Thermo-Economic Comparisons of Different Types of Solar Desalination Processes

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Many types of desalination technologies are widely used around the worldwide. Thermal and membrane types dominated the market share among the other technologies (freezing, electrodialysis, and ion-exchange). Currently, multistage flash considered the power house of desalination technologies; however, in the last few decades, multi effect distillation and reverse osmosis (RO) technologies were proven as reliable and cost efficient processes. But comparing and electing the most efficient type between conventional desalination technologies is still under scope. It is very hard to decide which type or technique is reliable and thermo-economically efficient. Also, it becomes harder to decide which type is thermo-economically efficient when desalination process is combined with solar energy. In this work, different types of solar desalination processes are thermo-economically compared and analyzed. Results revel that RO and multi effect distillation-thermal vapor compression are recommended according to specific solar area (SSA $m^2/(m^3/d)$), total water price (TWP $\$/m^3$), thermo-economic product cost (c_p $\$/GJ$), and the gain ratio (GR). The comparisons were performed based on two scenarios: (1) different operating conditions due to each individual technology and (2) uniform operating conditions. [DOI: 10.1115/1.4005752]

Keywords: solar organic cycles, solar desalination technologies, thermo-economic, SDS software package

1 Introduction

As result of the growing human demands for fresh (potable) water, several desalination methods have been consequently suggested during the past three decades. Examples of great interest can be easily found in many industrial applications. At present, the RO and multistage flash (MSF) are the mostly used industrial techniques. Also, the mechanical and thermal vapor compressions (MVC-TVC) and multiple effect distillation (MED) are used on much limited scales to produce water from sea, that is to say the largest water supply on the earth [1]. These standard desalination techniques are only reliable for large capacity ranges of 100–50,000 m^3/day of fresh water production [2]. Using conventional energy sources to drive on such technologies has a negative impact on the environment. To reduce the negative impacts from the conventional desalination plants, solar energy considered an alternative solution to reduce the negatives from desalination processes to the environment. To combine desalination processes with solar energy, there are many aspects should be taken in consideration such as:

- **The location of operation:** It is very important to allocate solar desalination plants in the Sunbelt area and near the saline water source (sea or well).
- **The amount of water production:** It is very important to decide the amount of fresh water production (small–medium–large capacities) based on the remote area need.
- **The size area of the site:** Size area of the site considered a vital parameter to decide the type of solar desalination plant.
- **The type of the technology:** There are many techniques of combining the solar energy and desalination processes such as direct vapor generation, indirect vapor generation, and combination with organic Rankine cycle [3–5].
- **The production cost:** It is very important to decide the price of the fresh water production based on the region of the sink (local and/or tourism sectors).

Combining the solar energy with desalination processes takes an important place of studies along the near decades. Voros et al. [6] studied the possibilities and cost aspects for solar power plant for RO desalination process. Nafey et al. [7] investigated the possibilities of driving a small unit of flash evaporation by solar energy. The productivity was not exceeding 20 kg/day. During the 1990s, an experiment in solar seawater desalination at the Plataforma Solar de Almería coupled a parabolic-trough solar field with a conventional MED unit was constructed [8]. For large capacity, MED plant with capacity of 6000 m^3/day driven by parabolic-trough collectors (PTCs) are designed and constructed in Arabian Gulf [9]. For lower capacities, an MED-14 effects plant with capacity of a 40 m^3/day driven by evacuated tube collectors is constructed in La Desired Island, French Caribbean [10]. Also, a 16 effect-MED (plant capacity, 16 m^3/day; solar collectors, flat plate) is constructed in Takami Island, Japan [11].

Also, the stand alone desalination processes are widely different in the manner of TWP ($\$/m^3$). The example of some case studies about thermal desalination processes shows some differences in capacities and total water price. Al-Sahali and Ettouney [1] investigated that the TWP of a MSF with a capacity of 68,333 m^3/day is about 0.958 $\$/m^3$. For MED capacity of 20,000 m^3/day [1], the TWP is found as 0.86 $\$/m^3$. Nafey et al. [12] indicated a value of 2.58 $\$/m^3$ for a capacity of 5000 m^3/day of MED with parallel feed configuration. However, the cost of MED-MVC for 1500 m^3/day was about 1.7 $\$/m^3$ [13]. It is clear from the literature that the possibility of utilizing solar thermal power with different types of distillation processes such as MED, MSF, and RO already exists. However, such plants are not widely used especially in Middle East region where the solar potential is great and the sun shine hours almost 3600 h/year. To construct such plants, there are many obstacles like what is the most reliable, efficient, costly effective technique. Also, it become very

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hard to compare and elect a solar desalination technique to be constructed due to many aspects such as productivity, cost, exergy destruction, solar field area, and specific power consumption. Moreover, each technique has an individual operating conditions differed from the others techniques. In this work, two case studies are performed to compare and elect the most reliable solar desalination technique. The study is performed based on two different methods. The first method is to compare the techniques based on individual operating conditions for each technique, and the second method is to compare based on uniform operating conditions for all techniques. The aim of this work may be concluded into these points:

- Solar desalination processes are compared based on uniform and different operating conditions putting in consideration the design limits of each process.
- Electing the most reliable technique based on the aspects that mentioned above (productivity, solar field area, total water price, and location of operation).
- The terms of comparison are solar field area m^2, productivity m^3/day, specific power consumption kWh/m^3, total exergy destruction rate MW, thermo-economic product cost \$/GJ, specific solar field area $m^2/(m^3/day)$, and hourly costs \$/h.
- Solar Desalination Systems (SDS) software package [5,14–19] is used to run out the different results of solar assisted RO, MVC, TVC, MED, and MSF processes.

2 SDS Software Package

Using the developed SDS software package [14], different types and configurations of solar thermal desalination plants can be easily designed and simulated. The process units are modeled then the design and performance calculations are performed using the developed SDS program. 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 Ref. [14]). Figure 1 shows an SDS library interface under MATLAB/SIMULINK program. The developed SDS package has some features concluded in: easy model construction, easy to convert the designed code to be self executable and work under different computer languages (VISUAL BASIC, VISUAL C, VISUAL C++). The model allows users easily change to the plant variables and different operating conditions with ultimate stream allowance. The developed program overcomes the problem that appears in other techniques of simulation such as sequential approach and matrix manipulation technique.

