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Solar Desalination Methods and Economics (Literature Review)

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Abstract: The shortage of drinking water source limits the socio-economic development of many areas of the world. Saudi Arabia is one of the poor countries in fresh water source and around 40 to 50% of portable water is produced by desalination technology that depends on using oil and natural gas. The high cost of the water and electricity production reflects depleting the natural source of the country. This paper show literature review for using solar energy in desalination application. The direct electrical method PV–RO combination works like two independent units also there is still much room for improving the combination of both technologies. A direct thermal method such as solar still is applicable for small scale since the productivity is very low and the required area to produce water in commercial scale is huge. CSP systems can be combined with different desalination methods (RO, MSF and MED). The researches show that CSP-MSF seems to be not feasible compared to MED CSP. CSP coupled with MED and RO appear to be promising since the water cost ranges 0.62 to 3.09 $/m^3$. Besides, it was shown that MED-CSP suits more the stand-alone option while CSP+RO is preferred for cogeneration plants. The water cost for CSP+MED in the previous literature shows variation from 0.62 to 3.09 $/m^3$.

Keywords: Economic Solar Desalination, Solar, Desalination, Cost of Water (LCOW)

1. Introduction

With increasing of water demand and depleting of fresh water resources many countries will face fresh water challenges [1]. The worldwide solar desalination is less than 1% of that of conventional desalination because high capital and maintenance costs linked with using renewable energy. Therefore, further comparison between different technologies and techno economic evaluations are needed and are essential steps to select the promising configuration before commercialization.

Most water in the earth 97% is salty water in the oceans and sea however only 3% remained is fresh water. Around 70% of the fresh water is glaciers in the earth poles and the other 30% is ground water and rivers, which used for drinking water [2]. This amount of water is not sufficient for drinking, industrial and agriculture activities. Desalination is the solution of the scarcity of fresh water however it is high energy consumption 42-55% of the water cost is energy cost which is depleting the resources. There are two techniques main commercial desalination: by evaporation (MSF and MED) or by using of a semi-permeable membrane to separate fresh water from a concentrate (RO).

Solar energy can play major role in desalination where the energy is sustainable and friendly to the environment. Focus has been directed towards improving the conversion efficiency of solar energy systems, in other hand desalination technologies are highly intense power consumption industry. The main issue in the solar energy is capital cost which is important role in energy cost however study of coupling between different type of solar collectors and different type of desalination plant shall be conducted to find out the optimum hybrid system can be feasible for desalination applications.

Alnaimat et al. discussed mathematical model for different types of solar desalination technically, Li Chennan et al. discussed special cases of solar desalination. Refer to this literature review it was concentrated to integrate technical and economic benefits of most commercial solar desalination techniques.

2. Water Desalination Technology

Desalination is the process of removing salt and other minerals from saline water. More than 15,000 desalination plants had been installed worldwide by 2010 with a cumulative production capacity of approximately 86.55 million m^3/day. The majority of water desalination processes can be divided into two types: phase change thermal processes and membrane processes, as shown in Figure 1 [4], both encompass a number of different processes. In addition, other alternative technologies such as desalination by freezing and by ion exchange.

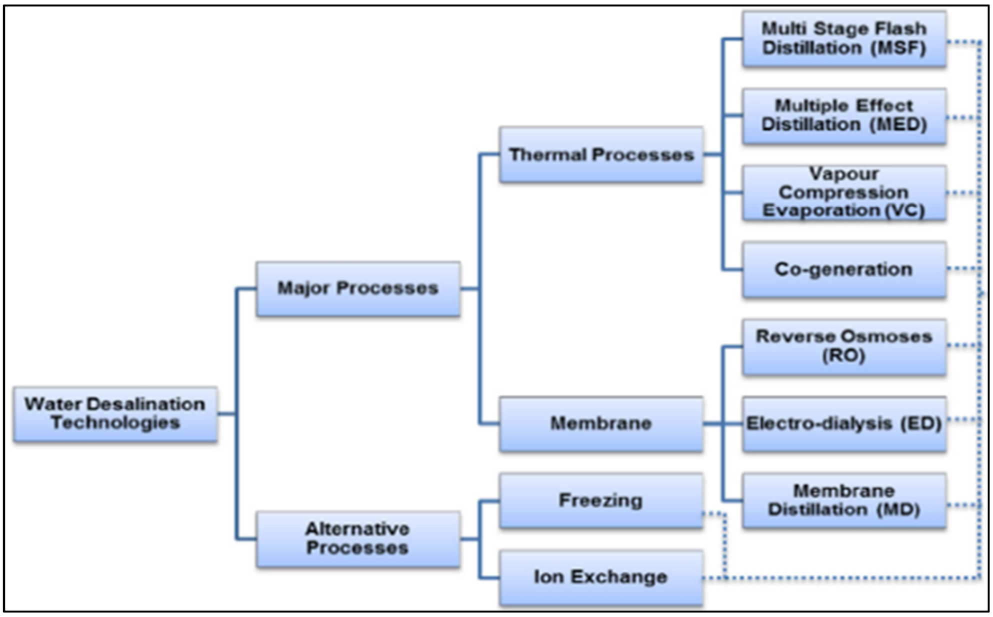

Figure 1. *Water desalination technologies [4].*

Among all desalination, technologies mentioned on Figure 1, Multi Stage Flashing (MSF), Multi Effect Desalination (MED) and reverse osmosis (RO) are the most used technologies nowadays as shown in Figure 2. Figure 2 shows worldwide desalination capacity based on technology. RO process has highest installed capacity compared to MSF and followed by MED.

