Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27288

226 (2021) 1–8
June

Concentrated solar thermal cogeneration for zero liquid discharge seawater desalination in the Middle East: case study on Kuwait

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Received 7 November 2020; Accepted 2 April 2021

ABSTRACT

Processes have been developed for seawater desalination and for producing the required heat and power. To produce high-pressure steam and generate heat and electrical energy, solar thermal technologies can be directly applied. The design and development of water desalination technologies in the Middle East considering the particular geographic and weather conditions are the main challenges addressed in this study. Reverse osmosis in series with thermal methods is employed to prevent the environmental impact of the conventional methods, including the release of greenhouse gases and saline water rejection into seas. A design procedure is presented to calculate the equipment size and the process parameters in a concentrated solar thermal cogeneration and desalination plant with zero liquid discharge. In this case study, the available hourly solar irradiance data of Kuwait are directly input during designing. Based on the minimum and maximum values of the available solar energy, which correspond to the shortest and longest days of a year, production capacities of 400,000 and 865,000 m^3/d in winter and summer, respectively, are obtained for the desalination plant. The calculations yield a total reflector surface area of 2,670,000 m^2 and molten salt heat storage of 85,500 tons.

Keywords: Desalination; Solar thermal; Cogeneration; Solar irradiance; Design

1. Introduction

Currently, water, energy, and a clean environment are the three essential global requirements. The demand for desalinated water in the Middle East by the end of 2020 was estimated to be approximately 40 million m^3/d, with the required electrical energy being mainly produced from fossil fuels [1]. Countries in the Middle East are mostly located close to large water bodies with rich sources of saline water, and they have abundant solar energy, with more than 300 sunny days annually on average. Consequently, these specific geographic and weather conditions should be considered in the design, selection, and development of water desalination technology.

Several commercial thermal- and nonthermal-based processes are known for conducting water desalination [1]. Therefore, selecting the best process among these methods and designing a new energy production unit for desalination plants remain challenging [2,3]. Multistage flash distillation (MSF) [4,5] and multi-effect distillation (MED) with vapor compression [6] are examples of thermal methods. Reverse osmosis (RO) and membrane-based technologies [7] are nonthermal methods. Regardless of the type of energy (electric or thermal), the RO method consumes less energy per unit volume of the produced water [8] than thermal methods, and it is commonly used for large-scale applications because it requires low investment [9]. However, the RO method needs a more efficient form of electrical energy, and it may have

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more environmental impact than thermal methods because of the rejected saline water and the pre-treatment of fresh water. By providing the necessary energy using renewable sources, such as solar power, and combining thermal processes with RO, a water desalination plant with zero liquid discharge (ZLD) may be realized.

The most conventional methods for large-scale water desalination using renewable energy sources are RO and thermal methods [10–12]. However, supplying their energy needs is a major challenge when achieving ZLD systems [13]. The electrical and thermal energies required by a water desalination plant can have different forms. The choice of a photovoltaic (PV) plant or a solar thermal power plant to generate electricity depends on the geographical location and the local weather conditions. For example, in a major part of Europe and North America, where the weather is mostly cloudy, a PV plant may be a better option than a solar thermal power plant. However, in the Middle East, at locations close to deserts, there are approximately 300 sunny days in a year; thus, solar thermal methods are better options than PV plants. The first plant for water desalination using solar thermal energy was established in Chili in 1872 [14].

Cogeneration is the simultaneous production of heat and electrical power, and it is the preferred process compared with power production alone [15,16]. Concentrated solar thermal cogeneration (CSTC) has the advantage of simultaneous cogeneration and uses renewable energy sources. According to the International Renewable Energy Agency (IRENA) [17], the selection of STC-MSF and STC-RO processes depends on the salt concentration in the water that will be desalinated. In the Persian Gulf region, where the salt concentration in water is high, STC-MED and MSF are the appropriate processes.

Desalination technologies are energy-intensive, produce large amounts of greenhouse gases, and reject large volumes of saline water. For example, desalination by thermal methods requires seawater in the range of 5–10 m^3, and the total CO_2 emissions are 7–25 kg for each cubic meter of the produced desalinated water [18].

