outlet enthalpy:

$$h_4 = \frac{W_p}{m_{\text{ORC}}} + h_3 \quad (10)$$

4.1. ORC model validity

The process units are modeled for design and performance calculations by using a program developed under MatLab/Simulink computational environment. All the considered and selected working fluids in this work is established and operated with different types of solar collectors. Under the same operating conditions, the obtained results are compared with the results of Torres et al. [12]. The comparison shows a good agreement between the two results as shown in Table 3. This indicates the validity of the results and the reliability of the developed program for Rankine cycle computation.

5. Reverse osmosis unit (RO)

Reverse osmosis (RO) is a modern process technology to purify water for a wide range of applications, including semiconductors, food processing, biotechnology, pharmaceuticals, power generation, seawater desalting, and municipal drinking water. The driving force of the reverse osmosis process is applied pressure. The amount of energy required for osmotic separation is directly related to the salinity of the solution. Thus, more energy is required to produce the same amount of water from solutions with higher concentrations of salt. In the last few years RO seawater desalination technology has gone through a remarkable transformation. The number and capacity of large RO plants have increased significantly. Systems with permeate capacity up to $300,000 \text{ m}^3/\text{d}$ are currently being built [28]. In this work the analysis is made to design conventional RO module unit without adding Pelton wheel turbine or pressure exchanger unit.

Table 3

A comparison between the present work and reference [11] results for DVG.

Parameter:	Present work: $\varepsilon_{\text{reg}} = 0$	Ref [11] $\varepsilon_{\text{reg}} = 0$	Present work: $\varepsilon_{\text{reg}} = 0.8$	Ref [11] $\varepsilon_{\text{reg}} = 0.8$
Working fluid	Toluene			
Evaporation temp, $^\circ\text{C}$	300	300	300	300
Evaporation pressure, bar	32.75	32.757	32.75	33.737
Superheating temp, $^\circ\text{C}$	300	300	380	380
Condenser pressure, bar	0.06215	0.0624	0.06215	0.0624
Working fluid flow rate, kg/s	0.5744	0.563	0.4511	0.442
Rejected power, kW	323.2	318.4	208.9	209.8
Rankine efficiency, %	22.82	23.37	31.33	31.78
PTC area, m^2	681.3	672	500	514.3

Table 2
Efficiency parameters for different collectors types.

Solar collector	a_1 , W/m^2	a_2 , W/m^2	a_{11} , W/m^2	a_{21} , W/m^2	a_{31} , W/m^2	η_0	Operating temp, $^\circ\text{C}$
FPC	2.9	0.0108	—	—	—	0.768	80–100
CPC	0.59	0.0019	—	—	—	0.665	120–170
PTC	—	—	4.5×10^{-6}	0.039	3×10^{-4}	0.75	>170–300

5.1. RO mathematical model

The mathematical model for the proposed RO unit is developed as presented in Dessouky [33].

The feed mass flow rate M_f based on recovery ratio RR and distillate mass flow rate M_d is:

$$M_f = \frac{M_d}{RR} \quad (11)$$

The distillate product salt concentration X_d :

$$X_d = X_f \times (1 - SR) \quad (12)$$

where X_f is the feed flow rate salt concentration, and SR is the salt rejection percentage and the rejected brine is found from:

$$M_b = M_f - M_d \quad (13)$$

The rejected salt concentration kg/m^3 is estimated by:

$$X_b = \frac{M_f \times X_f - M_d \times X_d}{M_b} \quad (14)$$

The average salt concentration kg/m^3 is estimated as:

$$X_{av} = \frac{M_f \times X_f - M_b \times X_b}{M_b} \quad (15)$$

The temperature correction factor TCF is found by the relation below:

$$TCF = \exp\left(2700 \times \left(\frac{1}{273 + t} - \frac{1}{298}\right)\right) \quad (16)$$

The membrane water permeability k_w :

$$k_w = 6.84 \times 10^{-8} \times (18.6865 - (0.177 \times X_b)) / (t + 273) \quad (17)$$