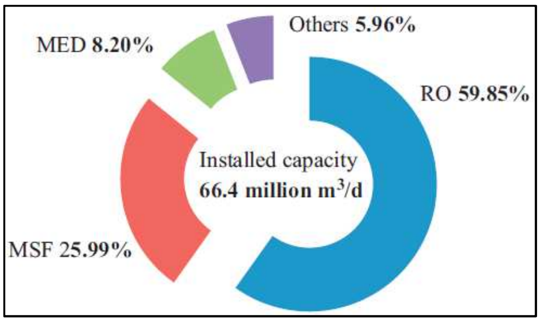

Figure 2. *Worldwide installed desalination capacities by technology [5].*

2.1. Thermal Desalination

Thermal desalination process is a phase change process based on the principles of evaporation and condensation. Water is increased in temperature until it reaches its saturation temperature, beyond which evaporation occurs. The salt is left behind while the vapor is taken away to condense in another heat exchanger to produce fresh water. Thermal process included two major processes [4, 6]: Multi Effect Distillation (MED) and Multi Stage Flashing (MSF). Both processes are used in large-scale cogeneration for water and power production utilizing low quality steam heat rejected from power cycles. The MSF and MED operate at low temperature levels. The top brain temperature in MSF and MED are about 90°C and 65°C respectively [1]. Therefore, the integration of MSF or MED with solar energy appear to be promising. Figure 4 and Figure 5 show the principle of MED and MSF respectively.

2.1.1. Multi Effect Distillation Desalination Process

In the Multi-effect desalination (MED) process, the feed water is sprayed and distributed onto the surface of the evaporator tubes for different effects making a thin film to promote evaporation on the tubes surfaces. The evaporator tubes in the first effect are heated by steam extracted from a power cycle or from a boiler. The steam produced in the first effect is condensed inside the evaporator tubes of the next effect, where again vapor is produced. Each effect must have a lower pressure than the preceding one. The steam produced in the last effect is condensed in a condenser cooled by the incoming seawater; the heat of condensation of the vapor is used to preheat the feed water [1, 6]. The MED process is generally coupled with thermal vapor compressor (TVC) which enhances its performance. The MED and MED-TVC systems are classified as small and medium scale capacity desalination systems.

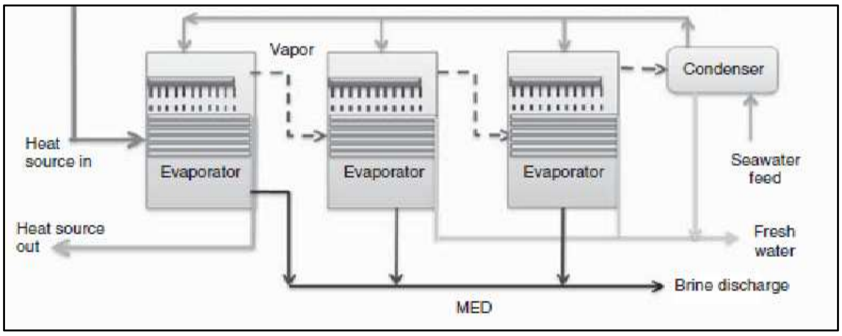

Figure 3. *Schematic of MED process [1].*

2.1.2. Multi Stage Flashing Desalination Process

In MSF process, seawater moves through a sequence of vacuumed stages that are held at successively lower pressures where seawater is preheated. External heat is supplied to heat the preheated seawater above its saturation temperature. Seawater is then passed from one stage to the next in which part of water flashes to steam in each stage and the remaining brine flows to the next stage for further flashing. The flashed steam is condensed and collected as fresh water after removing the latent heat of condensation to preheat the entering seawater at each stage [3]. MSF unit are in general constructed in once through (OT) and brine recirculation configuration. The capacity in each MSF unit is considered as high capacity scale.