Both thermal and electrical energy demands are of major importance in designing the energy production units in water desalination plants [19], and the amounts and proportions of both energy types depend on the selected desalination method. In this study, the main objectives are to present the steps of a CSTC process and propose a flow diagram for a water desalination plant by considering the advantages of the specific geographical, climatic, and solar irradiation conditions of the Middle East.

2. Methods

During the design and selection steps of the process and utilities for a water desalination plant, the number of sunny days and the solar irradiance data of the subject region are important. Direct normal irradiance (DNI) is the component of solar energy that can be collected by a thermal collector and a receiver. The applied methodology and the proposed algorithm are shown in Fig. 1. DNI, weather measurement data, and seawater temperature are used to calculate the energy consumption per unit volume of the freshwater produced in a desalination plant, which may be a combination of RO and MSF systems. A solar thermal energy model is used to determine the necessary surface area of the mirrors and other process and design parameters. A thermal power plant model based on mass and energy balance is developed to determine the process parameters of a CSTC desalination plant.

3. Results and discussion

3.1. Water desalination: thermal vs. non-thermal methods

Fig. 2 shows the schematics of different possible scenarios depending on whether the energy requirements of

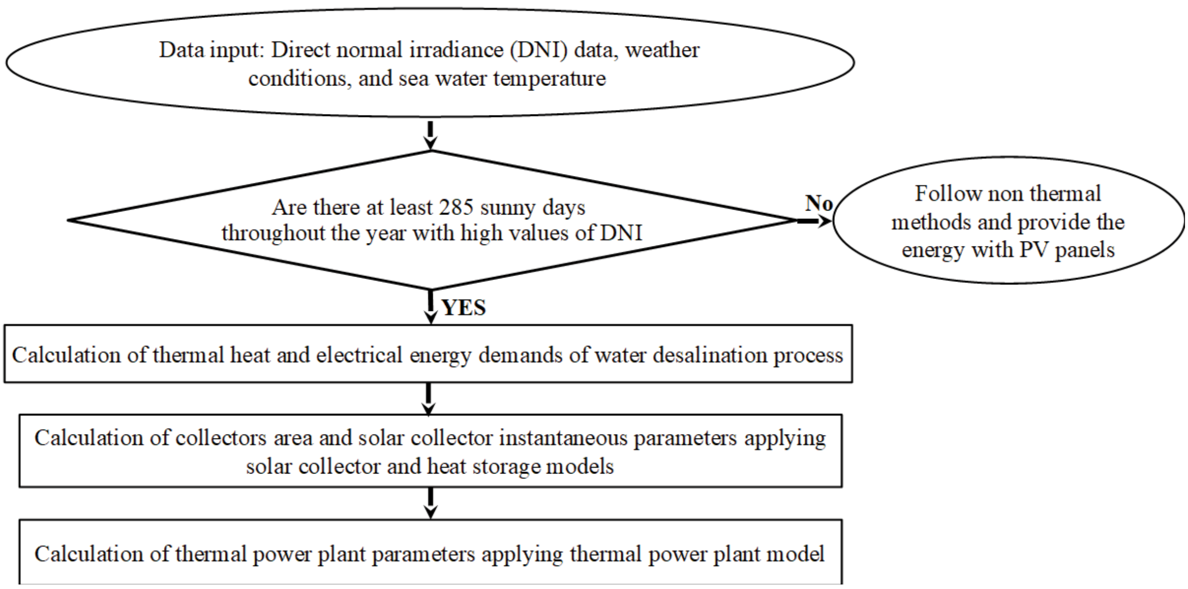

Fig. 1. Methodology of energy and process assessment for water desalination based on CSTC.

