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Desalting seawater in Qatar by renewable energy: a feasibility study

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ABSTRACT

Qatar is an arid country and suffers severe lack of natural water resources. Groundwater is overexploited and has become seriously depleted with deteriorating quality. Non-conventional alternative water resources, mainly desalted seawater (DW) and treated wastewater are used and are slowly being expanded to serve potable agricultural, and industrial needs. Qatar's population growth, almost doubled in less than 10 years, has increased the demand for potable water and is exerting pressure on the government to build additional desalting plants. The multi-stage flash (MSF) desalting is the predominant method that is used in Qatar. Its energy consumption is high—an average 270 kJ/kg thermal energy and 14.4 kJ/kg pumping energy. In the present paper, several different types of desalting sweater methods of less consumed energy than the MSF are reviewed. Burning fossil fuel, mainly natural gas, to supply the energy needed for DW units increases the emission of air polluting gases as well as greenhouse gases such as CO_2 and NO_x. Moreover, concentrated brine that is discharged from the MSF plants pollutes the marine and terrestrial environment. This brine is at higher temperature than the seawater temperature and is mixed with chemicals such as chlorine. The present paper also examines the feasibility of using renewable energy resources, such as solar and wind energies, to run the SWRO desalting plants, as well as selecting the suitably driven renewable energy operating the SW. To protect the environment and to make the DW more sustainable as a potable water source, renewable energy and more energy-efficient desalting methods should be used.

Keywords: Desalination system; Multi-effect; Multi-stage flash; Reverse osmosis; Electrodialysis; Solar energy; Concentrating solar power; Parabolic trough solar collectors

1. Introduction

The rapid economic growth in Qatar is leading to a substantial increase in electric power (EP) and desalted seawater (DW) demands. Fossil Fuel (FF), usually natural gas (NG), is the prime fuel used for EP and DW production. The DW is the main source (more than 99%) of potable water in Qatar. The FF has finite reserves; its combustion pollutes the air and emits greenhouse gases (GHG) causing climate change.

The multi-stage flash (MSF) desalting is the predominant method used in Qatar and other Arab Gulf Co-operation Countries (GCC). It has high-energy consumption, average 270 kJ/kg thermal energy, and 14.4 kJ/kg pumping energy. The equivalent mechanical energy (EME) for both thermal and pumping energies is at least 20-kWh/m^3. Burning fossil fuel, mainly NG,

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to satisfy the energy needed for desalting seawater increases the emission of air polluting gases as well as GHG such as CO_2 and NO_x. Moreover, concentrated brine discharged from the MSF plants pollutes the marine and terrestrial environment. This brine has higher temperatures than seawater and is mixed with chemicals such as chlorine.

To protect the environment and to make the DW more sustainable potable water source, renewable energy and more energy-efficient desalting systems compared to MSF system should be used for desalting seawater. The seawater reverse osmosis (SWRO) desalting method consumes only 4–5 kWh/m^3 pumping energy; which can be compared with an EME of more than 20 kWh/m^3 used by the MSF system. A pilot plant project of SWRO is to be installed in Qatar as a prerequisite for building a large SWRO desalting plant. Renewable prime energy is being considered to replace the fossil fuel in running these desalting plants to mitigate the GHG emission. Compared to the rest of the world, Qatar has the highest per capita level of GHG emissions.

This problem of EP and DW growing consumption can be solved by (i) using renewable energies (RE) to generate EP and DW, (ii) EP and DW conservation by demands management, and (iii) raising the efficiency of EP and DW production. The solar energy and wind energy are viable RE resources and can be directly transferred to EP by photovoltaic (PV) solar cells. The solar energy can be concentrated to generate a high temperature thermal energy source to operate the power cycles. The use of RE prolongs the life of fuel oil and NG resources, and permits their use for the petrochemicals industry and other economic benefits.

The solar energy in Qatar is highly available, and wind energy is available high offshore. Developing RE ensures sustainability since it is free and inexhaustible. It diversifies the energy sources with less negative impact on environment, compared to the FF. It is reported that Qatar has 2,000-$kWh/m^2/y$ direct normal irradiance, used for concentrated solar power, and 2,140-$kWh/m^2/y$ global horizontal irradiance, used for PV [1]. Although the average wind velocity in land is not high enough to justify building large land wind farms, except in limited areas, the possibility of using offshore wind farm, where the mean wind speed approaches 12.5 m/s, is encouraging.

The solar energy can be directly converted to EP by photovoltaic (PV) cells. Also, concentrated solar energy (CSP) can be used to produce high temperature thermal energy that is required to operate a heat engine power cycle producing EP. The concentrated solar energy collectors include parabolic trough, solar towers, and parabolic dishes to concentrate the incident direct solar energy. The Solar Power Plants (SPP) using CSP can be considered to produce mechanical work to run SWRO and/or mechanical vapor compression (MVC) desalting systems. Also, thermal desalting system such as MSF or multi-effect distillation (MED) systems can be operated by low pressure steam extracted (or exhausted) from the steam turbine of the SPP using CSP. A detailed analysis of the SPP using a parabolic trough collector (the only commercial type used in power plants) is presented. The suggested SPP can produce power to operate the SWRO desalting plant producing one million imperial gallons per day (MIGD) of desalted water. Solar thermal storage, and assisted natural gas fuel can be used to raise the capacity factor of the plant. This analysis gives us an idea about the size of the plant (solar collector areas, storage tanks, membranes, etc.).

In the present paper, the available desalting seawater methods with their consumed energy are reviewed. The possibilities of using solar energy to drive some of these desalting processes are outlined and assessed.

2. Desalting systems overview

Commercial desalination can be classified into distillation and membrane processes. The most used distillation (phase-change) methods are: MSF, MED, and Vapor Compression (VC). The compressor used in the VC [2] system can be thermally operated (TVC) or mechanically operated (MVC). In distillation systems, seawater is partially vaporized, and the generated vapor (almost pure water) is condensed to be distilled water.

2.1. Conventional distillation processes

2.1.1. Multi-stage flash

In the MSF, brine is heated before being exposed to a low pressure causing its partial evaporation by flashing in successive stages as shown in Fig. 1a. The flashed vapor is condensed in a condenser mounted in the upper part of each stage where the brine is primarily pre-heated. The brine is finally heated in a brine heater before entering the first stage for partial evaporation by flashing as shown schematically in Fig. 1b.

2.1.2. Multi-effect distillation

In the MED, steam is used to heat (by its latent heat as it condenses) and partially boils the feed seawater to the first effect. The generated vapor in the first effect is used as a heating source in the second effect, where it is condensed by generating (or gener-

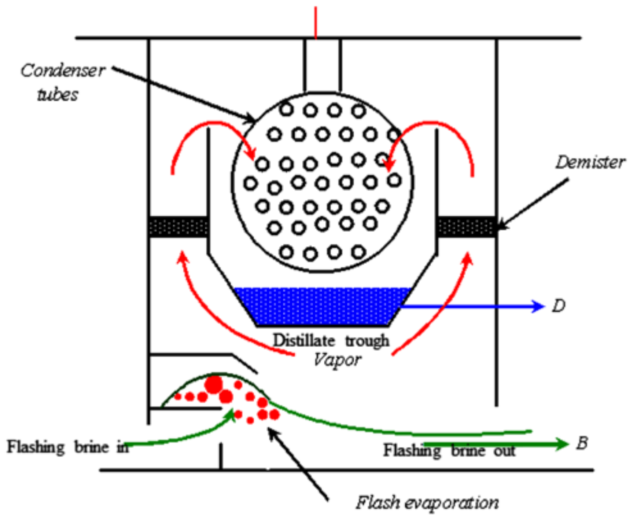


Fig. 1a. Schematic presentation of brine exposed to pressure a of lower saturation temperature than the incoming brine temperature.

ated) vapor in the second effect. The process is repeated in successive effects. The generated vapor in the last effect is directed to an end condenser, where it condenses, Fig. 2.