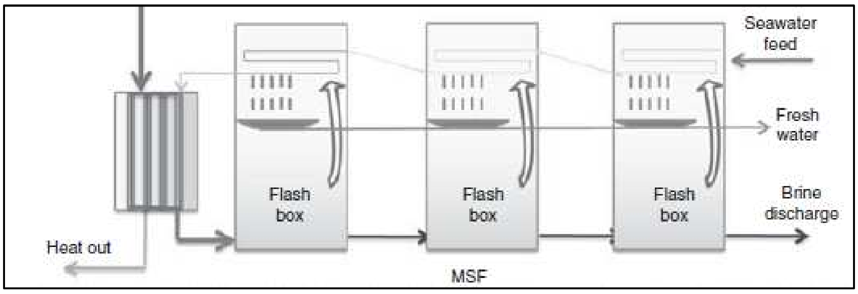

Figure 4. *Schematic of MSF process [1].*

2.2. Membrane Desalination Process

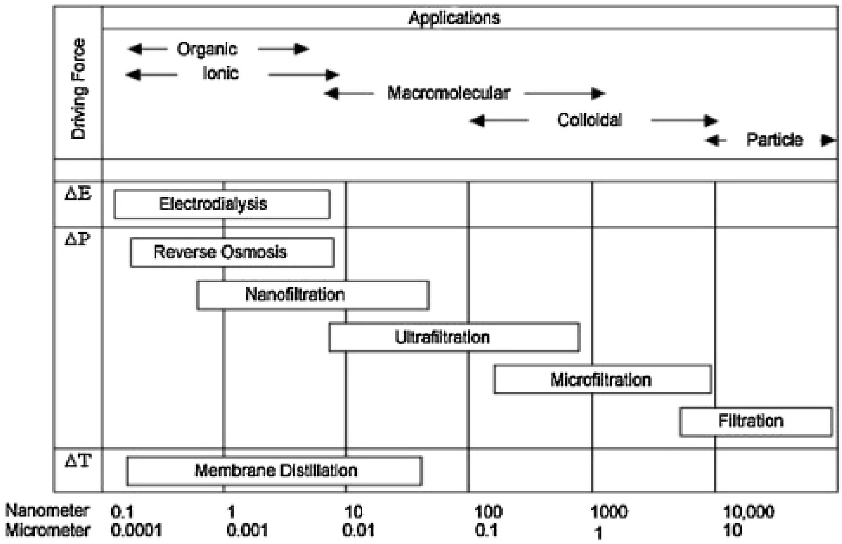

Figure 5. *Effective range of membrane processes and applications [4].*

Membrane technology was originally limited to municipal water treatment such as micro-filtration and desalination, but with the development of new membrane types, uses have expanded to cover not only the water industry, but also high return processes such as chemical separations, enzyme concentration and beverage purification. This technology uses a relatively permeable membrane to move either water or salt to induce two zones of different concentrations to produce fresh water. A membrane is a thin film of porous material that allows water molecules to pass through it, but simultaneously prevents the passage of larger and undesirable molecules such as viruses, bacteria, metals, and salts. Membranes are made from a wide variety of materials such as polymeric materials that include cellulose, acetate, and nylon, and non-polymeric materials such as ceramics, metals and composites. Two of the most successful membranes are spiral wound and hollow fine fiber (HFF) and both of these are used to desalt brackish water and seawater. Figure 5 shows applications and range for membrane types.

3. Solar Desalination

Conventional processes like MSF, MED and RO require large amounts of energy in the form of thermal energy or electric power. Most desalination plants using these technologies are fossil fuel driven. This results in a large carbon footprint for the desalination plant, and sensitivity to the price and availability of oil [7]. To avoid these issues, desalination technologies based on renewable energy are highly desirable. One of the best sources of renewable energy with minimal negative impact to the environment is solar energy. Solar energy is one of the cleanest energy that does not contribute to global warming. It is abundant and readily available. Solar energy can provide the required energy to desalination processes. It can drive both types of commercial desalination methods thermal and membrane system. Solar collectors can be divided to two types; photovoltaic system (PV), which converts sun light to electricity directly, and concentrated solar power (CSP) in which lenses and mirrors are used to concentrates sun light on the receivers producing thermal energy.

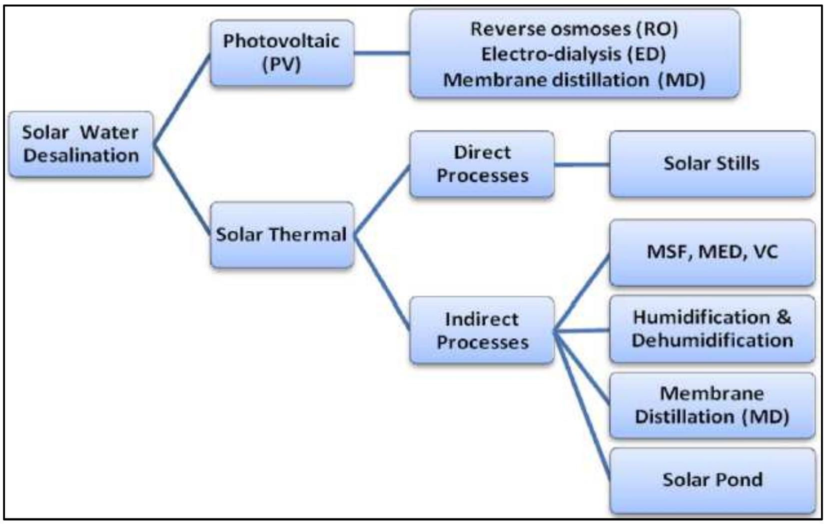

Figure 6. *Solar desalination classification [4].*

3.1. Classification of Solar Power Assisted Seawater Desalination

The solar collection subsystem is used either to collect heat using solar collectors and supply it to a heat exchanger to a thermal desalination process or converted heat to electricity using photovoltaic cells to power physical desalination process (Reverse osmosis) [1]. Figure 6 shows the classificatioan of solar assisted desalination systems as PV and thermal systems. The thermal systems can be divided to two main classes, The direct systems are those where the thermal desalination processes take place in the same device and they are mainly suited to small production systems, such as solar stills, in regions where the freshwater demand is less than 200 m^3/day the second class is indirect systems where each plant is separated into two subsystems, a solar collector and a desalination unit. The solar collector can be a flat plate, evacuated tube or solar concentrator and it can be coupled with any of the thermal desalination processes types, which use the evaporation and condensation principle, such as multistage flash distillation (MSF), thermal vapor compression (TVC), multiple effect evaporation (MED), and membrane distillation (MD). Systems that use photovoltaic (PV) devices tend to generate electricity to operate reverse osmoses (RO) and electro dialysis (ED) desalination process [4].

3.2. Direct Solar Desalination Solar Stills

In a solar still, the heat collection and distillation processes occur within the same structure where solar energies used directly for distillation by means of the greenhouse effect. Seawater is placed in a blackened basin inside an airtight transparent structure where it evaporates due to absorption of solar radiation then condenses on the sloping structure by losing its latent heat of condensation to the surroundings. Condensed droplets run down the cover to accumulating troughs to be collected as fresh water.

Solar stills are a small-scale hydrological cycle, and their efficiency is dependent on meteorological limitations such as solar radiation, sky clearness, ambient temperature, wind and velocity as well as operating factors such as brine depth, vapor leakage, thermal insulation, cover slope, shape material, and others [1] Figure 7 shows a solar stiller. The production of simple solar stills is low ranging between 1 to 6 kg/m^{2}day [3, 5].