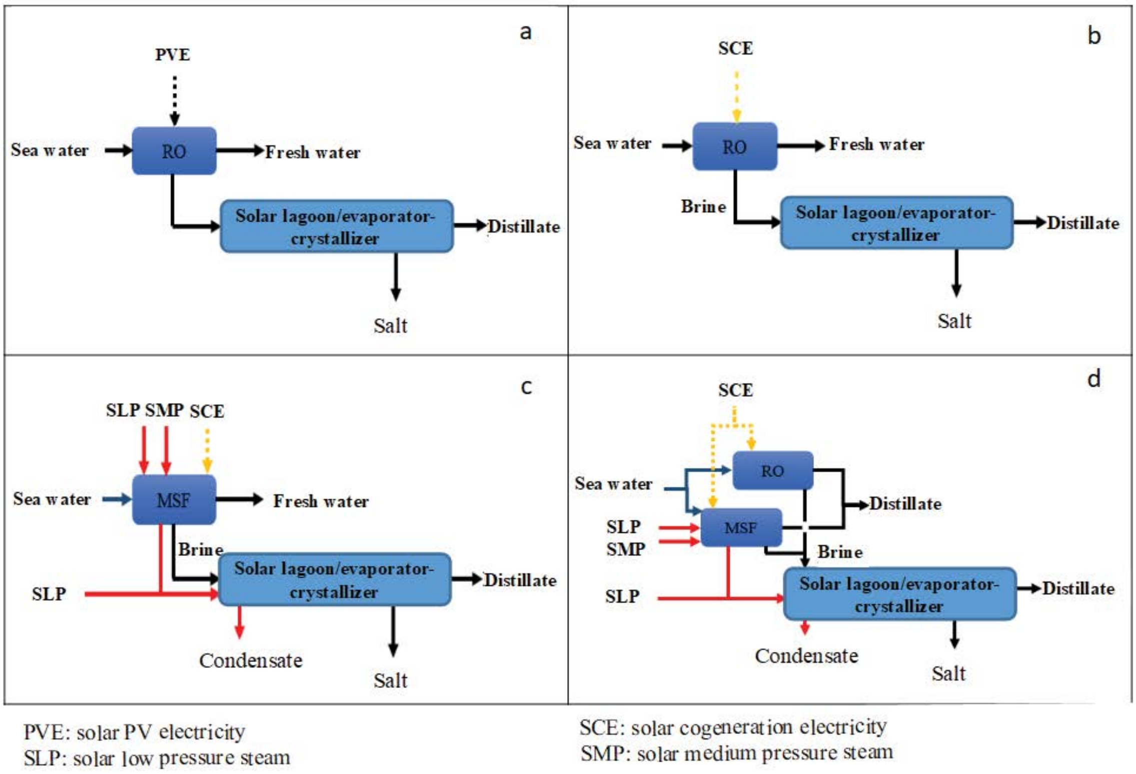

Fig. 2. Different scenarios of water desalination applying solar energy.

the plant are met by a PV or thermal source and the use of RO, thermal MSF, or their combination. Among the four scenarios, the fourth one is the best choice. In this scenario, fresh seawater with a salt concentration of approximately 50,000 mg/L is first pretreated and subsequently fed into the RO plant to be concentrated. The concentrated stream is further desalinated by MSF to produce nearly saturated brine. Finally, the saturated brine is dewatered by evaporation–crystallization or in solar lagoons to yield powdered salt.

Currently, in most large-scale seawater desalination plants, the concentrated saline water is rejected into the sea. This may generate local high-saline zones, particularly in areas with limited water bodies, such as the Gulf of Oman and the Persian Gulf. Concentrating the rejected water in an evaporator, a crystallizer, or a solar lagoon may be an option to prevent the rejection of large volumes of saline water to the sea.

3.2. CSTC desalination plant

The process flow diagram of a CSTC plant is composed of two cycles of heat exchange: a solar heat transfer fluid cycle, which collects concentrated solar heat, and a steam cycle, which generates electrical and thermal energies, as shown in Fig. 3. The plant equipment comprises two heat storage tanks, a reflector concentrator, a receiver, pumps, a steam generator, a turbine, and a condenser.

Solar radiation is first concentrated and reflected by the mirrors of the collector, and it is subsequently absorbed by the receiver, where a heat-transfer fluid, hot oil, or salt melt absorbs the heat. Both heat and cold storage tanks ensure a steady flow of the thermal energy to the steam generator, considering solar irradiation continuously varies during the day (Fig. 4a). Another important role of these tanks is to store thermal energy for nighttime/cloudy hours. High-pressure (HP) steam is generated in the boiler and sent to the back-pressure steam turbine, which converts the steam kinetic and pressure energies into mechanical work to generate electricity. The HP steam stream is changed into low-pressure (LP) and medium-pressure (MP) steam streams. The electrical energy provides the energy required in the water desalination plant.