3 Environmental Conditions and Process Configurations

The techniques of combining solar power (organic) cycles with desalination processes are wide and vary. In this work, two different techniques of combining solar power cycle with desalination technologies are utilized. The first is via mechanical power developed by solar organic Rankine cycle (SORC) and the second is by thermal power transferred via boiler heat exchanger (BHX) unit between the solar field and the desalination process. The first method usually performed for RO and MED-MVC technologies (mechanical types). The second method is performed for thermal types of desalination processes such as MED, MED-TVC, and MSF.

3.1 Environmental Conditions. Direct normal irradiance under winter operating conditions is assumed in this study [16]. The values of (latitude: 30 deg N; longitude: 32.55 deg E-Egypt-Suez Gulf region) are considered for this study. It is estimated by SDS [14,16] that the daily average global radiation in a typical day in winter would be in the range of 21–22 MJ/m^2. To dominate long operation along the day light (11 h), the solar radiation would be estimated and fixed at 503 W/m^2 (21.4 $MJ/m^2 \approx 503.7$ W/m^2). For all day operation (24 h), the daily average is estimated at 252 W/m^2. Figure 2 shows the variations of solar radiation on the specified location in Jan. 21. Also, Table 1 illustrates the data results of the solar model according to the specified location.

Designing the solar field based on lower values of solar radiation, for example, winter conditions (for example, 252 W/m^2) gives the allowance to collect huge amount of solar radiation based on larger expected area. Although the PTC operates at 850 W/m^2 this value could cause the very need for storage element (extra costs) during winter or may also not be able to power on the plant based on lower operation area service against the demanded productivity. However, under summer conditions, it will be expected that there is an excessive power due to large solar field area and it might be handled through bypassing some loops in the solar field for maintenance and cleaning operations.

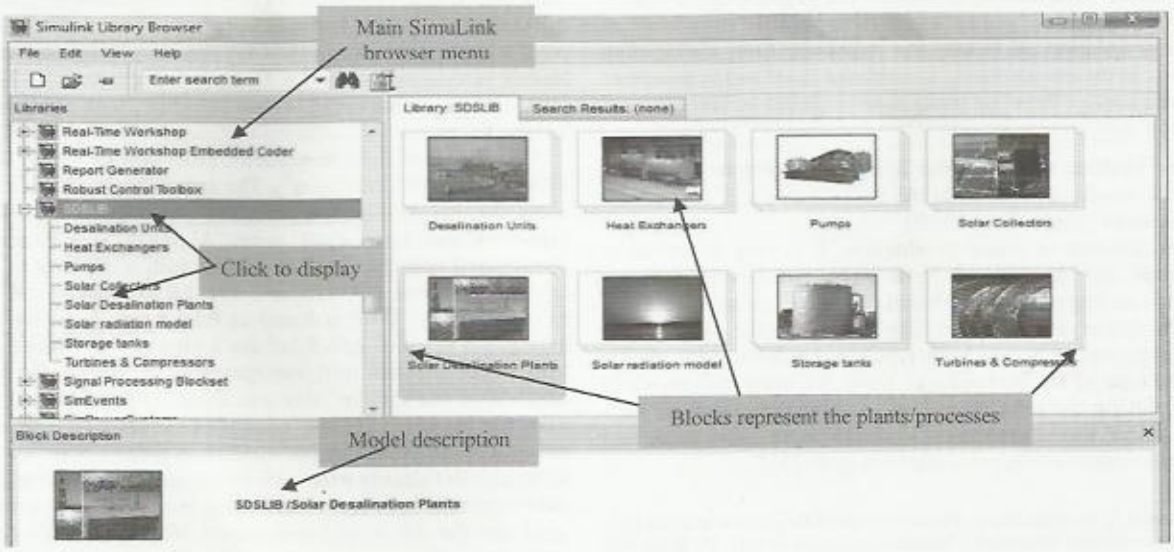

Fig. 1 SDS software library browser under MATLAB/SIMULINK interface [14]

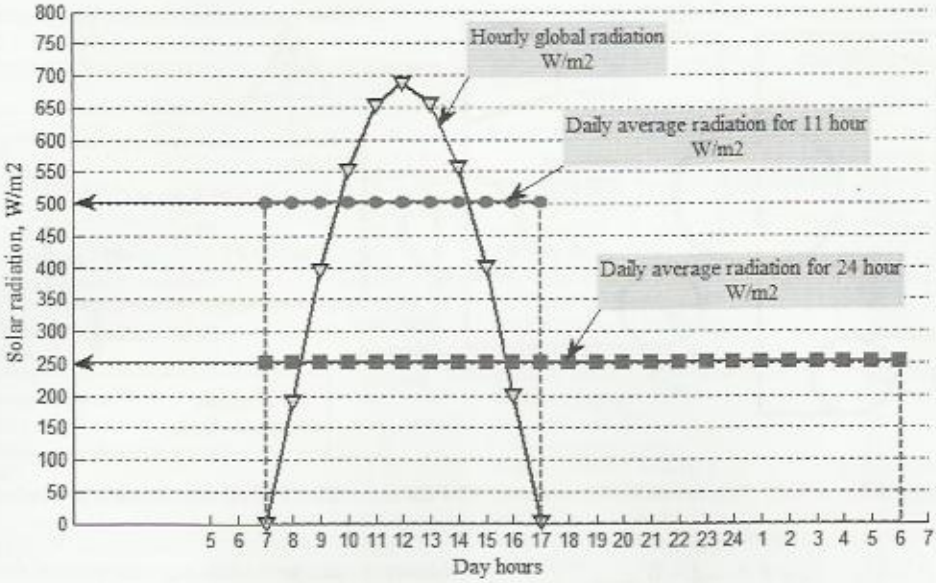

Fig. 2 Global solar radiation data results based on hourly, daily average (11 h), and daily average (24 h) variations (winter condition)

3.2 Solar Organic Rankine Cycle for RO and MED-MVC Processes. SORC often contains solar PTC, BHX unit, circulation pump, turbine, generator, recuperator, and condenser/preheater unit. In this technique, SORC is utilized to develop the sufficient power to operate the high pressure pump (HPP) in the RO and the vapor compressor in the MED-MVC. Heat transfer oil (HTO) is used through the solar PTC field [4] to transfer the collected thermal power via BHX unit to any process heat. Thence, HTO would transfer the thermal power to the organic oil (Toluene) passes through the Rankine cycle. The generated power from the organic turbine would power on the high pressure pump for the RO process and/or the mechanical vapor compressor for the MED-MVC process. Also, the preheated seawater from the Rankine cycle condenser unit goes directly to the RO process and/or the first effect of the MED-MVC process. RO with pressure exchanger unit configuration (RO-PEX) and MED parallel feed configuration (MED-PF) are confirmed in this study [5,14,17]. Figure 3 shows schematic a diagram of the SORC powered on the RO-PEX and MED-MVC processes.