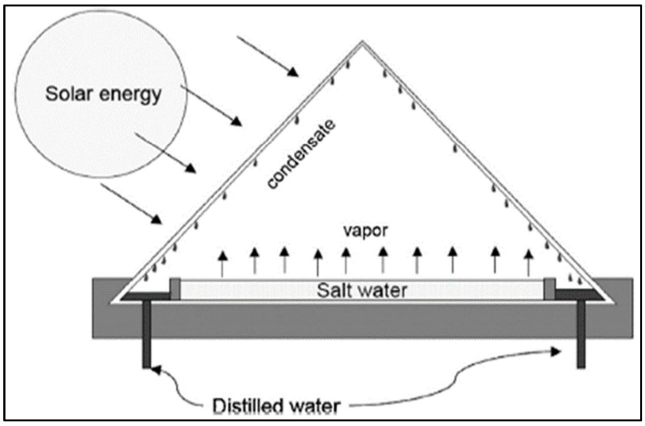

Figure 7. *Solar still desalination unite. [4].*

Solar stills can be classified as passive or active stills. Passive stills use only the solar energy falling into the unit. In active stills, an external thermal energy source is added. In addition, they can be classified based on geometry as single slope, double slope, vertical, horizontal and multi effect. Table 1 shows the various values of still yield reported in the literature [5]. The solar still production is limited. Therefore, the area for commercial scale production is huge However; such systems can be economically viable for small-scale production for households and small communities, especially where solar energy and low cost labor are abundant [4].

Table 1. *Production rates of various solar stills as reported in the literature [5].*

Production L/m^2-day	Geometry
2.8-5.7	Hemispherical
4	Double slope
6.1	Double effect
9	Multi stage solar still
18	Multi stage solar still with vacuum pump

3.3. Indirect Solar Desalination

In this category, the plant separated in two subsystems; solar collector and desalination plant. The integration of those systems (solar collector and desalination plant) requires also several auxiliary components such as storage tank and pumps.

3.3.1. Concentrated Solar Power Technology (CSP)

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high- temperature heat for electricity generation within conventional power plants using steam turbines, gas turbines or Stirling engines. For sun concentration, most systems use glass mirrors that continuously track the position of the sun. In the case of CSP, the sunlight is focused on a receiver that is specially designed to reduce heat losses. A fluid flowing through the receiver takes the heat away towards a thermal power cycle, where high pressure and high temperature steam is generated to drive a turbine. Air, water, oil and molten salt can be used as heat transfer fluids [2]. Central receiver tower, solar dish, linear Fresnel and parabolic trough are the main solar concentrated collector's types.

3.3.2. Parabolic Trough

Parabolic trough-shaped mirrors produce a linear focus on a receiver tube along the parabola's focal line as shown in Figure 8. Trough systems using thermal energy collection via evacuated tube receivers are currently the most widely deployed CSP technology. In this configuration, an oil heat transfer fluid is usually used to collect the heat from the receiver tubes and transport it to a central power block [8].

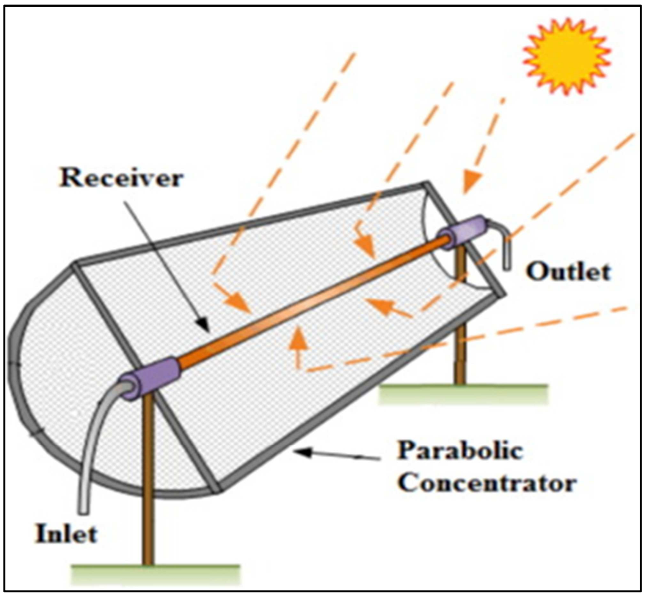

Figure 8. *Diagram of Parabolic trough collector (PTC) [8].*

3.3.3. Linear Fresnel

Linear Fresnel reflector (LFR) systems produce a linear focus on a downward facing fixed receiver mounted on a series of small towers as shown in Figure 9. Long rows of flat or slightly curved mirrors move independently on one axis to reflect the sun's rays onto the stationary receiver [8].

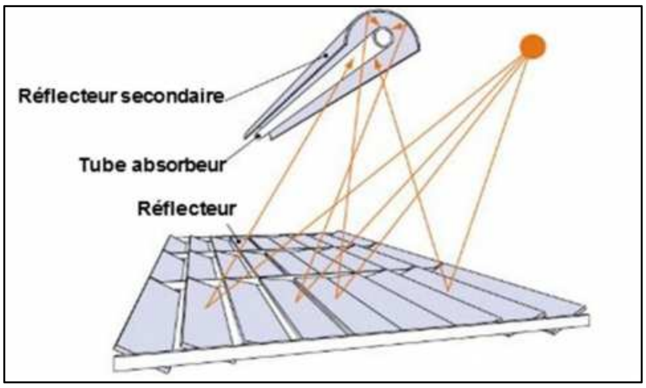

Figure 9. *Diagrame of linear Fresnel collector (LFR) [8].*

3.3.4. Central Receiver Tower

A central receiver tower system involves an array of heliostats (large mirrors with two-axis tracking) that concentrate the sunlight onto a fixed receiver mounted at the top of a tower as shown in Figure 10 [8].