2.1.3. Vapor compression

In the VC desalting system, the vapor is generated from the seawater feed in an evaporator at pressure P_1 and saturated temperature T_1. This vapor is compressed to a higher pressure P_2 and a saturated temperature T_2, returns to the evaporator, and becomes a heating vapor for the incoming feed. While the heating vapor is condensed on one side of the evaporator at T_2, it heats and partially generates vapor at T_1 from the feed on the other side of the evaporator. Figs. 3a and 4a show schematic diagrams for mechanically driven VC, (MVC), and thermally driven VC, (TVC), compressors. The limited volumetric flow rates of both TVC and MVC compressors lead to reducing the flow rates to the compressors using multi-effect evaporators, Figs. 3b and 4b. However, this raises the pressure difference across the compressor, with almost no change in the consumed energy.

2.2. Non-conventional distillation processes

Other distillation methods, but not at commercial status yet, are humidification–dehumidification (HDH) and membrane distillation (MD) separation/ distillation techniques.

2.2.1. Humidification-dehumidification

In HDH process, air is humidified by extracting the water vapor from the feed seawater (either by heating the air flowing in contact with the seawater or by heating the seawater while air flows in contact with it).

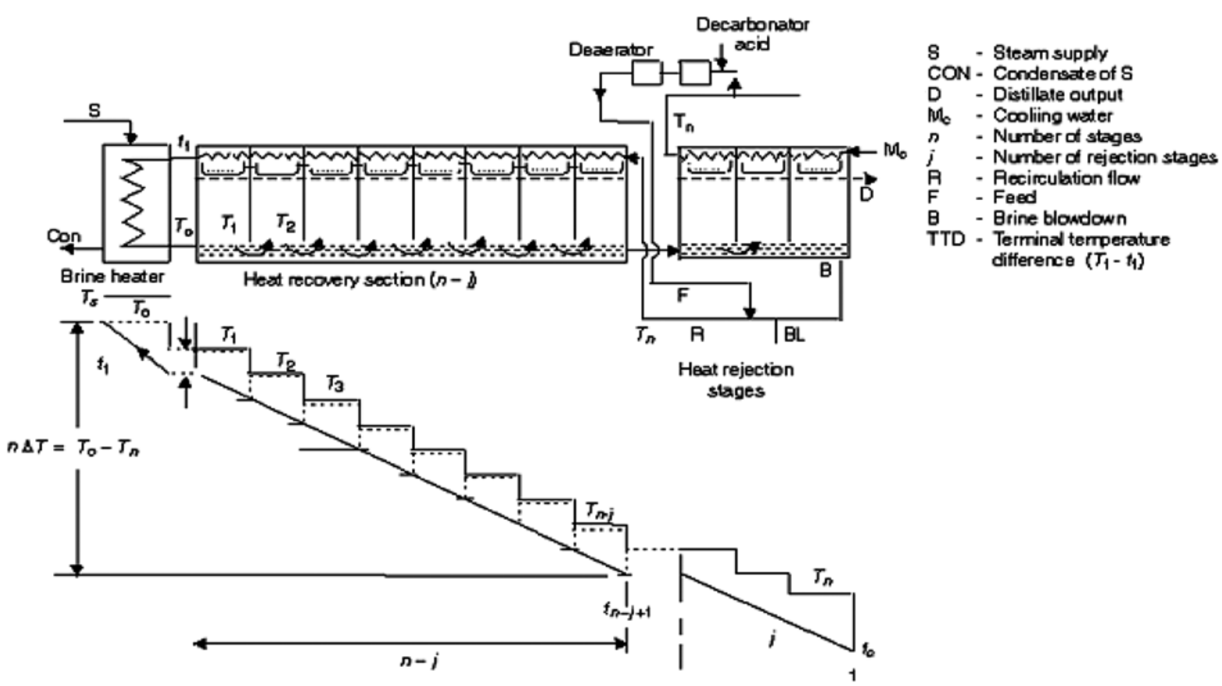


Fig. 1b. Arrangement of recirculation multi-stage flash desalting system [3].

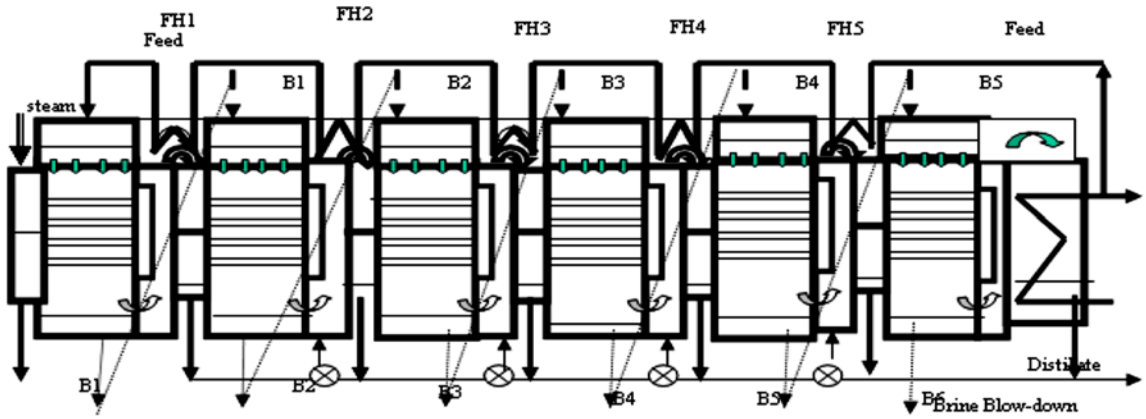


Fig. 2. Multi-effect boiling MED desalting system [4].

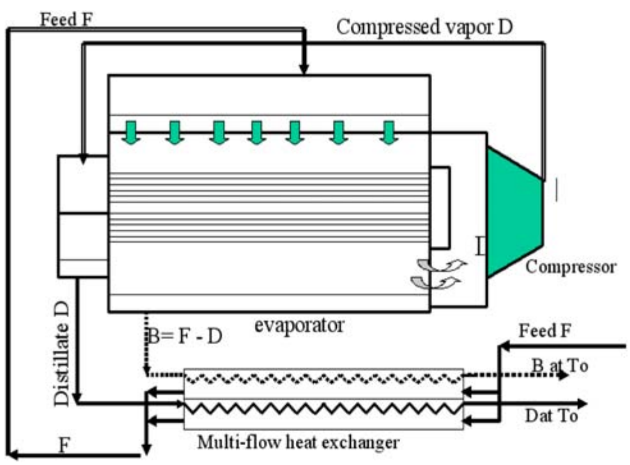


Fig. 3a. Single effect mechanical vapor compression desalting unit [5].

Then, the humidified air is cooled to condense its loaded vapor, and the condensate is collected in a condenser. The amount of vapor loaded with air depends on air temperature. The HDH process is simple, can be operated at low temperature, and can be easily combined with solar energy. Two different cycles are available for the HDH units. One is working on open-water closed-air cycle with seawater heated first, say by solar energy, and is then sprayed into the air in the evaporator, Fig. 5a. The humidified air reaches a condenser where some vapor is condensed, and distilled water is collected in a container. Some of the brine can also be recycled in the system to improve the efficiency, and the rest is removed.

In the other cycle (open-air closed-water cycle), air passes through the evaporator to be humidified, and then forced to pass through a condenser, where the water vapor is condensed and collected, Fig. 5b.

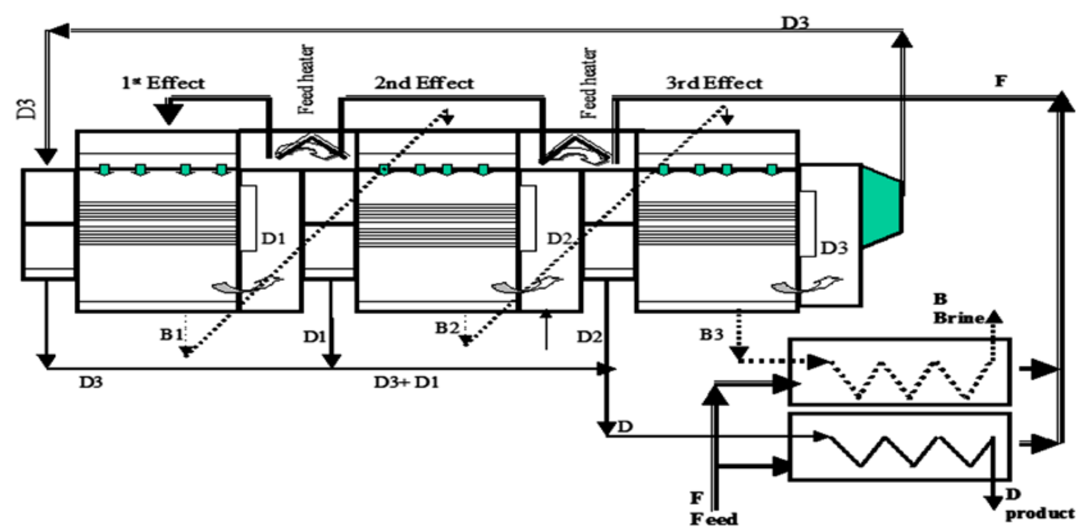


Fig. 3b. Multi-effect vapor compression desalting system [6].