3.3 Solar Thermal Organic Cycle for MED, MED-TVC, and MSF-BR Processes. In this technique, solar thermal power from the solar field is directly transferred to the BHX unit. Thence, the thermal power would be transferred to the steam cycle to power on the thermal desalination process. Such cycles often contain solar PTC collector with HTO, which is directly fed toward the BHX unit for thermal power transmission, and pump unit for circulation and to overcome pressure losses, and the desalination process for fresh water production. Such configurations need not any turbine, however, it would consume larger thermal power compared against the previous technique. Moreover, it also consumes electricity for distillate, brine, seawater pumps, and other facilities. Brine heater unit is added in case of multistage flash brine recycle configuration (MSF-BR). Multi effect distillation with parallel feed configuration is considered for MED and MED-TVC. Figure 4 shows a schematic diagram of the solar thermal power cycle assisted MED-PF, MED-TVC, and MSF-BR desalination processes.

Table 1 Typical data results for solar radiation model based on the specified location of operation

Parameter	Data results
Location	Suez Gulf region
Longitude	Longitude: 32.55 deg E
Latitude	Latitude: 30 deg N
Equation of time, min	−11.25
Declination-angle	−20.138
Daily average solar radiation, MJ/m^2	21.76
Monthly average of daily total radiation, MJ/m^2	15.623
Extraterrestrial intensity, W/m^2	1409.19
Sun temperature, K	5833.11
Sun rise time	6.814
Sun set time	17.19
Julian day	Jan. 21

4. Exergy and Thermo-Economic Considerations

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 general form of the exergy is defined by the following equation [18]:

$$Ex_2 - Ex_1 = Ex_q + Ex_w + Ex_{fi} - Ex_{fo} - \dot{I} \tag{1}$$

where $Ex_2 - Ex_1 = 0$ is the nonflow exergy change in steady state condition, $Ex_q = \sum_J (1 - T_{amb}/T_J)Q_J$ is the exergy transfer due to the heat transfer between the control volume and its surroundings, $Ex_w = -W_{cv} + P_o(V_2 - V_1)$ 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, Ex_w can be further simplified. And $I = T_{amb} \times S_{gen}$ is the exergy destruction in the process. The flow availability expressed as $Ex_{fi,o} = \sum_{i,o} m_{i,o} e_{fi,o}$. So the general form in steady state condition would become

$$0 = Ex_q + Ex_w + Ex_{fi} - Ex_{fo} - \dot{I} \tag{2}$$

The exergy destruction rate (kW) in solar collector is obtained by Ref. [21] as

$$\dot{I}_{collector} = A_{col} \times G_b \times \left(1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right) + \dot{m}_{col}[h_i - h_o - T_{amb}(s_i - s_o)] \tag{3}$$

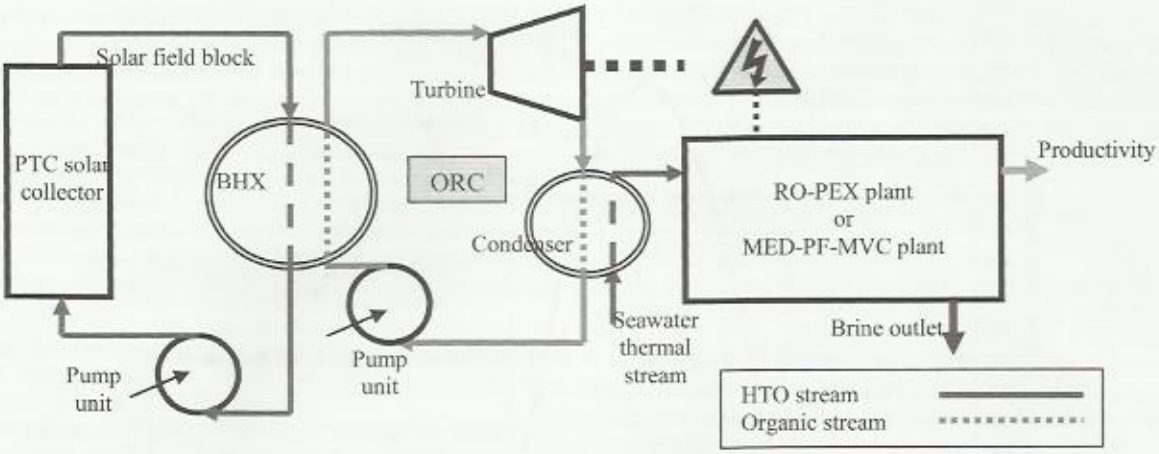

Fig. 3 A schematic diagram of SORC assisted RO-PEX and MED-PF-MVC desalination processes.