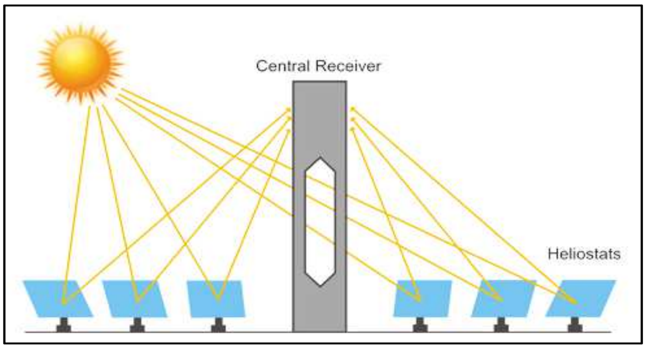

Figure 10. *Diagram of central receiver tower (CRT). [8]*

3.3.5. Parabolic Dish

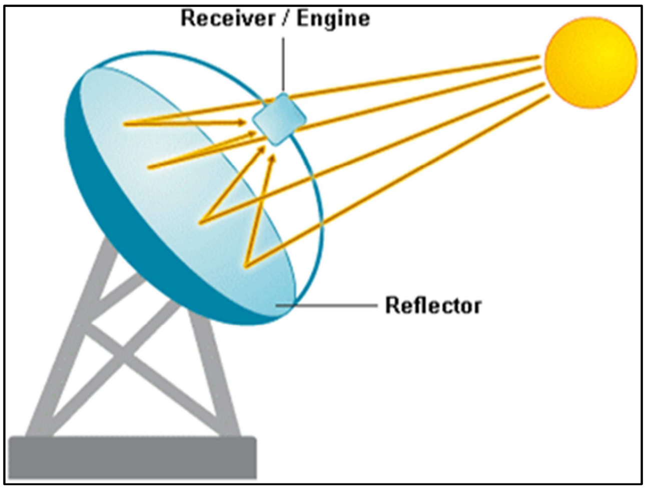

Figure 11. *Diagram of parabolic dish (PD) [8].*

Dish systems, like troughs, exploit the geometric properties of a parabola, but as a three-dimensional parabolic as shown in Figure 11. The reflected direct beam radiation is concentrated to a point focus receiver reaching operating temperatures of over 1,000°C, similar to central receiver tower systems [8]. Table 2 summarized useful information on solar collectors.

4. Combination Between Solar and Desalination Technologies

4.1. Combination of CSP+MSF

The concept of CSP assisted MSF is similar to that of CSP assisted MED. The main difference is that the top brine temperature (TBT) is higher for MSF than MED. The MED main benefits over the MSF are lower energy consumption, lower sensitivity to corrosion and scaling, and greater development potential. In addition, in contrast to MSF, the MED process can efficiently operate with low-temperature [10]. Table 3 shows selected CSP-MSF results reported in the literature [3]. Lourdes Garcia and Gomez [11] conducted an economic study for coupling MSF with Parabolic Trough. They also performed comparisons between conventional MSF and CSP coupled with MSF plants located in Almeria, Spain. The levelized cost of water for MSF producing 2400 m^3/day with a performance ratio of 10 was 2.5-4 \$/m^3. Figure 12 shows the variation of the levelized cost of water with the price of energy cost in Euro/kWh.

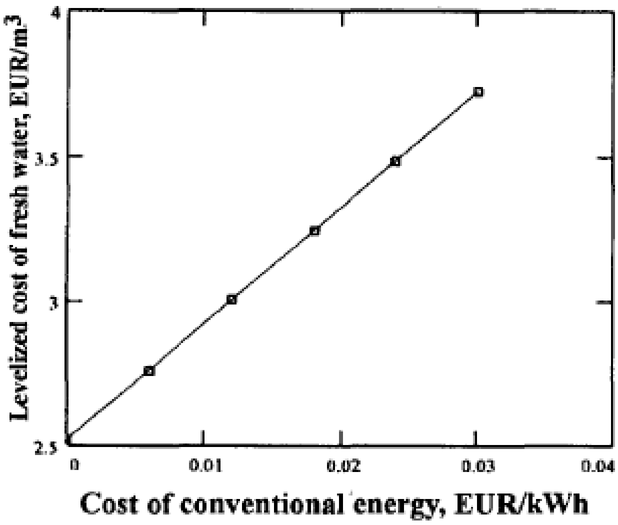

Figure 12. *Levelized cost of water MSF-PTC [11] (1 EUR equals 1.15 \$ at January 2019).*

Table 2. *Solar collectors and their characteristics [9].*

Operation range	Concentration ratio	Absorber	Collector Type	Tracking
30–80°C	1	Flat	Flat plate (FPC)	
50–200°C	1	Flat	Evacuated tube (ETC)	Stationary
60–240°C	1–5	Tubular	Compound parabolic (CPC)	
60–300°C	5–15	Tubular	Compound parabolic	
60–250°C	10–40	Tubular	Linear Fresnel Tubular	Single Axis
60–300°C	15–45	Tubular	Parabolic trough (PTC)	
60–300°C	10–50	Tubular	Cylindrical trough	
100–500°C	100–1000	Point	Parabolic dish	Double Axis
150–2000°C	100–1500	Point	Heliostat field	