The salt permeability k_s is:

$$k_s = FF \times TCF \times 4.72 \times 10^{-7} \times \left(0.06201 - \left(5.31 \times 10^{-5} \times (t + 273)\right)\right) \quad (18)$$

where FF is the membrane fouling factor. The calculations of osmotic pressure for feed side, brine side, and distillate product side are found as follows:

$$\Pi_f = 75.84 \times X_f \quad (19)$$

$$\Pi_b = 75.84 \times X_b \quad (20)$$

$$\Pi_d = 75.84 \times X_d \quad (21)$$

The average osmotic pressure on the feed side:

$$\Pi_{av} = 0.5 \times (\Pi_f + \Pi_b) \quad (22)$$

The net osmotic pressure across the membrane:

$$\Delta\Pi = \Pi_{av} - \Pi_d \quad (23)$$

The net pressure difference across the membrane:

$$\Delta P = \left(\frac{M_d}{3600 \times TCF \times FF \times A_e \times n_e \times n_v \times k_w}\right) + \Delta\Pi \quad (24)$$

where A_e is the element area in m^2 , n_e is number of membrane elements, and n_v is the number of pressure vessels. The required power input in kW to the RO driving pump is estimated as:

$$HP = \left(\frac{1000 \times M_f \times \Delta P}{3600 \times \rho_f \times \eta_p}\right) \quad (25)$$

where ρ_f is the feed flow rate density, and η_p is the driving pump mechanical efficiency. The specific power consumption in kWh/m^3 is estimated as:

$$SPC = \frac{HP}{M_d} \quad (26)$$

5.2. RO mathematical model validity

The validity of the above mathematical model is examined in this section. The real data for Sharm El-Shiekh desalination plant [3] is used for this purpose. The model results are compared with the ROSA6.1 [34] software program and VDS [3] software package. The plant design parameters are presented in Table 4.

For design calculation based on the RO mathematical model, it should be noted that the distillate product M_d should be specified with plant recovery ratio. The distillate product will decide the plant power capacity, specific power consumption SPC, the needed feed, the required feed pressure, the product salinity, the rejected brine, salt rejection percentage, and the pump horse power needed. The above plant has an element area fixed as 35.4 m^2 while using FTSW30HR-380. The RO pump efficiency is about 80% and the feed flow rate salinity is specified as 45,000 ppm. The input feed seawater temperature is fixed as 25°C . The plant recovery ratio is specified as 30%. The results of the developed program show a good agreement with the other software's (ROSA6.1, and VDS) as presented in Table 5. This indicates the validity of both the proposed RO mathematical model and the developed program.

6. Combined ORC and RO process

Coupling the solar Rankine cycle with the RO block is investigated in this section. Different working fluids and different solar collectors (FPC, CPC, and PTC) and different turbine inlet vapor conditions (saturation and superheated) are considered. The considered process consists of a solar collector field (FPC or CPC or PTC), expansion turbine for work output, condenser unit, organic fluid pump unit, and RO unit for total productivity of about $145.8 \text{ m}^3/\text{h}$. Energy, exergy analysis and cost analyses of the combined process is investigated in this section.

6.1. ORC/RO energy & exergy analyses

For exergy analysis, there are two main parameters to judge the system performance. The 1st is exergy destruction, and the 2nd is the exergy efficiency. Unlike energy, which is conserved in any process according to the first law of thermodynamics, exergy is

Table 4

Specified design parameters of Sharm El-Shiekh RO desalination plant [2].