$$\dot{I}_{turbine} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta s_{i-o}] - \dot{W}_{turbine} \quad (4)$$

$$\dot{I}_{rec,cond} = \dot{m}_{hot}[\Delta h_{i-o} - T_{amb} \times \Delta s_{i-o}]_{hot} + \dot{m}_{cold}[\Delta h_{i-o} - T_{amb} \times \Delta s_{i-o}]_{cold} \quad (5)$$

$$\dot{I}_{pump} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta s_{i-o}] + \dot{W}_{pump} \quad (6)$$

$$\dot{I}_{MED-PF-MVC} = \Delta \dot{Ex}_{steam} + \dot{W}_{pumps} - \dot{W}_{turbine} + \dot{Ex}_f - \dot{Ex}_b - \dot{Ex}_d \quad (7)$$

$$\dot{I}_{MED} = \Delta \dot{Ex}_{steam} + \dot{W}_{pumps} + \dot{Ex}_f - \dot{Ex}_b - \dot{Ex}_d \quad (8)$$

$$\dot{I}_{MSF} = \Delta \dot{Ex}_{steam} + \dot{W}_{pumps} + \dot{Ex}_f - \dot{Ex}_b - \dot{Ex}_d \quad (9)$$

$$\dot{I}_{RO} = \dot{W}_{pumps} + \dot{Ex}_f - \dot{Ex}_b - \dot{Ex}_d \quad (10)$$

where $\dot{Ex}_f$ represents the chemical and physical exergy of seawater feed stream to the MED effects, $\dot{Ex}_b$ is the exergy stream associated with brine and neglected as loss stream, while $\dot{Ex}_d$ is the chemical and physical exergy stream of distillate product, and $\Delta \dot{Ex}_{steam}$ is the exergy stream of steam conditions based on inlet and outlet cases. Exergy of saline streams is obtained based on physical and chemical components. For physical part, the exergy streams for feed, brine, and distillate are functions of h_f, h_b, and h_d which are calculated based on seawater specific heat capacity c_p, salinity s, and feed seawater temperature for each stream [15] where

$$h_{f,d,b} = h_0 + \left(A \times T + {}^{B}/_{2} \times T + {}^{C}/_{3} \times T^3 + {}^{D}/_{4} \times T^4\right) \quad (11)$$

where

$$h_o = 9.6296 \times S - 0.4312402 \times S^2$$

and

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

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

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

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

Therefore, the physical exergy equation (kg/s) for any saline stream is obtained as

$$\dot{Ex}_{ph} = \dot{m}\left(C_p(T,S) \times (T - T_o) \times C_p(T,S) \log \frac{T}{T_o}\right), \quad (12)$$

$$(T_o = \text{reference temperature})$$

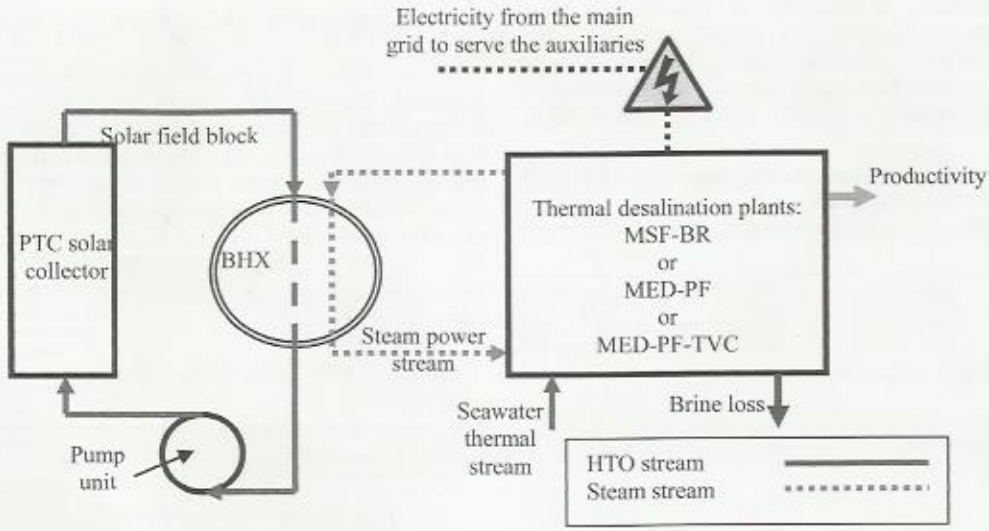

Fig. 4 A schematic diagram of solar thermal power cycle assisted thermal desalination processes (MSF-BR, MED-PF, MED-PF-TVC)

Table 2 Specifications and design input data based on S-RO-PEX (First method)

Parameter	S-RO-PEX
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	ORC/toluene [15]
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Top solar collector temperature, °C	350
Inlet turbine condition/condensation condition, °C	300/35
Seawater temperature, °C /seawater salinity, ppm	20/45,000
Turbine, generator, pumps efficiency, %	85%, 95%, 75%
Recuperator effectiveness, %	80
Productivity, m^3/day	3500
Recovery ratio, %	30
PEX, HPP, BP efficiencies, %	96%, 80%, 80%
Number of elements/number of pressure vessels	7/42
Area of the element, m^2	35.3
Fouling factor	0.85
Load factor	0.9
Membrane life time/plant life time, year	5/20

For chemical part, the exergy stream (kg/s) should be calculated according to the following relation:

$$Ex_{ch} = m^{\cdot}(N_{mol}(S, M_W, M_S) \times 10^{-3} \times 8.314 \times T_o\{-X_W \times \log X_W - X_S \times \log X_W\}) \quad (13)$$

and total stream exergy rate is then calculated

$$Ex_{total} = Ex_{ph} + Ex_{ch} \quad (14)$$

where

$$X_W = N_{pure}(S, M_W)/N_{mol}(S, M_W, M_S) \quad (15)$$

$$X_S = N_{salt}(S, M_W)/N_{mol}(S, M_W, M_S) \quad (16)$$

$$N_{pure} = (1000 - S)/M_W \quad (17)$$

$$N_{salt} = S/M_S \quad (18)$$

Table 3 Specifications and design input data based on S-MED-MVC (First method)

Parameter	S-MED-MVC
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	ORC/toluene [15]
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Top solar collector temperature, °C	350
Inlet turbine condition/condensation condition, °C	300/35
Seawater temperature, °C	21
Seawater salinity/brine blow-down salinity, ppm	42,000/70,000
Turbine, generator, pumps efficiency, %	85%, 95%, 75%
Recuperator effectiveness, %	80
Productivity, m^3/day	1500
Top vapor temperature, °C	65
Compression ratio	1.35
Compressor efficiency, %	75
Adiabatic index	1.32
Number of MED effects, #	2
Effects temperature drop, °C	5
Feed, brine, distillate pumps efficiencies, %	75%, 75%, 75%
Load factor	0.9
Plant life time, year	20

Table 4 Specifications and design input data based on S-MED (First method)

Parameter	S-MED
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	Indirect vapor generation/ steam
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Top solar collector temperature, °C	350
Top steam temperature, °C	73
Brine blow-down temperature, °C	36
Seawater temperature, °C	28
Seawater salinity/brine blow-down salinity, ppm	46,000/69,000
Pump efficiency, %	75
Productivity, m^3/day	4545
Number of MED effects, #	Four parallel feed configuration
Effects temperature drop, °C	9.3
End condenser effectiveness, %	59
Feed, brine, distillate pumps efficiencies, %	75%, 75%, 75%
Load factor	0.9
Plant life time, year	20

$N_{mol} = N_{pure} + N_{salt}$ is the number of particles, and X_w, X_s is the fraction of water and salt (mol), and the molar weight $M_{w,s}$ for water and salt is 18 g and 58.5 g, respectively.