Table 3. *Various value of CSP-MSF reported in literature [3].*

Model/Experimental	Location	Collector Type	Capacity m^3	Cost $/$m^3$
Model	Spain	PTC	3000	2.5-4
EXP	Tianjine, china	Flat	0.3	4.67
EXP	Gaza	Flat	0.145	NA
model	Bengazi, Libya	Flat	8.3	NA
EXP	Tamilandu, India	Flat	0.0085	9
model	Suez, Egypt	Flat	0.0025	NA

4.2. Combination of CSP+RO

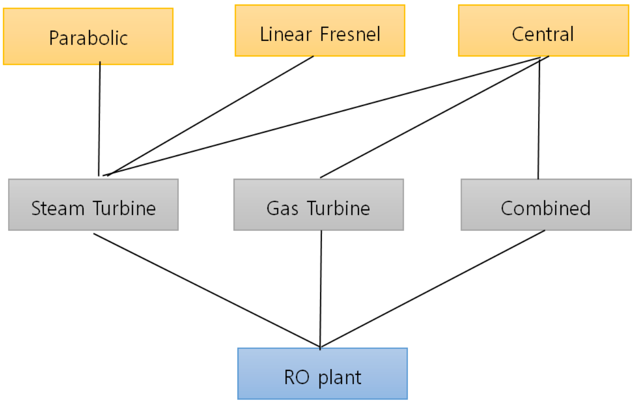

Figure 13. *Configuration of CSP coupled with RO [2].*

RO can be coupled with CSP by producing first electricity using steam turbine or gas turbine plant and then driving RO plant. Figure 13 shows possible options of coupling through the CSP system.

An economic comparison conducted in MENA region between CSP-MED and CSP-RO with different storage hours shows the CSP-MED results in lower unit price than CSP-RO [12]. Table 5 shows the details of such comparison. It is clearly shown that for the same power capacity, water capacity, fuel cost and storage hours CSP-MED given lower levelized cost of water (LCOW) than CSP-RO. Photovoltaic assisted reverse osmosis systems are popular for small-scale demonstration unit. Although there is still much room for improving the combination of both technologies, technical feasibilities normally are not the barriers as compared to the economic and reliability considerations [3].

Table 4. *Comparison between CSP-MED and CSP-RO LCOW [12].*

Economic parameter	Unit	CSP-RO	CSP-MED	CSP-RO	CSP-MED	CSP-RO	CSP-MED
Power capacity	MW	21	21	21	21	21	21
Water capacity	m^3/d	24000	24000	24000	24000	24000	24000
Fuel cost	$/MWh	20	20	20	20	20	20
Storage hours	Hr	0	0	6	6	12	12
LCOW	$/$m^3$	1.55	1.45	1.56	1.47	1.66	1.58

4.3. Combination of CSP+MED

Multi effect evaporation (MED) desalination technology operates at low top brine temperature of around 65°C, low energy consumption, lower sensitivity to corrosion and scaling [17]. MED can be coupled with any type of CSP in a standalone water production or cogeneration (water and electricity production) as in Figure 14.

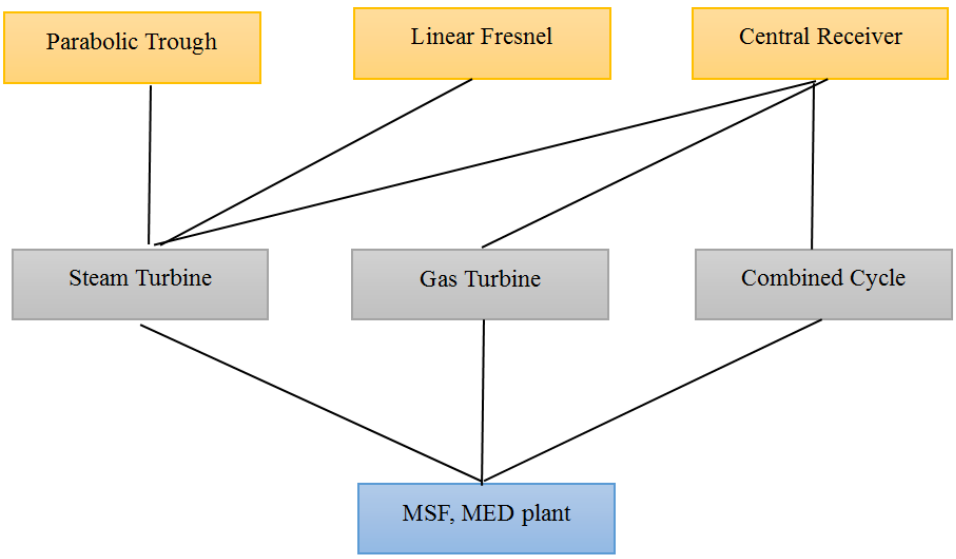

Figure 14. *Configuration of CSP coupled with MED.*

Table 5. *CSP-MED systems characteristics from various literature studies.*

Reference	Location	Collector	Capacity, m^3/day	DNI (kWh/m^2/day)	Cost \$/m^3
[13]	Aqaba, Jordon	PTC	24000	2461	NA
[3]	Eilate, Israel	PTC	100000	2522	0.92
[3]	Zikim, Israel	PTC	100000	2551	0.62
[13]	Ashdod, Israel	PTC	24000	1984	NA
[14]	Mediterranean	PTC	14400	1990	1.87-1.93
[15]	MENA region	PTC	100000	2000	1.94-2.03
[16]	Mediterranean	PTC	43000-48000	1900	1.03-1.17
[17]	Egypt	PTC	4645	2308	0.97-0.73
[18]	MENA region	PTC	48500	1500	0.72-0.78
[19]	Kish island	LFR	9000	2000	1.63-3.09
[20]	Mediterranean	PTC	47000	1990	0.94