Variable	Value
Feed flow rate, m^3/h	468
Feed salinity, TDS, ppm	45000
Recovery ratio	0.30
# of stages	1
# of pressure vessels	42
Feed temperature, $^\circ\text{C}$	24–40
Fouling factor	0.85
Feed pressure, bar	67
# of elements	7
Element type	FTSW30HR-380

destroyed due to irreversibilities taking place in any process, which manifest 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 Eq. (27) [29].

$$A_2 - A_1 = A_q + A_w + A_{fi} - A_{fe} - I \quad (27)$$

where $A_2 - A_1 = 0$ is the non-flow availability change in steady state condition, $A_q = \sum (1 - (T_{amb}/T_j)) Q_j$ is the availability transfer due to the heat transfer between the control volume 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 $A_{fi,e} = \sum m_{i,e} a_{fi,e}$. So the general form in steady state condition would become:

$$A_q + A_w + A_{fi} - A_{fe} = I \quad (28)$$

By simplifying A_{fi} and A_{fe} , Eq. (28) will be as follows:

$$A_{fi} - A_{fe} = m_{i,e}((h_i - h_o) - T_0(s_i - s_o)) \quad (29)$$

Based on the above general equations of exergy destruction, analysis can be performed unit by unit. Total exergy destruction rate in kW can be found by the summation of all the units irreversibilities as follows:

$$I_{total} = I_{collector} + I_{turbine} + I_{condenser} + I_{pump} + I_{RO} \quad (30)$$

$$I_{collector} = A_{col} \times G_b \times \left(1 - \frac{T_{amb}}{T_{sun}}\right) + m_{col}[h_i - h_o - T_{amb}(s_i - s_o)]_{col} \quad (31)$$

where $T_{sun} = 6000$ K [30]:

$$I_{turbine} = m_{ORC}[h_i - h_o - T_{amb}(s_i - s_o)]_{turbine} - W_t \quad (32)$$

$$I_{condenser} = m_{ORC}[h_i - h_o - T_{amb}(s_i - s_o)]_{cond} + m_{cw}[h_{cw_i} - h_{cw_o} - T_{amb}(s_{cw_i} - s_{cw_o})]_{cw} \quad (33)$$

$$I_{pump} = m_{ORC}[h_i - h_o - T_{amb}(s_i - s_o)]_{pump} + W_p \quad (34)$$

$$I_{RO} = W_{HPP} - M_b \times (h_f - h_b) + M_d \times (h_f - h_d) \quad (35)$$

where h_f , h_b , and h_d is calculated based on seawater specific heat capacity, salinity, and feed seawater temperature [35] where:

$$h = h_o + \left((A \times T) + \left(B/2 \times T^2\right) + \left(C/3 \times T^3\right) + \left(D/4 \times T^4\right)\right)$$

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 or the ratio of net exergy output to the actual exergy input for any given system when achieving the required task.

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \quad (36)$$

The assumptions and specified parameters for the proposed cycle mathematical model may be listed as follows:

- Rankine cycle gross work will be consumed by RO unit.
- Turbine, generator, and the pump efficiencies would be fixed as 0.75%, 0.95%, and 0.75% respectively.
- Condensation and inlet cooling water temperatures would be fixed at 35 °C and 20 °C, respectively.
- For climate conditions, solar flux is given as 850 W/m², and ambient temperature is fixed as 25.4 °C.
- Feed water salinity is about 45,000 ppm.
- Inlet seawater temperature to the RO module is depending on the outlet temperature value from condenser unit.
- RO product will be set as 145.8 m³/h.
- Other specifications of Sharm El-Shiekh RO desalination plant like fouling factor, recovery ratio, and high pressure pump are presented in Table 6.

For DVG saturation operation, maximum operating temperature for FPC is set as 80 °C, and 130 °C for CPC and 300 °C for PTC. However, for DVG superheat operation, the deference temperature between saturation and superheat degrees is set as 20 °C for all collector types. The obtained results are illustrated in Table 6.