4.2 Thermo-Economic Analysis. In this part, investment and operating & maintenance costs analyses are performed for each unit (solar field, steam turbine, condensers, and pump units). The interest rate set as 5%, LT_p is the plant lifetime and set as 20 years. 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 [19]. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as following [19]:

Table 5 Specifications and design input data based on S-MED-TVC (First method)

Parameter	S-MED-TVC
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	Indirect vapor generation/ steam
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Top solar collector temperature, °C	350
Top steam temperature, °C	62
Brine blow-down temperature, °C	46.8
Seawater temperature, °C	30
Seawater salinity/brine blow-down salinity, ppm	46,000/69,000
Steam ejector compression ratio, CR	2.165
Motive steam pressure, kPa	2500
Expansion ratio, ER	250
Pump efficiency, %	75
Productivity, m^3/day	4545
Number of MED effects, #	Four parallel feed configuration
Effects temperature drop, °C	4
End condenser effectiveness, %	66
Feed, brine, distillate pumps efficiencies, %	75%, 75%, 75%
Load factor	0.9
Plant life time, year	20

Table 6 Specifications and design input data based on S-MSF-BR (First method)

Parameter	S-MSF-BR
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	Indirect vapor generation/ steam
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Top solar collector temperature, °C	350
Top steam temperature, °C	116
Top brine temperature, °C	106
Brine blow-down temperature, °C	40.2
Seawater temperature, °C	25
Seawater salinity/brine blow-down salinity, ppm	42,000/70,000
Cooling water splitter ratio	0.5082
Chamber load, kg/s m	180
Vapor velocity, m/s	12
Pump efficiency, %	75
Productivity, m^3/day	32728
Number of MSF-BR stages, #	24 (21/3)
Stages temperature drop, °C	2.8
Feed, brine, distillate pumps efficiencies, %	75%, 75%, 75%
Load factor	0.9
Plant life time, year	20

$$\sum_{out} \dot{C} = \sum_{in} \dot{C} + Z^{IC\&OM} \tag{19}$$

where $\dot{C}$ the cost rate according to inlet and outlet streams, and $Z^{IC\&OM}$ is the capital investment and operating & maintenance hourly costs (\$/h). 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 write as following:

$$\dot{C}_{i,o} = c_{i,o}\dot{E}_{i,o} \tag{20}$$

$$\dot{C}_W = c_W \dot{W} \tag{21}$$

$$\dot{C}_q = c_q \dot{E}_q \tag{22}$$

where $c_{i,o,w,q}$ denote average costs per unit of exergy in \$/kJ for inlet (i), outlet (o), power (w), and energy transfer (q), respectively. Thermo-economic balance for the SMED-PF-TVC technique units is developed as following. For turbo machinery units, the cost of electric power is assigned based on the price of the electricity 0.06 \$/k W h [21]. Therefore, the specific thermal power cost would be converted to become 0.06/3600 \$/kJ. The cost equation for the pump unit stream toward the solar collector should become as

$$C_{pump-col} = C_W + C_{bhx-pump} + Z^{IC\&OM}_{pump} \tag{23}$$

For solar collector, the relation should become

$$C_{col-bhx} = C_q + C_{pump-col} + Z^{IC\&OM}_{col} \tag{24}$$

Thermo-economic balance for BHX unit is performed as

$$C_{bhx-med} + C_{bhx-pump} = C_{col-bhx} + C_{med-bhx} + Z^{IC\&OM}_{bhx} \tag{25}$$

For recuperator unit

$$C_{rec-bhx} + C_{rec-cond} = C_{turbinr-rec} + C_{pump-bhx} + Z^{IC\&OM}_{rec} \tag{26}$$

For MED-VC process streams:

$$C_p + C_{brine} + C_{steam-pump} = C_{steam-med} + C_{fi} + Z^{IC\&OM}_{med-VC} \tag{27}$$

where C_p is the hourly product cost \$/h, C_{brine} is the brine blow-down cost and is specified as zero cost, and C_{fi} is the feed stream cost.

For the solar MSF-BR, RO and MED-PF cases, the thermo-economic product equation would become as follows:

$$C_p + C_{brine} + C_{steam-pump} = C_{steam-msf} + C_{fi} + Z^{IC\&OM}_{msf} \tag{28}$$

$$C_p + C_{brine} + C_{steam-pump} = C_{steam-med} + C_{fi} + Z^{IC\&OM}_{med} \tag{29}$$

$$C_p + C_{brine} = C_{fi} + Z^{IC\&OM}_{RO} \tag{30}$$

5 Methods of Comparison

Solar desalination processes combined from two major parts. The first is the solar cycle and the second is the desalination process. For the first part, there is no comparison difficulty while trying to assign or specifying the operating conditions because the same components are already used for all processes (PTC, BHX, and pump). However, desalination processes are different types, different configurations, and different techniques. Moreover, each type has its own operating conditions (productivity, salinity range, temperature, etc). Therefore, in this section, the comparisons are performed based on two main methods. The first is performed based on individual operating condition for each type, and the second is performed based on uniform operating conditions to give a clear judge about the most reliable technique.

5.1 Individual Operating Conditions. In this subsection, the proposed configurations are compared based on different operating conditions (salinities, productivities, etc) and different design limits (number of stages or effects, temperature drop, etc). It does not make sense to compare deferent techniques based on deferent design limits because it would give different results. However, this is actually exist when any investor/designer wants to construct or evaluate such technology. Therefore, it is very important to demonstrate such comparison and its defect. For solar assisted RO (S-RO), it is required to desalinate and produce a total capacity of 3500 m^3/day (Sharm El-Shiekh desalination plant [15]). The number of pressure vessels is 42 and the element number is about 7 elements per each vessel. The element area is about 35.3 m^2 and the feed seawater salinity is 45,000 ppm. Solar assisted MED-MVC (S-MED-MVC) is performed based on a capacity of 1500 m^3/day [13].