Table 5 compiles main characteristics and main outcomes of several CSP-MED systems investigated in previous works. The capacities in those systems are between 4645 to 100000m^3/day while the DNI solar radiation is about 2000kWh/m^2. The obtained LCWO is ranging between 0.62 and 3.09. The variation in cost comes from the different radiation intensities between a region to another and the model of combination CSP-MED. Some of these systems are standalone, other not, MED with TVC or plain MED. On another side, a techno economic study was conducted on PTC combined with power plant combined with MED or RO units of 24000 m^3/day capacity [13]. Three thermal storage scenarios were considered in both systems. These scenarios correspond to 0.6 and 12 storage hours. The investigation was performed for Aqaba, Jordan and Ashdod, Israel. Figure 15 summarizes the main findings of this study [13] in terms of LCOW as function of electricity cost for Aqaba and Ashdod sites. The LCOW lower in Aqaba than Ashdod due to better irradiation condition and lower national wages for stuff in Aqaba. This study proved that using CSP desalination configurations can be realistic economic future option for the fresh water production to meet demand of MENA region. The implementation of national regulations concerning a feed-in tariff for electricity produced by CSP plants would help to develop the use of solar energy in desalination.

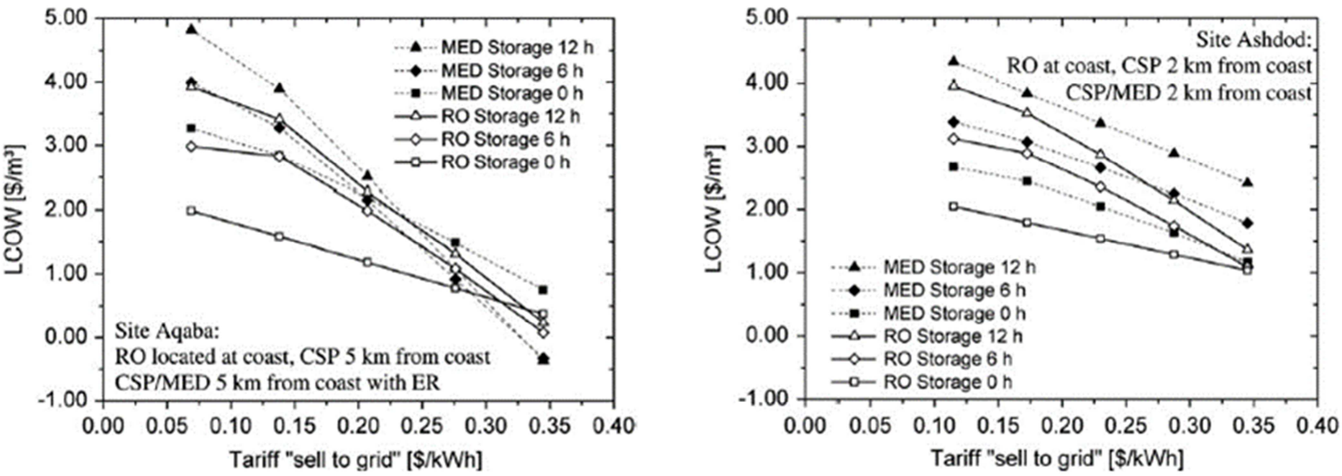

Figure 15. *LCOW for the CSPD configurations in Ashdod and Aqaba as a function of the feed-in tariff for the electricity produced [6].*

Another study was also conducted in Israel, in Eilate and Zimik, to produce electricity first from solar energy and then produce water by MED from the produced electricity. The LCOW values 0.92\$/m^3 in Eilate and 0.62\$/m^3 in Zimik for 100000 m^3/day production [3].

Blanco and Zaragoza [20] presented a comprehensive research on solar desalination in Spain. Five cases are considered, two MED cases and three RO cases. A low temperature multi-effect distillation (LT-MED) plant is coupled with power plant coupled to a CSP plant, replacing the condenser of the power cycle. In first case, a LT-MED plant is fed by steam at the outlet of the turbine expanded to 70°C. In the second case the LT-MED is fed by the steam obtained from a thermal vapor compressor (TVC) which uses the exhaust steam of the CSP plant (at 37°C, 0.063 bar) together with some steam from the high pressure turbine extraction (17 bar). The two cases are compared with three cases of a reverse osmosis (RO) unit powered by eclectric power produced by the CSP plant. In these cases, two different wet cooling technologies, once through and evaporative water-cooling, and a dry air-cooling are considered for the CSP plant. The results show that replacing the condenser by low-temperature MED is more efficient than using MED-TVC which takes steam from high pressure turbine in case of producing same amount of electricity. Also, the comparison has been performed for LCOW between RO and low-temperature MED as given in table 6 [20].

Table 6. *Comparison between CSP-MED and CSP-RO LCOW [20].*

	unit	LT-MED	RO once through cooling	RO Evaporative water cooling	RO dry cooling
Power production	MWe	55	62.8	59.7	62.5
LCOE	$/Kwh	0.243	0.246	0.241	0.249
LCOW	$/m^3	0.919	0.844	0.905	0.844

The results shows LT-MED has LCOW higher slightly than that of RO with different cooling systems, but it is lower LCOE than once through cooling and dry cooling.

Blanco and Zaragoza presented a simulation and evaluation of the coupling of desalting unit to Parabolic Trough solar power plant in Mediterranean region [14]. The study investigated two cases of coupling MED to CSP power plant. First is coupled CSP power plant to plain MED and the second coupled CSP power plant to MED-TVC. Also the study including compression with RO plant if connected with same CSP power plant. Thermal storage has been considered for extending the operation to 24 hours at design day. The results show that the combination with plain MED is more efficient thermodynamically than with MED-TVC. In addition, the CSP plant coupled with TVC-MED is more cost-effective than the independent processes because it requires a smaller solar field. The integration of a MED plant reduces the cooling requirements of a CSP power plant but the CSP-RO combination has a better thermodynamic efficiency. However, the difference with respect to CSP+LT-MED is small [14].