From the above table, saturation operation for Butane with (FPC) collector gives lower values of collector area, and total exergy destruction than superheat operation. Therefore, saturation operation for Butane (FPC) would give higher values of power output, Rankine efficiency, mass flow rate, overall exergy efficiency, and specific power consumption than the superheat operation. While comparing with the conventional working fluid (water), water (FPC) gives lower values against butane (FPC) with respect to evaporation pressure, collector area, mass flow rate, and total exergy destruction. Also, water with (FPC) gives higher values with respect to power output, Rankine efficiency, overall exergy efficiency, and specific power consumption. However, water with (FPC) needs an expansion wet turbine for dryness fraction of about 0.92 otherwise the superheat operation should be implemented with the expense of reducing in overall exergy efficiency and increasing in collector area. Saturation operation of hexane (CPC) would give the same behavior as butane results. Hexane under saturation operating conditions gives lower values according to solar collector area, and total exergy destruction than superheat operation. And that would be followed by an increase in power

Table 5
Present results of Sharm El-Shiekh desalination plant Vs ROSA6.1 and VDS [2].

Variable	Developed program	ROSA6.1	VDS [2]	Unit
SPC	7.68	7.76	7.76	kWh/m ³
HP	1131	1131.42	1130	kW
M_f	485.9	458.9	486	m ³ /h
M_b	340.1	340.15	340.23	m ³ /h
X_b	64,180	62,005	66,670	ppm
X_d	250	283.83	200	ppm
SR	0.9944	—	0.9927	—
ΔP	6850	6670	6700	kPa

Table 6

Results of ORC/RO process with different working fluids and different types of solar collectors.

Parameter	Saturation Butane, FPC, $T_{co} = 80\text{ }^{\circ}\text{C}$	Hexane, CPC, $T_{co} = 130\text{ }^{\circ}\text{C}$	Toluene, PTC, $T_{co} = 300\text{ }^{\circ}\text{C}$	Superheat Butane, FPC, $T_{co} = 100\text{ }^{\circ}\text{C}$	Hexane, CPC, $T_{co} = 150\text{ }^{\circ}\text{C}$	Toluene, PTC, $T_{co} = 320\text{ }^{\circ}\text{C}$
P_{ev} , bar	10.14	4.992	32.78	10.14	4.992	32.78
A_{col} , m ²	2.111E+04	1.506E+04	6747	2.14E+04	1.696E+04	6734
W_t , kW	999.4	1065	1119	997.8	1054	1120
η_R , %	8.15	14.46	25.81	8.07	13.89	26
m , kg/s	28.31	13.94	5.75	26.16	13.8	5.24
I_{total} , MW	16.48	11.65	4.951	16.7	13.18	4.94
η_{ex} , %	5.22	6.5	14.04	5.2	5.85	14.06
SPC, kWh/m ³	6.855	7.302	7.677	6.84	7.231	7.679
Parameter	Water Saturation FPC, $T_{co} = 80\text{ }^{\circ}\text{C}$	CPC, $T_{co} = 130\text{ }^{\circ}\text{C}$	PTC, $T_{co} = 300\text{ }^{\circ}\text{C}$	Superheat FPC, $T_{co} = 100\text{ }^{\circ}\text{C}$	CPC, $T_{co} = 150\text{ }^{\circ}\text{C}$	PTC, $T_{co} = 320\text{ }^{\circ}\text{C}$
P_{ev} , bar	0.576	2.755	85.9	0.576	2.755	85.9
A_{col} , m ²	1.864E+04	1.27E+04	5949	1.82E+04	1.626E+04	5851
X , quality	0.92	0.86	0.74	0.93	0.93	0.76
W_t , kW	1019	1084	1130	1022	1055	1131
η_R , %	8.89	17.68	29.93	10.17	13.34	30.47
m , kg/s	4.12	2.38	1.407	3.97	3	1.335
I_{total} , MW	14.48	9.731	4.28	14.13	12.6	4.2
η_{ex} , %	5.64	7.64	16	6.82	7.86	22.52
SPC, kWh/m ³	6.988	7.437	7.748	7.01	7.24	7.756