Parallel feed configuration is maintained for the use in MED process. The number of effects is not exceeded above two effects and the compression ratio of the compressor is in the range of 1.35. For solar MED (S-MED), solar thermal power plant is utilized to target a capacity of 4545 m^3/day [22]. The heating steam temperature is in the range of 70–73 °C and the blow-down brine salinity is about 69,000 ppm. The number of effects is maintained at four effects. For solar assisted MED-TVC (S-MED-TVC), a capacity of 4545 m^3/day is targeted [23]. The top steam temperature is in the range of 60 °C for only four effects. The motive steam pressure is about 2500 kPa and the ejector compression ratio is about 2.165. A productivity of 32728 m^3/day is produced by solar thermal power assisted MSF-BR type (S-MSF-BR) [21]. The top brine temperature is not exceeded above 106 °C and the total number of stages is about 24 stages. Tables 2–6 illustrate the specifications of all introduced techniques according to different operating conditions.

5.2 Uniform Operating Conditions. In this method, all the operating conditions are uniformly confirmed. Productivity, salinity, solar radiation, and efficiencies are maintained at the same values. This method is very important because it gives a clear decision about the most effective technique. However, sometimes it becomes nonrealistic because it takes the designer to assign nonreal data for some techniques. However; it can help the decision makers of the field of research to assign the best type based on the

Table 7 Specifications of solar assisted thermal and mechanical desalination processes (Second method)

Parameter	Solar-RO, MVC, MED, TVC, MSF
Solar collector type/working fluid	PTC-LS-3 [4]/ therminol-VP1 [24]
Developed power type/working fluid	ORC/Toluene [15]
Solar radiation, W/m^2	252 (winter)
Ambient temperature, °C	30
Capacity, m^3/day	5000
Top solar collector temperature, °C	350
Top steam temperature, °C	60
Inlet turbine condition/condensation condition, °C	300/35
Seawater temperature, °C /Seawater salinity, ppm	25/45,000
Brine blow-down temperature, °C /blow-down salinity, ppm	40/65,500
Power cost, $/kJ	1.6×10^{-5}
Condenser's efficiency, %	80
Pumps efficiency, %	75
Turbine, generator efficiencies, %	85, 95
Plant life time, year	20
Load factor	0.9
Fouling factor	0.85
Interest rate, %	5

same base line. Table 7 demonstrates the specifying parameters for the proposed types of solar desalination processes.

6 Results and Discussions

Results are run out from SDS software package [14] based on the earlier two methods related to some indicators. The indicators are listed as

- Solar field area (A_{col}), m^2 and Specific solar field area (SSA), $m^2/(m^3/day)$.
- Specific power consumption (SPC), kWh/m^3.
- Thermo-economic product cost (c_p), $/GJ.
- Total exergy destruction rate (I_{total}), MW.
- TWP, $/$m^3$.
- Gain ratio ($GR = M_{distillate}/M_{steam}$).
- Area of desalination unit, m^2.
- Operating hours cost, $/h.

6.1 Results of the First Method. The main criteria of this method that the investor/sponsor would be able to judge and elect the process based on the above indicators regardless different specifications or design limits. The investor that would like to construct or design a solar assisted desalination plant would judge the process based on the above indicators regardless the differences in the specifications. Suppose that the investor wants to elect the technology regardless the specifications. As shown from Table 8 that S-RO exhibits lower solar field area meaning by this it is highly recommended to be operated in small remote areas (tourist sector). Also, it achieves lower results related to TWP, I_{total}, SPC, operation costs, and SSA. However, the thermo-economic product cost is in the range of 65–72 $/GJ and this is recorded highly comparing against the remaining processes. Also, it is noticed that the desalination processes that operated by SORC (S-RO, S-MED-MVC) normally give high thermo-economic product cost comparing with the thermal ones such as S-MSF-BR, TVC, and MED. That is because the existence of organic turbine which cause an increase in the thermo-economic product cost due to its operating cost and the cost of power produced. It is clear now that the investor would elect the S-RO technique however there are many limitations should be pinpointed

- Use of Toluene is risky because it is flammable and toxic and has a negative impact on the environment.
- Noise from the Organic Rankine Cycle (ORC) operation related to the turbine existence.
- Hazards.
- Limited capacity within the range of 100–5000 m^3/day.

For larger capacities, MED and MSF are dominant and reliable however; the irreversibility would become massive and the solar field area becomes larger than S-RO case. As it shown from Table 8 that S-MSF-BR consumes the largest area with a SSA about 20 $m^2/(m^3/day)$. Also, the operating hours cost reached about 1900 $/h against 90 $/h in the S-RO operation. But the TWP for S-MSF-BR still in the acceptance range depending on the type of consumption sector. For thermal desalination types (only MED, MED-TVC, MSF-BR), MSF and MED-TVC are attractive according to the lower values of GR, TWP, and thermo-economic product cost. MED is less in construction (area of desalination sector is about 6420 m^2) however; it would take the investor to sell the fresh production in the range of 2.8–3 $/$m^3$. Therefore, it depends on investor or the designer to elect the best technique according to the sector of consumption. Also, it is clear that S-MSF-BR and S-MED-TVC would be operated for industrial or local sectors. S-RO would be constructed for tourist sector. Generally, S-RO and S-MED-TVC gives attractive results regardless the target of operation or the type of consumption sink. However; MSF-BR stills the power house based on the capacity (32728 m^3/day versus 3500 m^3/day for RO and 4545 m^3/day for the

Table 8 Data results for all solar desalination processes based on different operating conditions method