3.3. Design of CSTC desalination plant for Kuwait

3.3.1. Applying hourly solar radiation data in design

Kuwait is located at the tip of the Persian Gulf and has a population of 4.2 million. The actual water requirement of this city is significantly high, that is, an average of 400,000 m^3/d water requirement is reported [19]. The available solar energy and the number of sunny hours on five selected days of the year 2018 in Kuwait are shown in Fig. 4a and b. The data in Fig. 4 clearly show that there are several sunny days, with a minimum of approximately 7 h of sunlight on the shortest day of the year (on December 21) and maximum of 12 h on the first day of summer.

The areas under the graphs in Fig. 4 represent the hourly available solar energy. The data indicate that on a mid-summer day, the available solar energy is approximately twice that in the winter. The diagrams show the "solar fuel" distributions in a day and throughout the year in the proposed sea water desalination plant. They indicate that the desalination

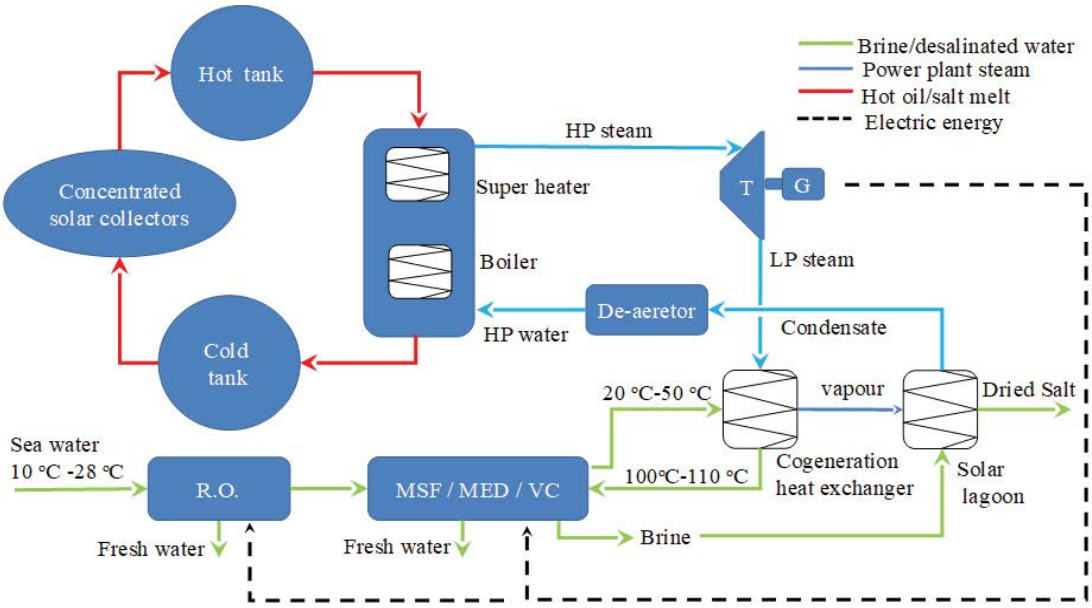

Fig. 3. CSTC desalination plant with heat storage.

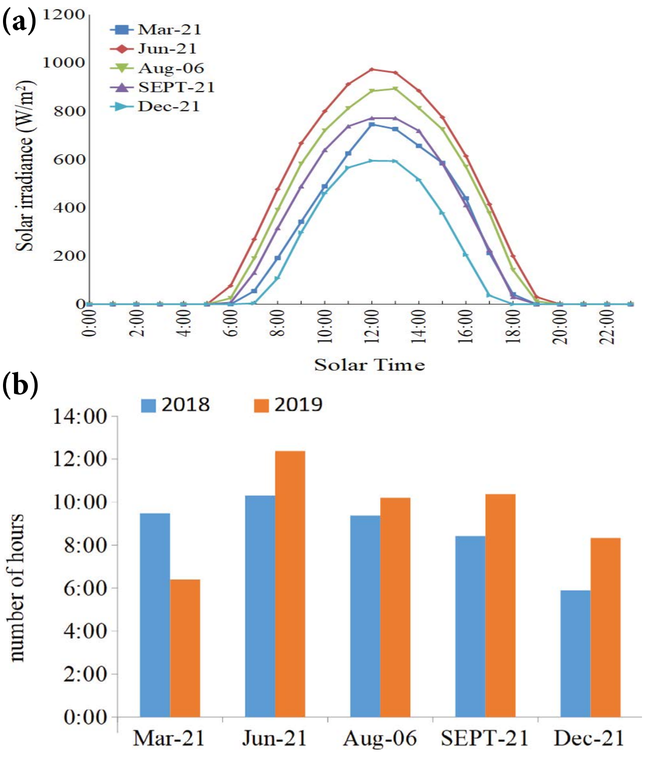

Fig. 4. The available solar energy (a) and the number of sunny hours (b) in Kuwait.