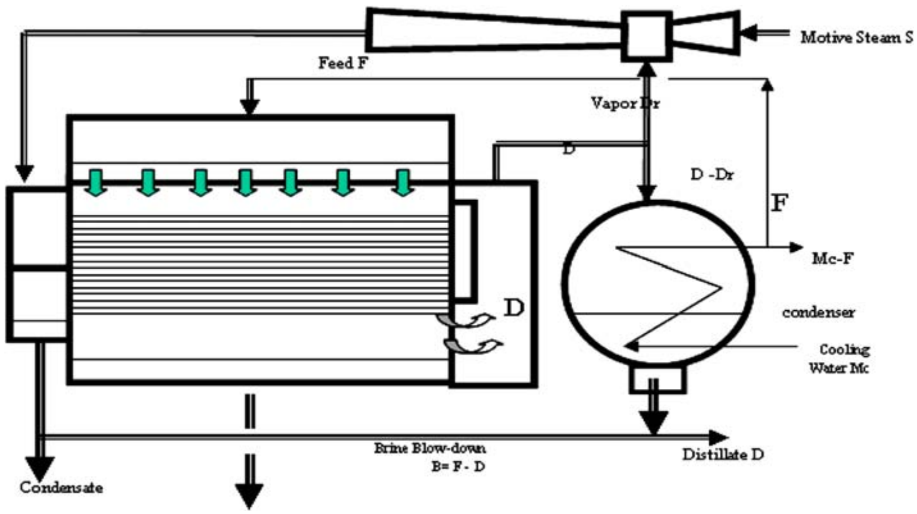


Fig. 4a. Single effect thermal vapor desalting unit [7].

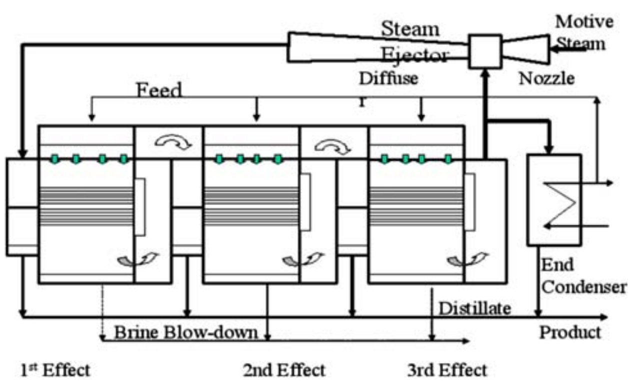


Fig. 4b. Thermal multi-effect thermal vapor compression system [8].

The performance of the HDH process has improved over the years. When combined with flat plate solar collectors, an average daily production of 11.8 l/m^2/day can be obtained. This is compared with the only 2.3 l/m^2/day obtained from solar stills, to be discussed later.

2.2.2. Membrane distillation separation/distillation technique

In the MD method, a hydrophobic membrane, permeable only to water vapor, but not to liquid phase and solutes, is used. Water is transported as a "hot" and a "cool" streams separated by a hydrophobic membrane. The permeation of water vapor is a function of the small temperature difference between the two streams. This gives a vapor pressure difference leading to vapor transfer vapor through the membrane from the hot stream side to the other side (condensation surface), Fig. 6. The seawater passes through the condenser, say at 25˚C and leaves at a higher temperature, and then it is heated to about 80˚C by an external source such as solar energy. The main advantage of using membrane distillation is its simplicity and the need for only small temperature differences to operate, see Fig. 6.

However, the temperature differential and the recovery rate determine the overall efficiency for the process. Thus, when it is run with a low temperature differential, large amounts of water must be used, which adversely affects its overall energy efficiency.

2.3. Membrane processes

The most used membrane process is the reverse osmosis (RO) desalting with seawater (SWRO), and brackish water (BWRO). Another membranes process is electro-dialysis (ED), which is mainly desalt BWRO.

2.3.1. Reverse osmosis

In RO, saline is pressurized against the semi-permeable membranes allowing almost pure water to permeate through while rejecting the salt. A typical SWRO system consists of a pretreatment system, high-pressure (HP) pump, membrane modules, and a post-treatment system. The membrane modules are sensitive to fouling, and thus the pretreatment is critical. The HP pump delivers the feed to the membrane modules at 17–27 bars for brackish water and 55–82 bars for seawater. The brine leaves the SWRO membranes at pressures high enough to justify

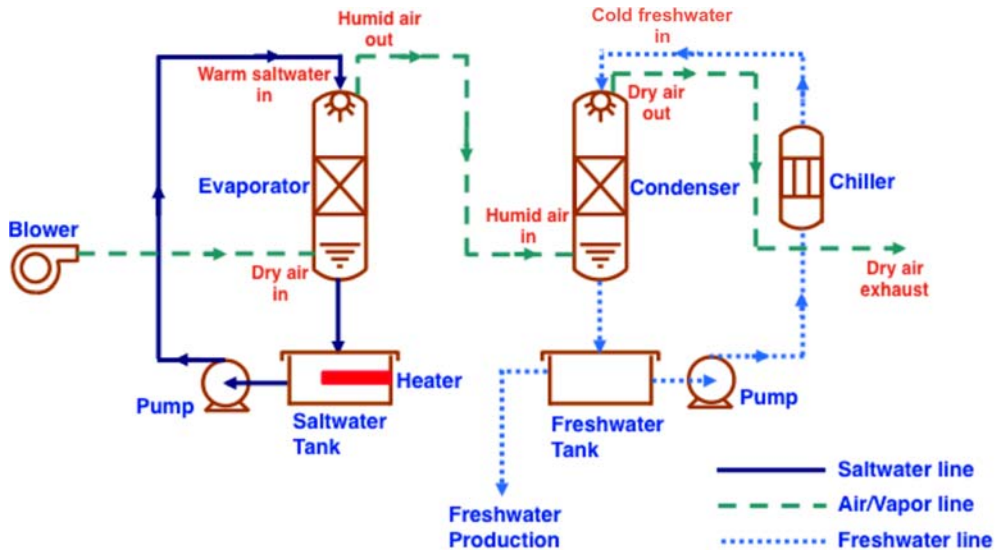


Fig. 5. Humidification–dehumidification desalination lab-scale section [9].