Parameters	*SRO*	*SMED-MVC*	*SMED*	*SMED-TVC*	*SMSF-BR*	*Election*
Md m3/day	*3500*	*1500*	*4545*	*4545*	*32728*	*SMSF-BR*
Acol m2	7359	12450	186113	123666	638011	*SRO*
SPC kWh/m3	2.8	11	7.23	3	7.847	*SRO*
cp $/GJ	72	2.186	1.712	1.09	1.07	*SMSF-BR*
Itotal MW	2.8	35.5	178.6	163	2018	*SRO*
TWP $/m3	0.616	2.968	2.854	1.944	1.548	*SRO*
GR	19.11	1.92	3.7	6.11	7.14	*SRO*
SSA m2/(m3/d)	2.113	8.3	41	27.2	19.5	*SRO*
No of units	nv=42 ne=7	Neff=2	Neff=4	Neff=4	Nstg=24	*NAN*
dT drop oC	nan	5	9.3	4	2.8	*SMSF-BR*
Area des unit m2	10437	3378	6420	14238	81153	*SRO*
Operating cost $/h	90	167	486	331	1900	*SRO*

Table 9 Data results for solar desalination processes based on the same productivity

Parameters	SRO	SMED-MVC	SMED	SMED-TVC	SMSF-BR	Election
Acol m2	10754	40252	132367	102374	115732	SRO
SPC kWh/m3	2.844	10.72	2.64	2.06	5.4	SMED-TVC
cp $/GJ	66	1.312	1.088	0.9147	1.35	SMED-TVC
Itotal MW	4.137	168.42	191	183	496	SRO
TWP $/m3	0.5728	1.714	1.887	1.55	2.006	SRO
GR	18.78	5.68	5.82	8.166	6.26	SRO
SSA m2/(m3/d)	2.151	8.05	26.47	20.47	23.15	SRO
No of units	nv=50 ne=8	Neff=6	Neff=6	Neff=6	Nstg=21	NAN
dT drop oC	nan	3.45	3.45	3.45	3.4	NAN
Area des unit m2	14120	22393	21801	18795	10105	SMSF-BR
Operating cost $/h	120	321	354	290	376	SRO

MED). It becomes very hard to elect a feasible process because of different operating conditions and different criteria. A configuration with higher productivity has a larger exergy destruction rate (MSF-BR case). Also, a configuration with lower productivity has a larger SPC or TWP (MVC case). Therefore, the second method could be useful to elect the reliable and feasible configuration under the same base line even with different technique of each process.

6.2 Results of the Second Method. It is clear from the previous method that the comparison could not give a clear or a final decision to elect the most reliable technique because there are a different design limits and productivity ranges. In this method, all operating conditions (temperature drop, salinity, feed temperature, etc) are uniformed to give a clear decision about the most reliable process regardless the sector of operation. The investor has to inspect the following scenarios:

- **Productivity (5000 m^3/day):** Suppose that the investor is concerned about the productivity regardless the other indicators or terms.
- **Same solar field area:** The investor has a limited area of operation.
- **Same TWP $\$/m^3$ ($0.5 < TWP < 1$):** The investor care about the price of the production regardless any other terms such as area or productivity.

In this scenario (Table 9), the RO productivity (5000 m^3/day) is assigned for all techniques. To ensure a uniform case especially for thermal desalination techniques, the temperature drop between effects or stages remains constant and has a range of 3.4 °C to 3.45 °C. It is found that S-RO gives the lower solar area followed by S-MED-MVC. That is explained by the operation of SORC, which causes a significant decrease in the solar field regardless the other aspects. However, the operation of S-MED-MVC would consume much power based on the vapor compressor. Among all thermal processes, S-RO gives enviable results based on total exergy destruction, SSA, TWP, and operating hour costs. Solar field considered a key factor of increasing or decreasing the TWP, I_{total}, and operating costs. As an example, S-RO gives about 0.5 $\$/m^3$ against 2 $\$/m^3$ for MSF-BR and 1.88 $\$/m^3$ for MED. Less solar field area means, lower results in these parameter specially the I_{total}. For thermal processes, S-MED-TVC significantly attractive and gives first-rate results based on SSA, TWP, I_{total}, and achieves higher GR. It is obvious from Table 9 that at the same productivity S-RO comes as first order. Moreover, the operation of SORC might be reducing the solar field area. Generally, S-MED-TVC is elected next after the S-RO technique and elected first while comparing against the thermal desalination processes. S-RO is quite suitable to be operated by solar-ORC and that is permit to harvest lower solar field area against the thermal processes. Table 10 shows the data results obtained due to the limited solar field scenario. In this scenario, solar field of 10,754 m^2 is assigned for the comparison. This specified value (10,754 m^2) is resulted by the operation of S-RO technique at productivity of 5000 m^3/day.

Table 10 Data results for solar desalination processes based on same solar field area

Parameters	SRO	SMED-MVC	SMED	SMED-TVC	SMSF-BR	Election
Md m3/day	5000	1334	405.2	522.3	461.5	SRO
SPC kWh/m3	2.844	10.67	2.134	1.57	4.71	SMED-TVC
cp $/GJ	66	1.436	4.264	3.312	4.788	SMED-MVC
Itotal MW	4.137	45	15.5	19.11	46	SRO
TWP $/m3	0.5728	1.889	6.377	4.933	6.486	SRO
GR	18.78	5.68	5.82	8.166	6.26	SRO
SSA m2/(m3/d)	2.151	8.06	26.6	20.6	23.31	SRO
No of units	nv=50 ne=8	Neff=6	Neff=6	Neff=6	Nstg=21	NAN
dT drop oC	nan	3.45	3.45	3.45	3.4	NAN
Area des unit m2	14120	5975	1766	1963	935	SMSF-BR
Operating cost $/h	120	94.5	97	96.6	118	SMSF-BR

Table 11 Data results for solar desalination processes based on low ranges of TWP

Parameters	SRO	SMED-MVC	SMED	SMED-TVC	SMSF-BR	Election
Md m3/day	5000	5000	25000	25000	45000	SMSF-BR
SPC kWh/m3	2.844	5.386	1.488	2.8	5.47	SMED
cp $/GJ	66	0.7	0.489	0.64	0.81	SMED
Itotal MW	4.137	164	850	885	4321	SRO
Acol m2	10754	20300	221513	378842	429390	SRO
GR	18.78	14.8	17.34	10.84	14.8	SRO
SSA m2/(m3/d)	2.151	4.06	8.861	15.15	9.54	SRO
No of units	nv=50 ne=8	Neff=16	Neff=18	Neff=8	Nstg=50	NAN
dT drop oC	nan	1.3	1.15	2.59	1.4	SMED-MVC
Area des unit m2	14120	114095	744817	125704	284323	SRO
Operating cost $/h	120	161	650	965	1584	SRO
TWP $/m3	0.57	0.86	0.69	1	0.9	SRO