capacity in summer is considerably greater than that in winter. This auto-adjustment of the desalination capacity, which is proportional to the demand, is a specific feature of solar desalination technology. In summer, when there is a higher demand for fresh water, there will be more solar fuel, thus resulting in a higher desalination production capacity.

The surface areas of the reflectors are calculated using the total solar energy collected during a day to generate the required steam in a cogeneration power plant cycle for 24 h. The surface area is calculated using Eq. (1).

$$\int_{t_{\text{sunrise}}+1}^{t_{\text{sunset}}-1} \text{SI} \times \text{Area} \times dt = \text{Q}_{\text{steamgenerator}}\left(\text{W}\right) \times 24\left(\text{h}\right) \times 3{,}600\left(\text{s}\right) \quad (1)$$

where SI is the available solar thermal energy in W/m^2, Area is the collector surface area, $Q_{\text{steamgenerator}}$ is the steam generator duty in *W*, and t_{sunset} and t_{sunset} are the solar hours at sunset and sunrise, respectively.

3.3.2. Mass and energy balance and process parameters of CSTC desalination plant

There are three thermal energy exchange systems in this type of a desalination plant: concentrated solar thermal collection and storage cycle, steam power plant cycle, and seawater desalination plant. The concentrated solar thermal system consists of concentrating solar collectors with a temperature range of 300°C–400°C. Fresnel or parabolic trough collectors may also be used for this [20]. Heliostat mirror types may be more suitable for comparatively higher temperatures and larger scales. The parameters for the calculation of the energy required in the desalination plant are listed in Table 1.

The mass balance results for a desalination plant with an average daily capacity of 400,000 m^3 are shown in Fig. 5. The gulf water contains an average of 40,000–50,000 mg/L of total dissolved solids (TDS). This capacity is assumed for the winter season, during which the available solar fuel is less than that in summer. During summer, the desalination capacity increases because there are more sunny hours and a larger DNI (as shown previously in Fig. 4).

This study aimed to provide the energy needed in a desalination plant in the form of solar energy. The existing technologies of MED and MSF are used. It is assumed that the effluent from RO has a TDS of 100,000. The existing pilot and laboratory-scale RO equipment can operate at very high concentrations, even up to 250,000 TDS. However, because of practical limitations, such as the maximum hydraulic pressure (70 bar), commercial membranes can process salt water having up to 82,000 TDS [21]. At higher operating pressures of approximately 100 bar, this level of separation is achievable at large scales and evidently with higher operating and investment costs. Currently, because of these limitations, RO plants do not operate at the maximum effluent concentration of 100,000 TDS. Consequently, large amounts of saline water are rejected and there is significant greenhouse gas release.

Approximately 500,000 ton/d of saline water is consumed by this plant, which produces 250,000 m³/d of fresh water and 150,000 m³/d of distilled water. As reported in the literature, the maximum allowable TDS to realize RO technologies is between 60,000 and 120,000 mg/L [8]. Here, the average maximum TDS of 100,000 mg/L is assumed for the rejected stream from the RO process, whereas the maximum TDS for the thermal process is assumed to be approximately 25%, that is, the brine discharged from the thermal process is assumed to be saturated with salt. Scaling on heating surfaces can be prevented at this large brine concentration. For example, in MSF, the only heating surface is the heating section in the heat exchanger located before the first stage. An auxiliary heat exchanger can be installed in parallel to the abovementioned one so that when the first heat exchanger stops or needs cleaning, the operation is continued by the second one.