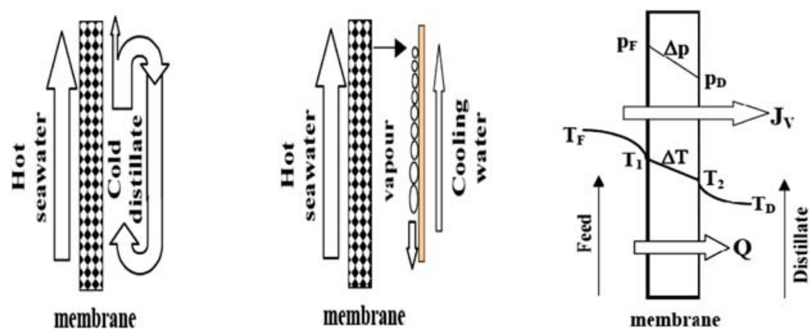
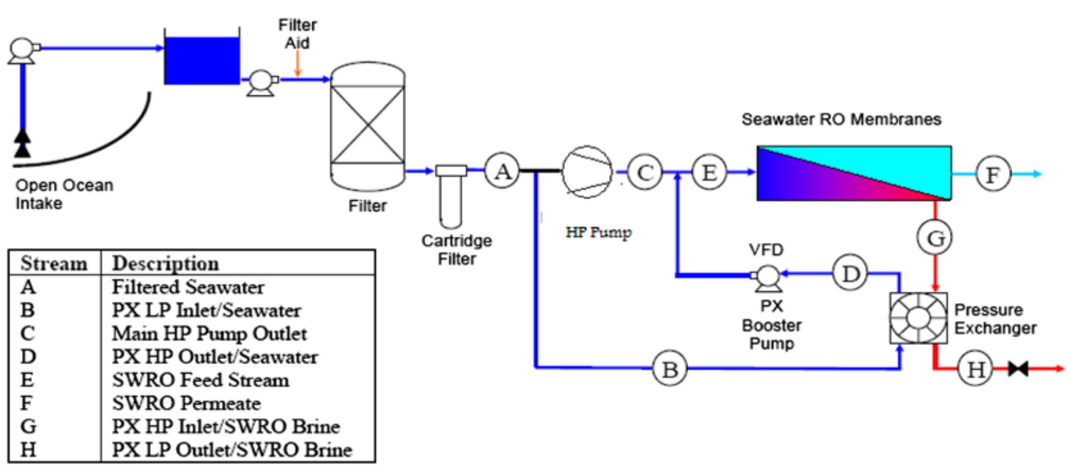


Fig. 6. Schematic of the membrane distillation process [10].



Stream	Description
A	Filtered Seawater
B	PX LP Inlet/Seawater
C	Main HP Pump Outlet
D	PX HP Outlet/Seawater
E	SWRO Feed Stream
F	SWRO Permeate
G	PX HP Inlet/SWRO Brine
H	PX LP Outlet/SWRO Brine

Process flow schematic

Fig. 7. Schematic diagram showing the main component of an SWRO system [11].

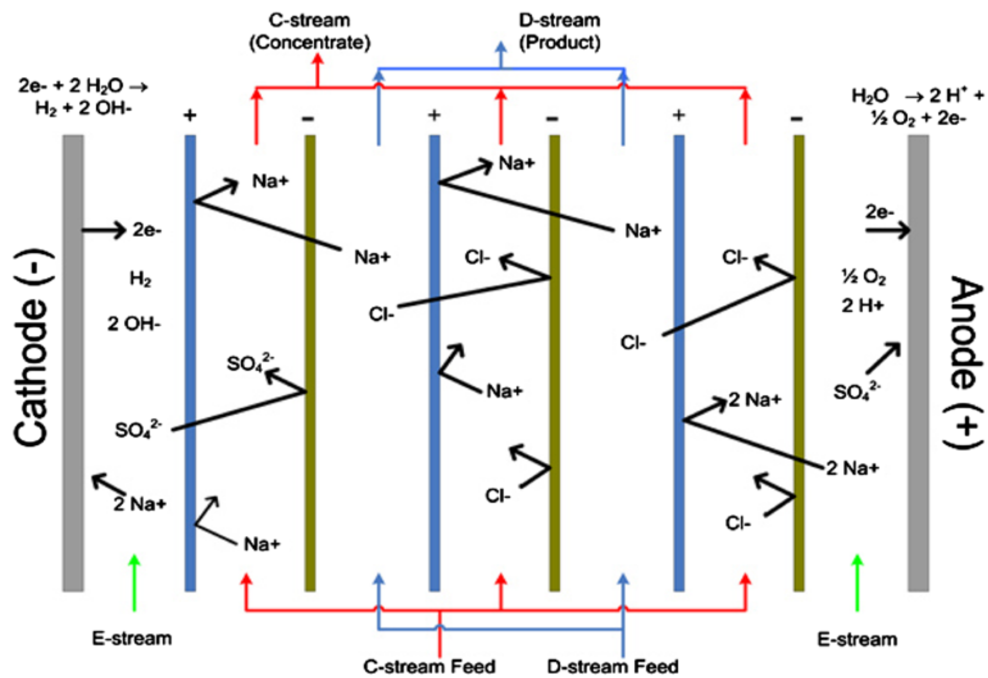


Fig. 8. Schematic diagram of the electrodialysis desalting process using ion exchange membranes.

recovering its energy by turbine, pressure exchangers (BX), or dual work exchanger energy recovery (DWEER) [11] (Fig. 7).

2.3.2. Electro-dialysis desalting system

The ED is an electrochemical separation process using direct current (DC) to transfer salt ions from incoming salty water through selective membranes in the form of flat sheets, Fig. 8. While the membranes in the RO system permeate water, but not solutes, the ED membranes allow the solute ions to cross, but not the water. The membranes are even selective with respect to the type of charge carried by of the crossing ions. One type of membrane allows only positive ions (cations) to cross and is called cation exchange membranes (CEM). The other type allows only negative ions to cross and is called anion exchange membrane (AEM).

The application of ED is limited to brackish water. In fact, the ED consumed energy (in the form of direct current DC) is a function of the feed water salinity, and desalting seawater of high salinity is not economical.

In the ED process, an electric field is applied through the electrodes (cathode and anode) enclosing the membrane stack consisting of successive CEM and AEM separating the dialysate and concentrate channels. Salt water flows through the channels. On applying the DC current through the electrodes, cations (e. g. sodium Na^+) move toward the cathode and cross the CEM to the concentrate channel. Meanwhile, anions (e.g. Cl^-) move in the direction of the anode and cross the AEM to the concentrate channels. By the time dialysate channels are depleted from salts, the water coming out becomes desalted water, while the solutes are concentrated in the concentrate channels, and the solution coming out of it becomes the brine to be rejected. Electrodialysis, like the RO unit, should have a pretreatment system, post-treatment, and a circulation pump, but of low pressure. The ED uses the DC power supply (battery or PV or DC rectifier from AC current) and membranes stacked with its electrodes.

One of the main factors affecting the choice of desalting system is the consumed energy (thermal or mechanical, or both) and its production cost. The energy cost represents a good portion of the final desalted water unit cost, and thus serious consideration should be given to the type and cost of the energy to be used. A comparison between different desalting systems consumed energy is given in Table 1, modified from Ref. [12].

3. Renewable energy operated desalting systems

Burning FF to satisfy the energy needs for desalting seawater has a negative impact on the environment, which is a major concern everywhere. This

Table 1
An overall comparison of the different desalting systems [12]

Item	MSF	MED	MVC	RO
Largest unit size (m^3/d)	57,600	18,000	3,600	10,900
Gain ratio (kg of distillate/ kg steam)	8	8–12	– NA	–NA
Consumed energy	Steam (thermal) + electricity	Steam (thermal) + electricity	Electricity	Electricity
Steam pressure (Bar)	~2	0.3 MED MVC 3–20MED–TVC		
Electrical (kWh/m^3)	4	2	10	5–8
Product quality (TDS)	25	25	25	400
Intake/product ratio	6	3	3	3
Pre-treatment	Simple	Simple	Simple	Extensive
Advantages	• Large sizes	High GOR	Electric only	• Technology improvements
	• Proven reliability			• Modular installation
	• More than 30 years			• Electric only
	• No affects by SW quality			• High recovery ratio
	• Large capacity			• Low initial and O&M cost (few equipment)
	• Good product quality			
Disadvantages	High-energy requirement	Smaller units	Small sizes	Pre-treatment

encourages the application of renewable energies in desalting seawater processes. Naturally, the variability of solar intensity and its need for collection large land areas, fluctuation of wind energy, and the high cost of DW by RE are the factors limiting the use of RE for desalting seawater. Sustainability is another reason favoring the use of RE, as FF has finite resources, fluctuating and increasing prices, and insecure availability in some remote areas.

3.1. Direct solar still desalting

3.1.1. Solar stills

Solar still, shown in Fig. 9, is the first and direct solar system used to desalt seawater. It has limited desalting capacity for each unit and consists of a rectangular box with a blackened base and a tilted transparent cover. An amount of shallow seawater in the box absorbs the solar heat and is partially evaporated. The vapor above the seawater is condensed on the inner surface of the cover inside the cover and is collected in a side trough. The average production is 3.26 l/m^2.day [13].