output, Rankine efficiency, mass flow rate, overall exergy destruction, and the specific power consumption. Water with (CPC) gives lower results in collector area, and total exergy destruction than that of hexane (CPC). However, the steam quality 0.86 is lower than that of the FPC. But, hexane (CPC) achieved lower results than butane (FPC) with respect to evaporation pressure, collector area, mass flow rate, and total exergy destruction. At the same time hexane (CPC) gives higher results than butane (FPC) with respect to power output, Rankine efficiency, overall exergy efficiency, and specific power consumption. The same behavior exists for water (CPC) results vs water (FPC) results regardless the quality of steam produced at the turbine last stage. PTC operation is quite different against the other two types. Saturation operation for Toluene (PTC) gives lower values than superheat ones with respect to Rankine efficiency, overall exergy efficiency, and specific power consumption. At the same time saturation operation gives higher results than superheat operation for toluene (PTC) with respect to collector area, mass flow rate, and total exergy destruction. Water with (PTC) produces more attractive results than toluene with (PTC) collector regardless the steam quality produced at the turbine last stage and the higher values of evaporation pressure (higher values of evaporation pressure may cause problems to the collector sealing and joints). From the above analysis it could be concluded that, toluene (PTC-superheat) and water (PTC-superheat) considered valuable for the operation of Sharm El-Shiekh RO desalination plant.

6.2. Solar ORC/RO process 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. There is no much precise information about the

current capital cost of ORC. By information obtained from literatures, solar collectors costs may be evaluated as 150–200 \$/m². The operation and maintenance costs for the case of these solar collectors have been estimated to be 15% of the investment cost. Table 7 shows the investment capital costs (ICC) and operation and maintenance costs (O&M) of solar Rankine cycle. For the RO, the operation and maintenance costs have been considered as shown in Table 8. The investment and operating & maintenance costs analyses are performed for each component, solar field, steam turbine, condenser, and pump unit. For that purpose, the amortization factor is estimated based on the following relation [31]:

$$A_f = \frac{i(1+i)^{LT_p}}{(1+i)^{LT_p}-1} \quad (37)$$

where i is the interest rate and set as 5%, LT_p is the plant lifetime and set as 20 years. For RO part, cost analyses are estimated based on direct capital costs (DCC), indirect capital costs (ICC), and the total capital costs (TCC). Table 8 illustrates the costs for RO desalination plant. Cost analysis are performed based on USD (\$) currency. The specific total cost for the ORC–RO plant may be estimated based on the following relation:

$$C_t = \frac{C_{ORC} + C_{RO}}{M_d} \quad (38)$$

The results for DVG process for both steam operating conditions (saturation and superheat) are shown in Fig. 4. The figure shows that water specific capital cost for superheated steam under FPC and CPC is higher than saturation operating conditions. This may due to the area added on the T – S curve for each working fluid based on mass flow rate, power produced, and condenser area. Butane

Table 7

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

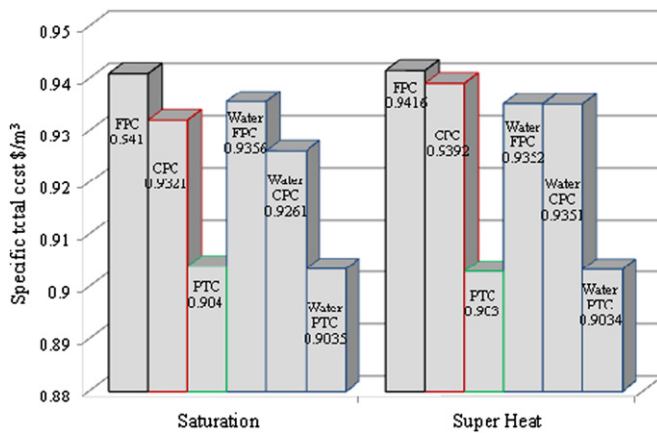
Parameter	ICC, \$	O&M, \$	TCC, \$/year	$Z^{IC\&OM}$, \$/h	Ref
Solar field	$639.5 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TCC_{col}/8760$	[32]
Steam turbine	$4750 \times (W_t)^{0.75}$	$25\% \times ICC_{st}$	$A_f \times (ICC + O\&M)_{st}$	$TCC_{st}/8760$	
Recuperator ^a	$150 \times (A_{rec})^{0.8}$	$25\% \times ICC_{rec}$	$A_f \times (ICC + O\&M)_{rec}$	$TCC_{rec}/8760$	
Condenser	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TCC_{cond}/8760$	
Pump	$3500 \times (W_p)^{0.47}$	$25\% \times ICC_{pump}$	$A_f \times (ICC + O\&M)_{pump}$	$TCC_{pump}/8760$	