Table 1
Parameters for the calculation of electrical and thermal energy needs in desalination plant

Parameter	Value
Daily need for desalinated water [19]	400,000 m³/d
Energy need in thermal desalination [22]	83 MJ/m³
Electrical energy need RO [22]	11 MJ/m³
Total dissolved solids in sea water [23,24]	50,000 mg/L

An advantage of operating solar thermal processes compared with a solar PV process is the low-cost energy storage of the former. With the energy storage, a desalination equipment design may be based on 24 h of operation; however, without it, the operation is limited to only the sunny hours of the day. Therefore, 27,500 GJ can be made equivalent to the energy in a continuous thermal power plant with a turbine, as expressed in the following equation:

$$\text{Power plant capacity: } 27{,}500 \text{ GJ}/(24 \times 3{,}600 \text{ s})/0.9 = 353.7 \text{ MW} \quad (2)$$

Similarly, 124,500 GJ/d of thermal heat is equal to 1,601.1 MW of LP steam, which yields the design parameters of the turbine and condenser in the solar thermal power plant. To ensure 24 h continuous operation of the desalination plant during sunny days of the year, the design of the solar heat collection system must be based on the solar irradiance data of the shortest day of the year.

A power plant model was developed using the gPROMS platform and was used and validated previously by the team [16]. It is updated and employed here to calculate the thermal cycle parameters. The available solar thermal energy in Kuwait, based on Fig. 4, on the first days of winter and summer are used to calculate the collector surface area. The equations used in the power plant model are listed in Table 2. Based on the electrical and thermal energy needs of the desalination plant, the required turbine power and the boiler duty are first estimated. The outlet temperature, T_{b}^{out} of the boiler is assumed to be 20°C less than that of the hot oil. The turbine outlet pressure, P_{t}^{out} is assumed to be 2 bar. First, the steam mass flow rate ($\dot{m}_{steam}$) is calculated from the energy balance over the boiler, as expressed in Eq. (2). The turbine isentropic work and temperature are calculated from the energy and entropy balances, as expressed in Eqs. (3) and (4), respectively. Further, the real turbine work and temperature are calculated by the energy balance over the turbine, Eqs. (5) and (6), respectively. Subsequently, the energy balance for the condenser is used to calculate the heat loss in the condenser, Q_c, as described in Eq. (7). Finally, the energy balance over the boiler at the hot-oil side is used to calculate the mass flow rate of the hot oil in the boiler, as expressed in Eq. (8). The capacities of hot and cold tanks can be obtained by applying the mass balance over hot and cold tanks using Eq. (9).

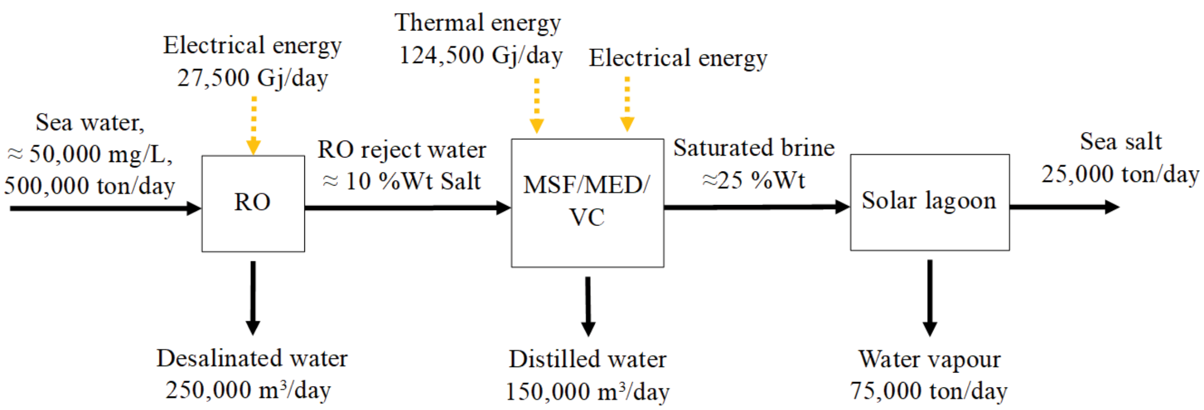

Fig. 5. Mass and energy balance results of ZLD solar desalination plant, winter.