3.2. Indirect solar desalination systems

3.2.1. Solar thermal to desalination

In indirect solar desalination systems, the solar energy is collected in a system separated from (but augmented with) DW system. The solar energy can be transformed to the thermal energy operating thermal DW systems such as the commercial systems of MSF, Fig. 1b, MEB, Figs. 2 and 10, and TVC, Fig. 4a; besides other systems such as HDH, Fig. 5, and MD desalting systems, Fig. 6.

3.2.2. Solar thermal to power to desalination

The solar energy can also be transformed to thermal energy to produce shaft work or electric power, which operates the DW systems. This is called cogeneration power desalting plants CPDP. The electric power can operate a mechanically operated DW system such as MVC, Fig. 11, and SWRO, Fig. 12. Meanwhile, the steam extracted from the steam turbine can operate thermally driven desalting systems such as MSF, Fig. 13, MED, or TVC.

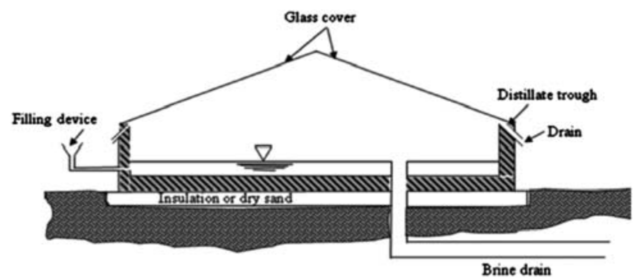


Fig. 9. Simple solar still for desalting seawater [13].

3.2.3. Solar to electricity to desalination

The solar energy can be transformed directly to electricity by using PV cell to operate a mechanically operated DW system such as SWRO, Fig. 14 and MVC. An excellent review of operating SWRO with solar energy is given by Ref. [15].

The PV systems use semi-conductor materials. A single-crystal silicon is presently the most popular option for commercial cells. Currently, PV modules generate electricity for homes, cottages, utility grids, and traffic signals, and are price competitive in meeting power needs in remote locations. The PV is an alternative to grid-extension or conventional stand-alone power systems, i.e. diesel generators.

Electrodialysis uses DC for the electrodes; therefore, the PV system does not include an inverter, which simplifies the system. Fig. 16 shows a schematic diagram of a PV-powered ED system.

The second most common RE technology is the wind energy (WE) after the solar energy. In the wind turbine, the wind kinetic energy is transferred to the shaft work, and then to electric power. The electricity generation from the wind can operate mechanically operated DW systems such as MVC and SWRO.

The high capital and maintenance costs of RE are behind the low share of RE operated desalting systems compared with FF operated systems.

4. Suggested solar DW plant for Qatar

There are several possible combinations of desalting systems with RE sources, but only a single arrangement is suggested here for a large capacity solar-operated DW plant suitable for being operated in populated areas for reasons outlined here.

Qatar and other GCC countries such as Kuwait, United Arab Emirates (UAE) and Bahrain usually produce DW in plants also producing electric power, and are called cogeneration power desalting plants (CPDP) for economic reasons. A CPDP consumes energy input less than two separate desalting and power plants producing the same outputs. Moreover, added power plant capacities are usually installed to satisfy the increase of peak EP load.

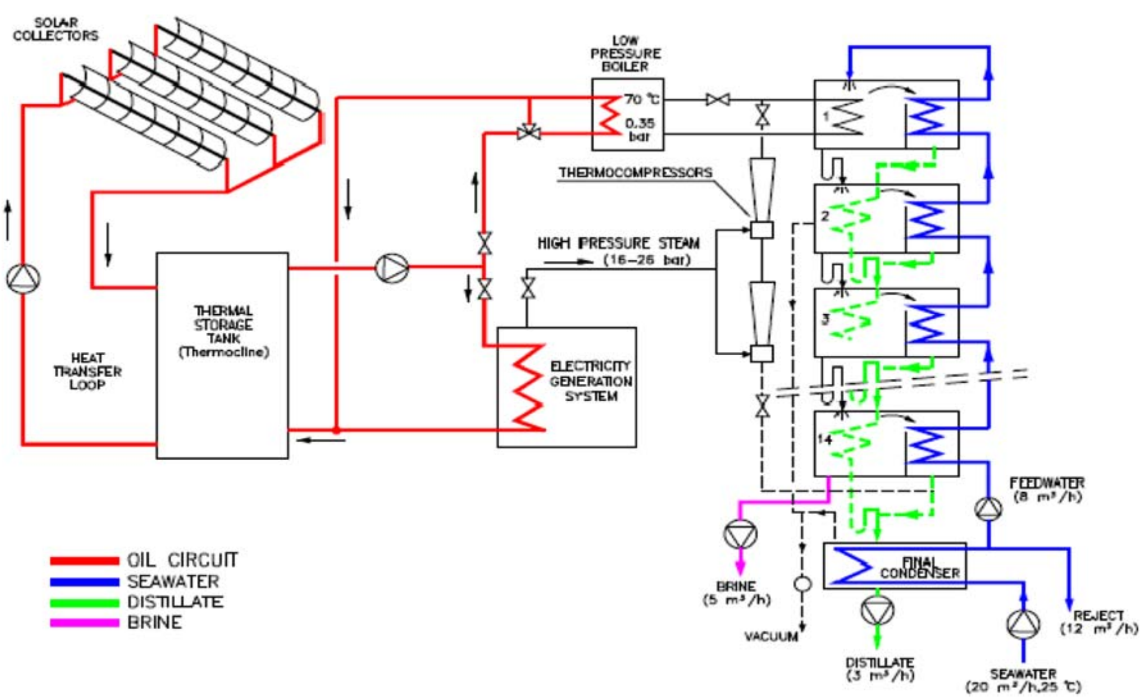


Fig. 10. Schematic diagram of the solar-operated MED system [14].

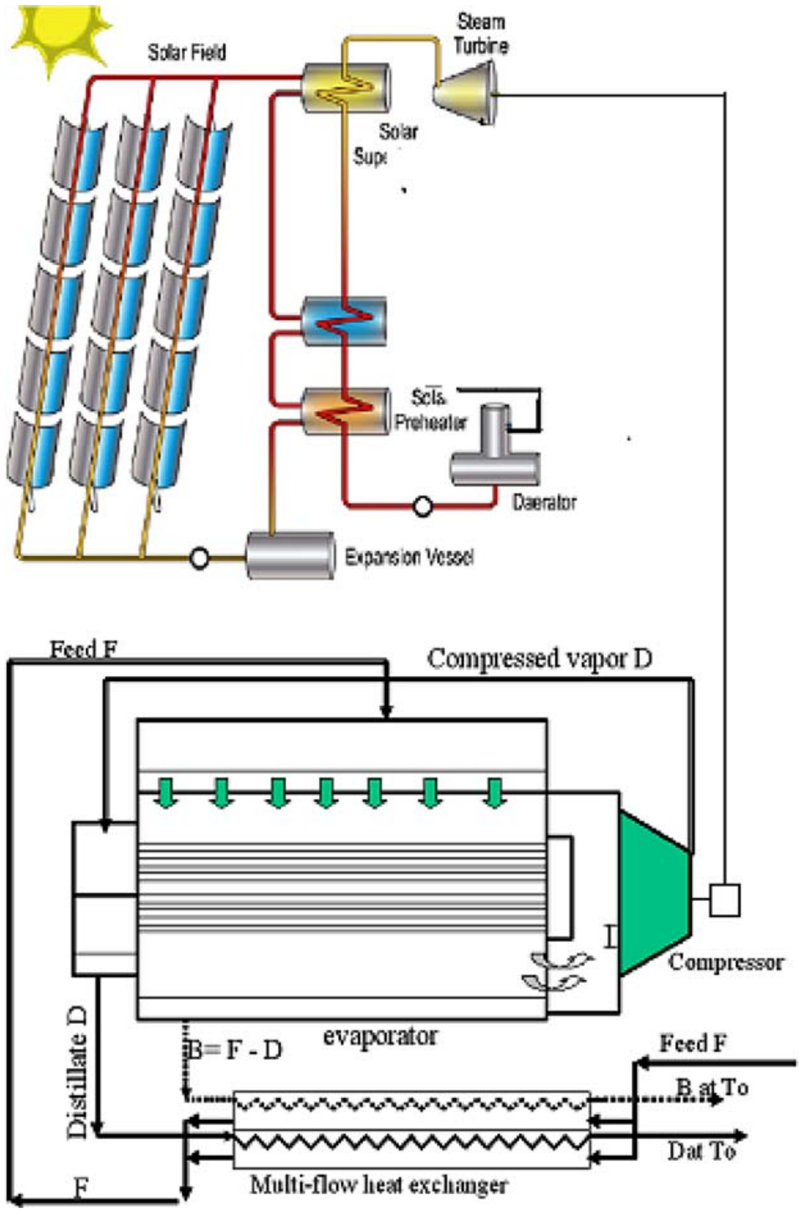


Fig. 11. Schematic diagram of the solar generating electric power to operate MVC system.