For the same specified solar field area by the investor/designer, S-RO would produce 5000 m^3/day, however, the remaining techniques would produce less, moreover, the TWP would be greater than the S-RO case. S-MED-MVC comes next after S-RO based on the production (1334 m^3/day), however; the SPC considered the uppermost between all processes related to the vapor compressor operation. But it achieves attractive results according to SSA, TWP, operating costs, and thermo-economic product cost. S-MSF-BR gives the highest TWP (6.48 $/$m^3$) among the remaining techniques. Also, it gives the highest value of total exergy destruction rate (I_{total} = 46 MW). However, it considered the less in desalination area condenser meaning by this less of complication. In the case of MSF-BR, the investor will produce an amount of 461 m^3/day which means very low compared against the RO case (5000 m^3/day), thence, higher TWP. It is not feasible to operate MSF-BR within this limited area combined with higher TWP and higher exergy destruction rate. According to the solar field scenario, S-RO and S-MED-MVC might be achieving attractive and significant results. The remaining techniques might be favorable for larger capacities.

Table 11 illustrates the data results for all process techniques based on the same TWP (0.5–1 $/$m^3$). For such operation, it is quite difficult to uniform all processes under the same TWP because each technique has it design limits that control the operating costs. In this scenario, the investor should be concerned about the total water prices of production regardless any other aspects. The TWP is a very important term because it concludes the costs of all process units. It is clear from Table 11 that S-RO gives the minimum values of solar field area (about 10754 m^2 versus 429390 m^2 in MSF-BR case) and the hourly operating costs (120 $/h versus 1584 $/h in MSF-BR and 965 $/h in MED-TVC cases). However, thermal desalinating technologies are quite attractive based on the remaining parameters such as productivity, and thermo-economic product cost. This scenario demands special designs for thermal processes as noticed in number of effects and stages. Moreover, it becomes very complicated referring to the increase in desalination area condenser. For such reasons, this makes it not feasible or hardly to be operated. Surley it would give a massive production with lower TWP, however, it costs time and materials. Therefore, S-RO still dominant based on solar field area and operating costs regardless the productivity.

7 Conclusion

A comparison involving different techniques of solar assisted desalination processes is performed. Concentrated solar power is utilized as indirect vapor generation with organic Rankine cycle for RO and MED-MVC desalination processes. And indirect vapor generation without turbine unit is used for MED, MED-TVC, and MSF-BR processes. SDS software package is used to run out the comparison results. The comparison is performed based on two main methods. The first is to compare based on individual design limits for each type. The other is to compare based on uniform parameters. Nowadays, the individual operating conditions method is the applicable method. However, it makes a difficult decision to elect the best option for the investor/designer while coupling with solar section. It becomes very attractive to compare between the proposed techniques at the same base line, i.e., salinity, productivity, operating conditions, site, etc. The results of the individual method reveal that S-RO is quite attractive according to lower TWP, lower SSA, lower SPC, and lower exergy destruction rate. The uniform method is performed according to three different scenarios such as the same productivity, the same solar field area, and the same TWP. For all scenarios, S-RO gives attractive results compared against the other techniques. Also, it is noticed that SORC could reduce the solar filed area because of the operation of Toluene (high molecular weight). S-MED-TVC gives attractive results while comparing with thermal desalination processes. The second technique has an advantage concluded in developing power but depending on the amount of distillate product and the outlet collector/boiler operating conditions. Generally, S-RO and S-MED-TVC are attractive mainly related to the solar filed area and TWP. However, the remaining processes could produce a massive fresh water quantity regardless the SPC or the solar field area.

Nomenclature

A_{col} = solar collector area, m^2
BHX = boiler heat exchanger
CSP = concentrated solar power
c_p = thermo-economic product cost, $/GJ
dT = temperature drop between effects or stages, °C
Ex = exergy rate, kW
Ex_b = brine blow-down exergy rate, kW
Ex_{ch} = chemical exergy rate, kW
Ex_d = distillate exergy rate, kW
Ex_f = flow exergy rate, kW
E_{xin} = exergy in, kW
Ex_{ph} = physical exergy rate, kW
Ex_q = exergy transfer, kW
E_{xout} = exergy out, kW
Ex_w = exergy of work, kW
GR = gain ratio, $M_{distillate}/M_{steam}$
HPP = high pressure pump
HTO = heat transfer oil
I_{total} = total exergy destruction rate, MW

MED-PF = multi effect distillation parallel cross feed arrangement
MED-PF-MVC = multi effect distillation parallel cross feed mechanical vapor compression
MED-PF-TVC = multi effect distillation parallel cross feed thermal vapor compression
MSF-BR = multi stage flash brine recycle
M_d = distillate mass flow rate
$m_{\cdot}$ = mass flow rate, kg/s
N_{eff} = number of effects for MED process
N_{stg} = number of stages for MSF process
N_{pure} = number of moles of pure water, g mol
N_{salt} = number of moles of salt, g mol
nv = number of pressure vessels
ne = number of elements
PEX = pressure exchanger
RO = reverse osmosis process
SSA = specific solar field area, $m^2/(m^3/\text{day})$
SORC = solar organic Rankine cycle
SPC = specific Power Consumption, kWh/m^3
S = salinity ratio, g/kg (ppm)
S_b = brine blow-down salinity ratio, g/kg
S_f = feed seawater salinity ratio, g/kg
TWP = total water price, $\$/m^3$
W_{turbine} = turbine power, kW
W_{pump} = pump power, kW
$X_{w,s}$ = fraction of water and salt contents
V = volume, m^3
$Z^{\text{IC\&OM}}$ = hourly operating and maintenance cost, \$/h

Subscripts

amb = ambient
av = average
b = brine
chm = chemical
col = collector
cond = condenser
d = distillate product
f = feed
i = in
MED = multi effect distillation
o = out
p = pump
rec = recuperator
RO = reverse Osmosis
s = salt, steam
steam = steam phase
t, turbine = turbine
v = vapor
w = water

Greek Symbols

η = thermal efficiency, %
η_g = generator efficiency, %
η_p = pump efficiency, %
η_t = turbine efficiency, %

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