Table 2
List of the equations applied in the power plant model

Definition	Equation	Equation no.
Energy balance over boiler	$Q_{th} = \dot{m}_{steam} \times [\text{VapourEnthalpy}(T_b^{out}, P_b^{out}) - \text{LiquidEnthalpy}(T_b^{in}, P_b^{in})]$	(2)
Entropy balance for isentropic turbine	$\text{VapourEntropy}(T_t^{in}, P_t^{in}) = \text{VapourEntropy}(T_{isen}^{out}, P_t^{out})$	(3)
Energy balance for isentropic turbine	$\dot{m}_{steam} \times \text{VapourEnthalpy}(T_t^{in}, P_t^{in}) = \dot{m}_{steam} \times \text{VapourEnthalpy}(T_{isen}^{out}, P_t^{out}) + W_{isen}$	(4)
Definition of isentropic efficiency	$W_e = W_t = \eta \times W_{isen}$	(5)
Turbine energy balance	$\dot{m}_{steam} \times \text{VapourEnthalpy}(T_t^{in}, P_t^{in}) = \dot{m}_{steam} \times \text{VapourEnthalpy}(T_t^{out}, P_t^{out})] + W_t$	(6)
Energy balance for condenser	$Q_c = \dot{m}_{steam} \times [\text{VapourEnthalpy}(T_c^{out}, P_c) - \text{LiquidEnthalpy}(T_c^{out}, P_c)]$	(7)
Energy balance for boiler	$\dot{m}_{hotoil} \times Cp_{hotoil} \times \Delta T_{hotoil} = Q_t$	(8)
Hot and cold tanks' mass balance	$\dot{M}_{hotoil} \times 24 \times 3{,}600 = M_{hot} = M_{cold}$	(9)

Table 3
Experimental data and model results for the CSTC plant

Parameter	Volume	
Heat collection and storage		
Storage time	16 h	
Collector temperature	370°C	
Hot oil temperature drop across boiler	100°C	
Reflectors' surface area	2,670,000 m²	
Hot and cold tank total mass	85,500 ton	
Overall solar heat collection efficiency [25]	60%	
Power plant cycle		
Turbine inlet steam temperature	350°C	
Turbine outlet steam temperature	130°C	
Turbine inlet pressure	12.5 bar	
Turbine outlet pressure	2 bar	
Isentropic turbine efficiency	80%	
Condensate temperature (boiler inlet)	80°C	
Desalination plant	Winter	Summer
Fresh water production (m³/d)	400,000	865,000
Steam recirculation rate (t/h)	324	700
Generator power (MW)	353.7	652
Desalination thermal heat (MW)	161.1	311
Steam to solar lagoon/vacuum ejectors (MW)	74	159

The results of this model are presented in Table 3. A total reflector area of 2,670,000 m² is required for the production rate of 400,000 m³/d. Based on the results, it is important to note that the thermal energy available for desalination is 218 MW; of which 144 MW is consumed for multistage thermal desalination, and the remaining 74 MW is consumed by vacuum ejectors or preheated solar lagoons. The designed surface area is subsequently applied in Eq. (1) to obtain the available solar fuel and other process parameters during summer. It is noteworthy that fresh water production rate increases to 865,000 m³/d. For energy storage, a molten salt is applied. The eutectic mixture of sodium nitrate, potassium nitrate, and sodium nitrite has a melting point of approximately 145°C a with a reasonable cost [25].

3.4. Sea salt: inevitable by-product of ZLD desalination plant

The solid powdered salt can be turned into value-added components, instead of rejecting the brine into the sea. Sea salt is a by-product of a water desalination plant with ZLD.

Some of the elements of sea salt, such as Li salts, are important and may be separated by physical processes, such as gradual melting, or chemical processes, such as adsorption. Because a large volume of saline water is processed, it is necessary to assess the possible processing methods, search for new applications, or evaluate the rejection into nature in an environmentally friendly manner.

The volume of the sea salts produced from a desalination plant in Kuwait is approximately 25,000 ton/d. Considering the fact that Kuwait is a smaller country than other countries in the Gulf region, if the salts are rejected to the Gulf, the ecosystem may be affected over a long term. Therefore, the challenge is to either find new applications/consumers or to reject the salts into large water bodies. In this context, industrial applications of sea salts need to be identified, such as in the construction, energy (as energy storage media), and transportation (for seasonal road de-icing) sectors.