4.1. Solar power-desalting arrangement

A solar CPDP plant is suggested to be built in Qatar. This CPDP can operate a mechanically driven SWRO or an MVC desalting system. Its EP output can be used to satisfy the peak load demand, while stopping the desalting systems. Since this plant is solar operated, it would work most of the time to produce EP, even when desalting is not required because it has a minimum operating cost due to the use of free solar energy. *Thus, it is considered as power plant capacity addition which can satisfy the peak load* that *lasts only for few hours annually*.

In thermal solar power plants, there are several technologies to concentrate solar energy, called CSP, to have high temperature heat source to operate the heat engine power cycle. These include: parabolic troughs, Linear Fresnel collectors, central receivers (towers) and parabolic dishes. The SPP using steam Rankine cycle is the well-proven and most used SPP worldwide. In this SPP, trough curved mirrors are used to reflect direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber, or collector) running along the length of the trough and positioned at the focal point of the reflectors. The hot fluid, usually oil, is directed to a heat exchanger to

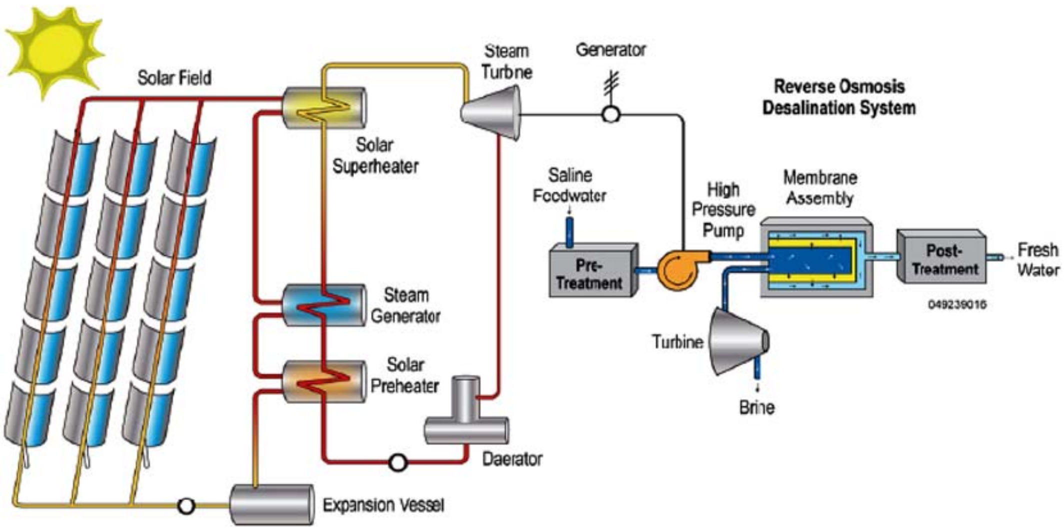


Fig. 12. Schematic diagram of the solar generating electric power to operate RO system [15].

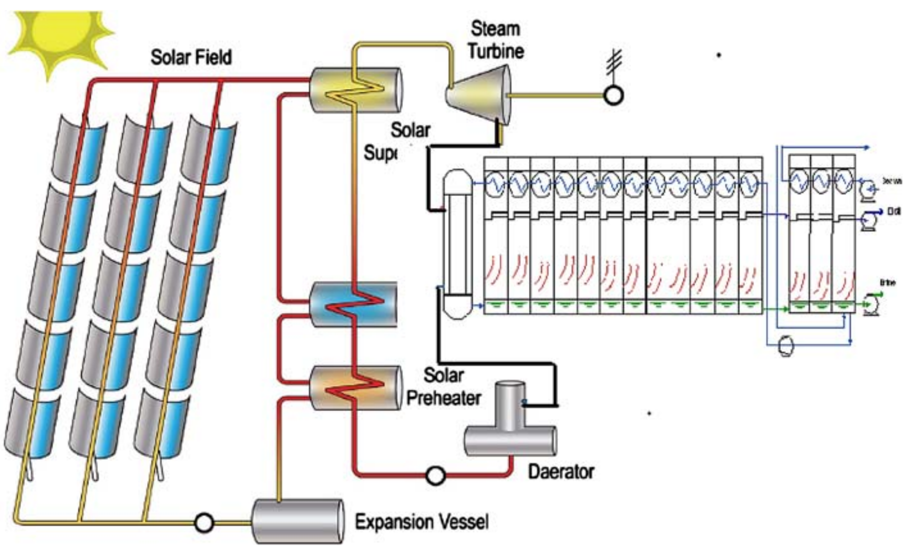


Fig. 13. Schematic diagram of the solar generating electric power by steam turbine extracting steam to operate MSF system.

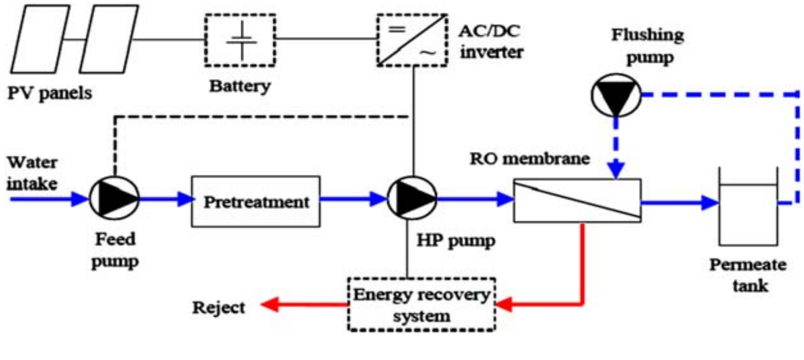


Fig. 14. Direct solar to electric power generating photovoltaic PV operating RO desalination system [15].

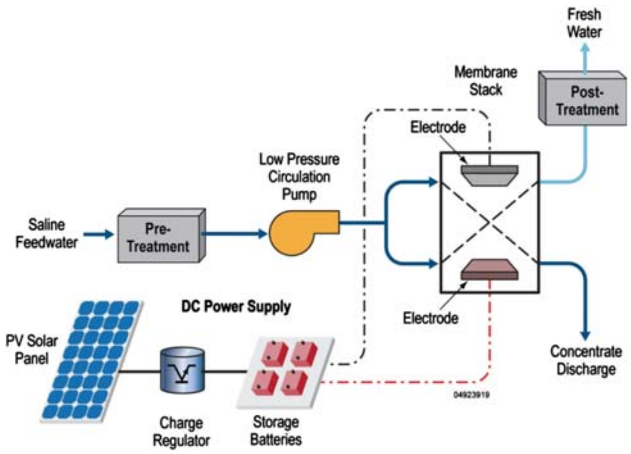


Fig. 15. Direct solar to electric power generating photovoltaic PV operating ED brackish water desalination system [15].

produce the steam required to run the steam turbine. Table 1 shows that this type of plant can supply steam to the steam turbine at a temperature of up to 377˚C, since the temperature of steam in/out of the solar field is in the range of 293/393˚C. The table also shows that this type of plant has a high solar area, and thus high land area requirements. The required land area is almost three times the used solar collector's areas.

While the linear Fresnel collectors have the advantages of using less space and produce steam directly in the collector tubes located in the focal point of the collectors, its maximum steam temperature supply is 270˚C and thus its power cycle operates at a lower efficiency compared to parabolic trough plants.