^a This relation is used for recuperator unit if it exists in the cycle.

Table 8

ICC and O&M costs for RO desalination plant.

DCC, \$	ICC, \$	TCC, \$	ACC, \$/year	O&M, \$/year	$Z^{IC\&OM}$, \$/h
$CC_{swip} = 996 \times M_p^{0.8}$ $CC_{hpp} = 393,000 + 10,710 \times \Delta P_f$ $CC_e = Fe \times P_p \times N_p + Fe \times PV_p \times nv$ $CC_{equip} = CC_{swip} + CC_{hpp} + CC_e$ $CC_{site} = 10\% \times CC_{equip}$ $DCC = CC_{equip} + CC_{site}$	$ICC = 27\% \times DCC$	$TCC = ICC + DCC$	$ACC = TCC \times A_f$	$OC_{power} = LF \times 0.06 \times SPC \times M_d$ $OC_{labor} = LF \times 0.01 \times M_d$ $OC_{chm} = LF \times 0.04 \times M_d$ $OC_{insur} = 0.005 \times TCC \times A_f$ $OC_{memb} = P_p \times N_p / LT_m$ $OC_{ro} = OC_{power} + OC_{labor}$ $+ OC_{chm} + OC_{insur} + OC_{memb}$	$Z^{IC\&OM} = (ACC + OC_{ro}) / 8760$

**Fig. 4.** Specific capital cost for cycles different working fluids & different steam operating conditions with different collector types.

(FPC)_{sat-sup} gives the highest values among the other fluids followed by Water (FPC)_{sat-sup}. And that is referring to the massive effect of solar field costs (larger area means higher costs) compared with the other unit's costs. Hexane (FPC)_{sat-sup} followed by water (FPC)_{sat-sup} comes next with an advantage for water (CPC)_{sat-sup}. Toluene (PTC)_{sat-sup} followed by water (PTC)_{sat-sup} give lowest values of specific capital cost with an advantage to water (PTC)_{sat-sup} operation. From the above techno-economic analysis for the considered cycles, it can be deduced that PTC is the best option in both steam operation conditions. Results show that PTC using toluene or water shows much better cost improvement in comparison with the remaining working fluids (butane and hexane). Superheat operation with toluene considered attractive in results against the remaining fluids however water needs wet turbine unit.

7. Conclusion

An analysis of a combined solar Rankine cycle for RO desalination process is presented. The cycle consists of solar field (FPC or CPC or PTC), turbine unit for power generation, condenser/pre-heating unit, pump unit, and RO module. A case study is presented by operating Sharm El-Sheikh reverse osmosis desalination plant (capacity of 145.8 m³/h) with solar organic Rankine cycle. The analyses are performed according to different types of operating conditions (saturation and superheat). The investigations are performed based on energy, exergy, and cost analyses. The results of butane, hexane, and toluene are compared with the conventional working fluid (water). Based on the analysis performed in this work, the following conclusions can be drawn:

- Different working fluids are analyzed and compared. Due to the solar collector operating temperature and thermophysical

properties of each working fluid, butane, hexane, and toluene are considered suitable for FPC, CPC, and PTC respectively.