The daily production of solid sea salt is 25,000 ton. As an example of potential consumption, the annual consumption of sea salt for de-icing in Canada was approximately 14.2 million tons in 2009 [26]. This salt type can be transported by ships from the seashore to the ocean and dumped in deep zones or ocean streams to minimize its adverse effects.

To convert this salt into value-added products, separation and purification processes are inevitable, which can be either chemical, electrochemical, or physical. These processes, in turn, would require thermal or electrical energy supply. The required thermal energy level is expected to be high and can be easily supplied by solar energy, as shown in Fig. 6.

In the future, a high-temperature free energy source will be essential in the production, practical separation, and processing of sea salt [27,28]. A high-temperature solar concentrator is shown in Fig. 7; it is sufficiently strong to melt a 1-mm-thick galvanized plate in less than 10 s. Experimental tests with this type of solar melter and reactor have shown that temperatures as high as 800°C can be obtained in an insulated graphite receiver installed at the focal point. In future salt refinery plants, this type of high-temperature reactor can be employed to melt solid salts for separation and further

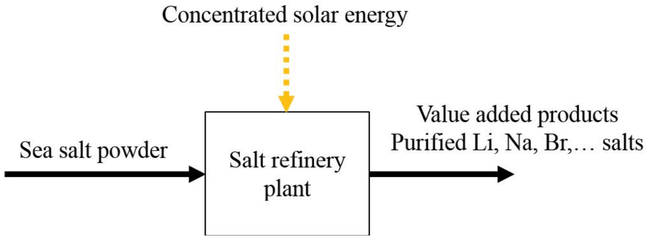

Fig. 6. Production of value-added product downstream of a water desalination plant.

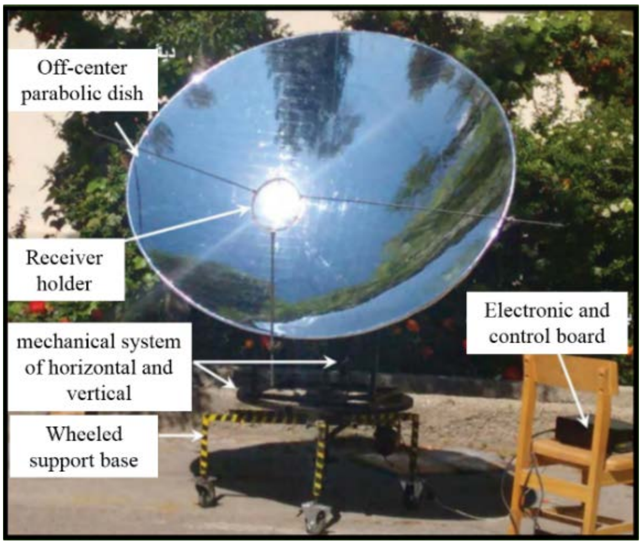

Fig. 7. An off-center parabolic dish concentrator for solar high-temperature studies.

processing. Alternatively, this reactor can be utilized to melt salt powder solids and fabricate bricks for the construction sector. A thermosetting polymer (fire-resistant) crust cube can be used to prevent salt from dissolving in water.

4. Conclusion

Seawater desalination with ZLD using solar thermal heat is of interest in areas with limited water access. Herein, a step-wise procedure is proposed to estimate the design and process parameters of a solar cogeneration desalination plant. The available solar irradiance and number of sunny hours data of Kuwait are used in this case study, in which the RO process is applied in series with thermal methods to establish a desalination plant with minimal environmental impacts. To supply 400,000 m^3/d of fresh water in winter, parabolic troughs or linear Fresnel collectors with a total surface area of 2,670,000 m^2 are necessary. A steam recirculation rate of 324 ton/h at 12.5 bar pressure and a turbine capacity of 353.7 MW at 2 bar LP steam are necessary to provide approximately 161.1 MW of thermal energy required by the plant. During summer, the production capacity of freshwater of the designed plant increases to 865,000 m^3/d. The total capacity of molten salt as sensible heat storage to ensure continuous plant operation during summer and winter is 85,500 tons.

Acknowledgments

We gratefully acknowledge Prof. Ali Akbar Alemrajabi at Isfahan University of Technology and Prof. Mojtaba Mostajaboddavati at the University of Isfahan.

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