Typical Spain solar power plants, [19]

The suggested low temperature of MED using steam supply of low saturation temperature (about 70˚C) is the most energy-efficient distillation system. A conventional MED plant can easily deal with a high seawater salinity of Qatar.

The suggested solar desalting plant is the well-proven type large solar steam Rankine power cycle working as CPDP. Its EP output operates an SWRO desalting system; while steam discharged from its turbine operates the MED desalting plant, Fig. 15. This steam at a low pressure (say of 70˚C saturated temperature) represents the thermal energy input to the MED. The operation of the SWRO can be stopped when the EP is needed at peak load. It uses concentrating parabolic trough solar collectors, Fig. 16, the most commercially proven type for solar PP. Solar energy is concentrated on the central receiving collector's tubes, where the thermal oil is circulated, and heated to 393˚C. This heat is used in heat exchanger(s) to produce steam in a second cycle. The steam is supplied to the steam turbine, say at 377˚C and 100 bar, to drive the electric generator. The steam discharged from the steam turbine to the MED plant eliminates the need a the steam power plant (PP) condenser, the expensive and less efficient last and large part of the steam turbine operating at low pressure with wet steam.

The use of solar thermal storage and assisted firing fuel makes this solar PP dispatchable and cost effective [17]. A reference solar plant is chosen here. It is a modification of the known Andasol 1, 2, and 3 PP [10] and the Extresol 1, 2, 3 solar PPs built (or under construction) in Spain, Fig. 17. Each of these PPs has an EP capacity of 50 MW and has a thermal storage system. Part of the heat absorbed by the

Name	Capacity (MW)	Storage (h)	DNI (kWh/m^2/y)	Solar area in (m^2/MW)	Plant hecta (MW)	Temperature In/out solar field
Alvarado1, Spain	50		2,174		2.7	?/393˚C
Andasol 1	50	7.5	2,136	10,202.4	4	293/393˚C
Andasol 2	50	7.5	2,136	10,202.4	4	293/393˚C
La Florida, Spain	50	7.5		11,055	4	298/393˚C
Extresol-2, Spain	50	7.5	2,168	10,202.4	4	293/393˚C
Extresol-1, Spain	49.9	7.5	2,168	10,222.85	4	293/393˚C
Ibersol Ciudad Real	50	0	2,061	5,755.2	3	304/391˚C
La Dehesa	49.9	7.5		11,077.15	4	29/393˚C
Majadas	50		2,142			
Manchasol-1	49.9		2,208		4	293/393˚C
Palma del Rio 2	50	0	2,291		2.7	?/393˚C

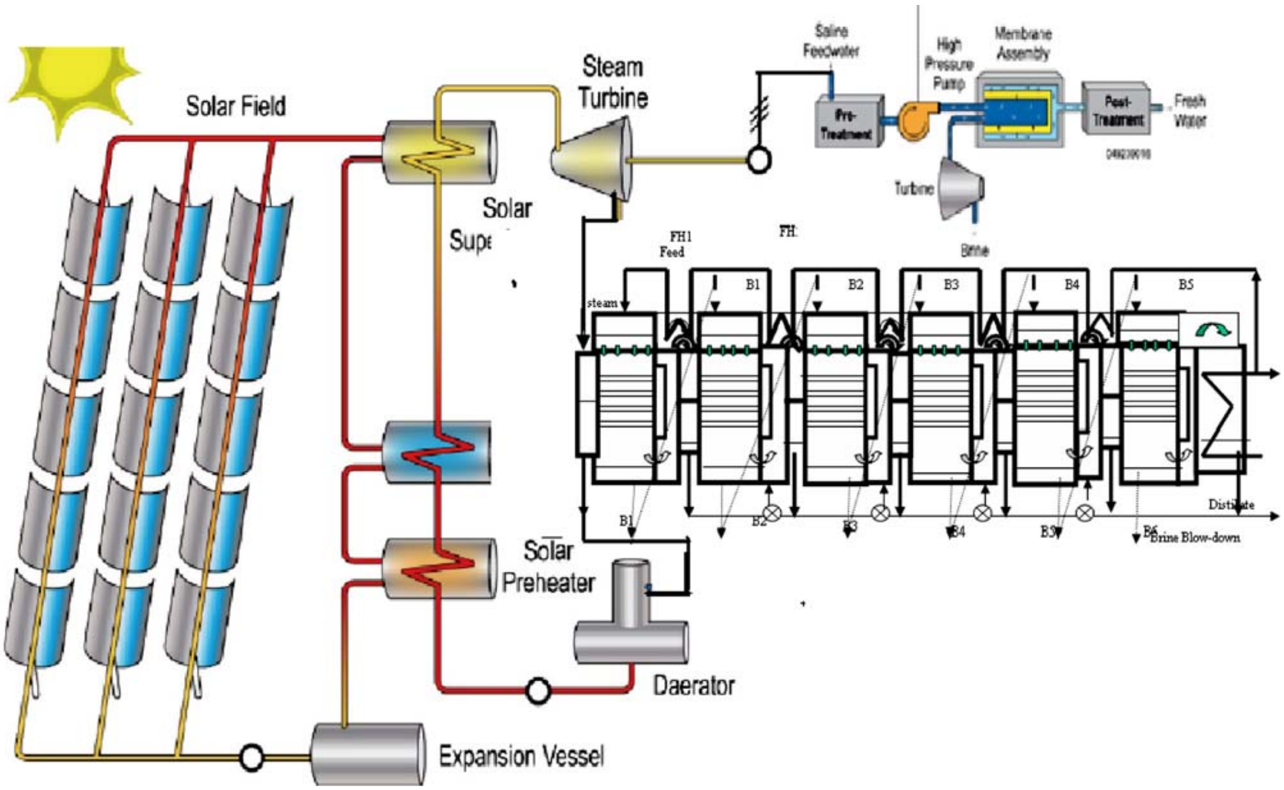


Fig. 16. Suggested CPDP using BPST discharging steam to MED plant and operating SWRO during non peak hours [16].

solar field during the day is stored in molten salts, to be used during night or cloudy nonshining hours. The cost of each plant is around 300 M€. The Andasol 1, as example, is the first solar PP using trough collectors in Europe and the first in the world using thermal storage and has been operating since 2008. The thermal storage system consists of two tanks of 16 m height × 36 m diameter, containing 28,500 tons of molten salt (60% sodium nitrate, 40% potassium nitrate) and has a 1,010 MWh thermal capacity. The reservoirs can run the turbine for up to 7.5 h at full load.

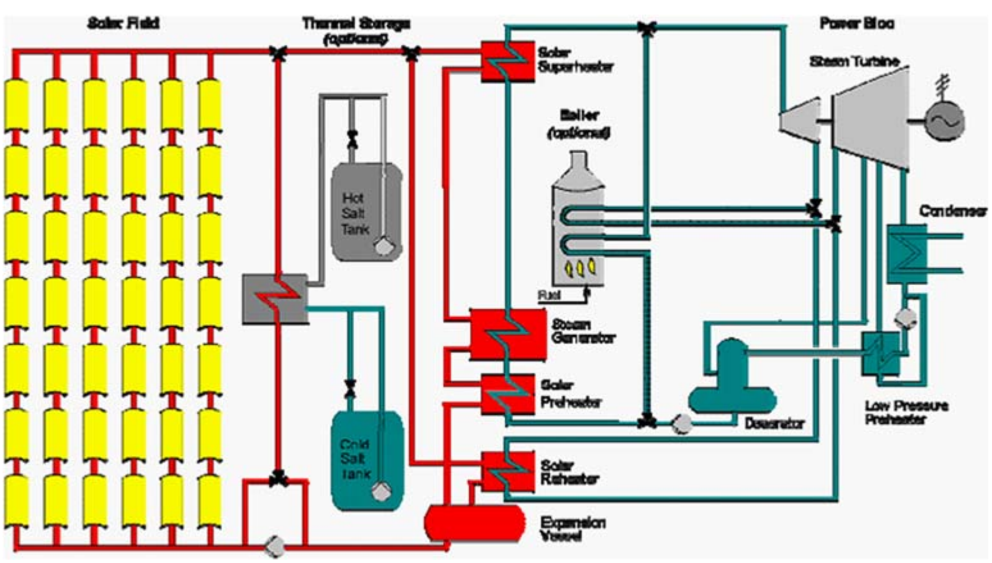


Fig. 17. Schematic diagram of Andasol-1 using molten salt thermal storage and assisted firing [18].