- By using MatLab/Simulink program, solar Rankine cycle with different working fluids is modeled by specifying the plant product. The cycle (ORC + RO) mathematical model shows a good agreement with the literature.
- Under saturation and superheat operations:
 - Butane_{sat} gives lower area than butane_{sup} and it achieves more power which leads to little increase in SPC. Moreover, the Rankine 1st and 2nd law efficiencies for butane_{sat} are higher than butane_{sup}. Water_{sat} gives lower values than butane_{sat} based on solar collector area, exergy destruction rate, and specific total cost.
 - Hexane_{sat} gives lower values against hexane_{sup} from a comparison based on solar collector area, exergy destruction, and specific total cost. Also Hexane gives higher values from 1st and 2nd law efficiencies. Water_{sat} results considered attractive against hexane_{sat}, hexane_{sup}, and water_{sup}.
 - Toluene_{sup} gives attractive results comparing next to the remaining fluids. Toluene_{sup} gives higher 1st and 2nd law efficiencies against toluene_{sat}. Moreover, it achieves a little but significant advantage in superheat operation according to total solar collector area.
- It is quite clear that water and toluene are suitable for both operations. However, Water needs expansion wet turbine for dryness fraction ranged between 0.7 and 0.95 for both operations. Moreover, the evaporation high pressure (85.9 bar) considered not safe for the collector design requirements. Between all units, solar collector field (based on area as a cost function) exhibits the largest effect on the cycle specific cost, minimum exergy destruction, and overall exergy efficiency. Generally and for both operations, increasing the collector evaporation temperature will cause an increase in turbine power, Rankine efficiency, pump work, SPC, and reverse osmosis operating pressure, with decrease in collector area, working fluid flow rate, condenser area, condenser heat load. Thus, according to the current techno-economic framework, the PTC system is the best choice.

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- Ex_{in}*: Exergy in, kW
Ex_{out}: Exergy out, kW
FF: Fouling factor
G_b: Beam radiation, W/m²
h: Enthalpy, kJ/kg
I: Exergy destruction rate, kW
ICC: Investment capital costs, \$
IDCC: Indirect capital cost, \$
i: Interest, %
k: Permeability
LF: Load factor
LT: Lifetime, year
m: Mass flow rate, m³/h, kg/s
n: Number, #
n_e: Element number
n_v: Number of pressure vessels
OC: Operating cost, \$
P: Permeator, or pressure, bar
ΔP: Pressure, bar
Q_u: Useful energy, kW
RR: Recovery ratio
S_{gen}: Entropy generation, kJ/kg K
SPC: Specific power consumption, kWh/m³
SR: Salt rejection
T: Temperature, °C
T_{sun}: Sun temperature, 6000 K
TCF: Temperature correction factor
TCC: Total capital cost, \$
TWC: Total water cost, \$/m³
W_t: Turbine work, kW
W_p: Pump work, kW
W_{HPP}: High pressure pump work, kW
X: Salinity, ppm, dryness fraction
V: Volume, m³
Z^{IC&OM}: Total investment and operating and maintenance cost, \$/h

Subscripts

amb: Ambient
av: Average
b: Brine
chm: Chemical
col: Collector
cond: Condenser
cw: Cooling water
d: Distillate product
e: Element
evap: Evaporation case
f: Feed
g: Generator
i: In
insur: Insurance
Mbne: Membrane
o: Out
ORC: Organic Rankine cycle
p: Pump–Plant–Permeator–Product
RO: Reverse osmosis
s: Salt
sat: Saturation
swip: seawater and intake price
site: Site costs
sup: Superheat
t: Turbine
v: Vessel
w: Water

Greek

η: Thermal efficiency, %
η_o: Collector optical efficiency, %
ε_{reg}: Recuperator effectiveness
Π: Osmotic pressure, kPa

Nomenclature

A: Area, m², availability rate, kW
A_f: Amortization factor, y^{−1}
ACC: Annualized capital cost, \$/year
C: Cost, \$
CC: Capital costs, \$
C_p: Specific heat capacity at constant pressure, kJ/kgK
C_f: Specific annual total costs, \$/m³
DCC: Direct capital cost, \$