The average solar intensity is estimated as 2,136-kWh/m^2/year, where the plant is located in Spain. This is very close to the Qatar figure of 2000 kWh/m^2/year. The steam conditions to the turbine are 100 bar pressure and 377°C temperature.

For Andasol 1, the solar field aperture area is 624 collectors × 817 m^2 per collector assemblies, or 510,120 m^2 total areas. The collectors were arranged in 156 assemblies' × 4 loops × 816 m^2 per assembly. The solar collector length is 144 m consisting of 12 modules, and thus the collector aperture width is about 6.7 m. The number of heat collector tube receivers is 11,232, and thus there are 11,232/624(# of collectors) = 18 receiver per collector of 144 m length. Then, the tube collector length is 8 m. The solar field temperatures at the inlet and outlet are 292°C and 393°C, respectively.

The reheat steam turbine has a 38% efficiency. It has a double-casing machinery train with intermediate superheating. The enthalpy–entropy (*h*–*s*) turbine line is expected to be similar to that shown in Fig. 18. The turbine steam conditions are given as follows: throttling condition, (point 1): 100 bar, 380 °C, 3,050 kJ/kJ enthalpy; cold reheat (point 2): 25 bar, 227 °C, 2,800 kJ/kJ enthalpy, high pressure (HP) turbine efficiency between points 1and 2 equal to 0.82; hot reheat, (point 3): 25 bar, 380 °C, 3,200 kJ/kJ enthalpy; discharge to desalting, (point 4): 0.5 bar, 72 °C, 2,550 kJ/kJ enthalpy with low pressure (LP) turbine efficiency between 3 and 4 (and 5) equal to 0.84; and discharge to condenser, (point 5): 0.09 bar, 45 °C, 2,335 kJ/kJ enthalpy.

The cycle turbine power = $m_1(h_1 - h_2) + m_3(h_3 - h_4)$ = $m_1(3{,}050 - 2{,}800) + 0.9m_1(3{,}200 - 23{,}350)$, where m_1 is the steam flow to the HP turbine, and m_3 the steam flow inlet to the LP turbine after extracting steam for feed heater. It is assumed that m_3 equals $0.9m_1$. The steam mass flow rate can be calculated from the steam cycle power output of 50,000 kW as $m_1 = 48.61$ kg/s and $m_3 = 48.61 \times 0.9 = 43.75$ kg/s.

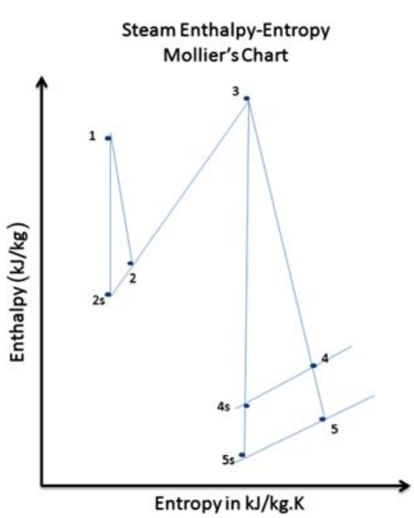


Fig. 18. Turbine steam line on the enthalpy-entropy chart.

When the solar plant is supposed to operate as a pure power plant, and its net EP, say 48 MW after deducting the power used for the plant facilities is used to drive SWRO desalting plant consuming 5 kWh/m^3 (18 kJ/kg), it produces desalted water at a rate of (48,000/18) 2,667 kg/s, or 50.7 million imperial gallons per day (MIGD). One MIGD is 4,546 m^3 per day (52.62 kg/s).

Consider an MED plant having the following data: heating steam supply (discharged from the BPST) is at 72°C saturation temperatures, and saturated vapor in the last effect is 40°C, when the seawater temperature is at 30°C. Then the temperature range across the effects is 32°C. Eight effects can be comfortably accommodated between this temperature range. This can give a gain ratio (GR), distillate output (D)/steam input (S), equal to 7, the GR is close but little less to the number of effects. Then the distillate output:

$$D = m_3 \times 7 = 306.25 \text{ kg/s} = 5.82 \text{ MIGD}$$

If the steam discharged to the MED plant was expanded in a LP turbine, it would produce more power equal to,

$$\begin{aligned} \text{WD} &= m_3(h_4 - h_5) = 43.75 \times (2{,}550 - 2{,}355) \\ &= 8531.25 \text{ kJ/s} \end{aligned}$$

This lost work is the work that is equivalent to the heat supplied to the MED plant. Also the MED consumes pumping energy WP to move its streams, say at a rate of 1.5 kWh/m^3 (5.4 kJ/kg), then

$$WP = 5.4 \times 306.25 = 1653.75 \text{ kW}$$

Total equivalent work consumed by MED = 1653.75 + 8531.25 = 101,85 kW = 10.185 MW.

Specific consumed equivalent mechanical energy by MED = 10,185/306.25 = 33.26 kJ/kg (9.23 kWh/m^3).

After discharging the steam to the MED plant, deducting its pumping energy and 2 MW facility EP consumption, the available power to operate the SWRO is (48 − 10.185) = 37.815 MW. This power can produce an SWRO permeate equal to (37,815/18) = 2,101 kg/s (39.93 MIGD). This gives a total desalted water flow rate by using the MED and SWRO which is (39.93 + 5.82) = 45.75 MIGD.

More on the MED and SWRO configurations and economics are given in Ref. [20].

5. Conclusion

The commercial desalting methods using distillation (MEB, MSF, VC, and MD) and membrane processes (SWRO and ED) were outlined. The possibility of using direct solar energy to desalt seawater by solar stills or indirect solar energy was discussed. The indirect solar energy for desalting seawater includes transferring solar energy to thermal energy at a moderately high temperature to operate TVC, MEB, and MSF systems using CSP was presented. Also, indirect solar energy for transferring solar energy to high temperature thermal energy to operate power plants operating SWRO; or exhausting steam to TVC, MEB, and MSF was presented. Transferring direct solar energy to electric power to operate SWRO or ED is also presented. A solar-operated large capacity desalting plant was suggested. The plant is solar operated steam Rankine cycle with back pressure steam turbine discharging steam to a multi-effect desalting system. The plant EP output is used to operate the SWRO. By stopping the EP supply to SWRO, the plant can satisfy part of the peak load, when needed. So, the plant is considered CPDP. The suggested plant is a modification of the well-known solar plant used in Andasol 1, 2, and 3 PP, and the Extresol 1, 2, 3 solar PPs built (or under construction) in Spain.

Abbreviations

AEM	—	anion exchange membranes
BPST	—	back pressure steam turbine
BWRO	—	brackish water reverse osmosis
BX	—	pressure exchangers
CEM	—	cation exchange membranes
CPDP	—	cogeneration power desalting plant
CSP	—	concentrated solar power
D	—	distillate flow rate
DW	—	desalted seawater
DWEER	—	dual work exchanger energy recovery
ED	—	electrodialysis
EME	—	equivalent mechanical energy for thermal and mechanical energy
EP	—	electric power
FF	—	fossil fuel
GCC	—	Arabian Gulf Co-operation Countries
GHG	—	greenhouse gases
GR	—	gain ratio, distillate mass flow rate/ steam supply in thermal desalination plant
HDH	—	humidification–dehumidification
HP	—	high pressure
kWh	—	energy unit equal to 3,600 kJ
LP	—	low pressure
MD	—	membrane distillation, separation/ distillation techniques
MED	—	multi-effect distillation
MIGD	—	million imperial gallons per day (4,560 m3/d)
MSF	—	multi-stage flash desalination system
MVC	—	mechanical vapor compression
NG	—	natural gas
PV	—	photovoltaic
RE	—	renewable energy
RO	—	reverse osmosis
S	—	steam supply flow rate
SPP	—	solar power plant
SWRO	—	seawater reverse osmosis
TVC	—	thermal vapor compression
VC	—	vapor compression

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