Another research was conducted in Egypt as pilot research to test new parabolic trough collector, CSP coupled with cogeneration system with molten salt heat transfer fluid to produce 1 MWe and 20592 m^3/day of water from MED and RO hybrid system. The results show that the LCOW 0.73-0.97$/m^3. The results indicate the impact of changing the fuel cost on the water cost as given in Figure 16 [17].

A research done in Iran to couple linear Fresnel with standalone MED-TVC with different configurations and different storage hours shows the variation in the LCOW is from 1.63-3.32$/m^3.

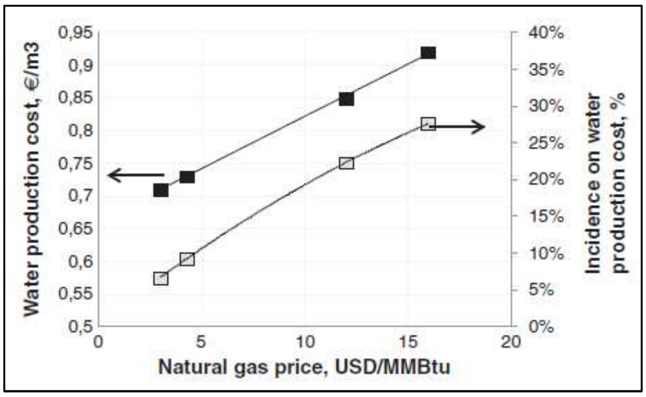

Figure 16. *Influence in natural gas price in water cost [17] (1 EUR equal 1.15 $ at Jan 2019).*

In Saudi Arabia, some research works have been conducted on solar desalination under various conditions. An interesting work was conducted in Jubail city, Eastern province of Saudi Arabia. Its objective was to evaluate an innovative LFR collector used for solar desalination application. The impact of climatic conditions on the operational performance of a pilot plant has been investigated for a period of one year. A feasibility study of combined LFR-thermal desalination with back up fossil fuel and no storage, to produce 1 million imperial gallon per day (MIGD) of fresh water was carried out. The study covered different back up fuel price from 10 to 120$/bbl. The results shown in the Figure 17 give a LCOW starting form 1.8$/m^3 for oil price 10$/bbl to 6.2$/m^3 for oil price 120$/bbl [21].

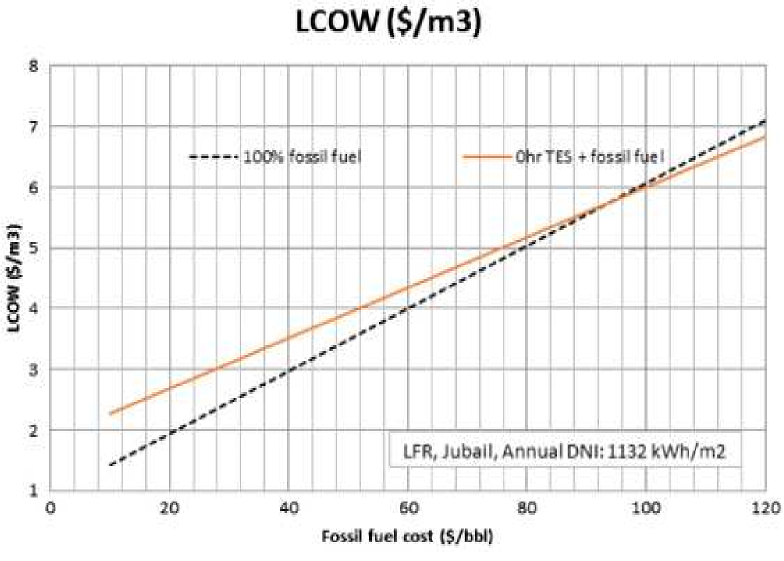

Figure 17. *Effects of fossil fuel cost on water cost without storage.*

5. Conclusions

A solar collector can be coupled with desalination plant by many methods. The direct electrical method PV–RO combination works like two independent units also there is still much room for improving the combination of both technologies. A direct thermal method such as solar still is applicable for small scale since the productivity is very low and the required area to produce water in commercial scale is huge. CSP systems can be combined with different desalination methods (RO, MSF and MED). They can be coupled directly to produce water only or to produce water and electricity in a cogeneration system. Although all three main types of CSP (PTC, LFR and CRT) can be used for water production purposes, CRT collector can be preferred for cogeneration system. The CRT can operate at high temperature level (over 500°C) and the produced steam has high quality (high pressure and temperature steam). Such system can be integrated in a cogeneration configuration. The LFR is preferred for operating standalone system (for water production only) for two reasons, 1) low capital cost, 2) low quality of the thermal energy. On the other side, PTC can be used for standalone and cogeneration options and it can be subjected to different operation conditions. Several previous studies on coupled solar desalination systems mainly MSF-CSP, MED CSP and RO-PV have been reviewed. The previous researches show that CSP-MSF seems to be not feasible compared to MED CSP. CSP coupled with MED and RO appear to be promising since the water cost ranges 0.62 to 3.09 $\$/m^3$. Besides, it was shown that MED-CSP suits more the standalone option while CSP+RO is preferred for cogeneration plants. The water cost for CSP+MED in the previous literature shows variation from 0.62 to 3.09 $\$/m^3$, that depend on different variables. Further studies on solar desalination systems with small to medium capacity are needed.

Nomenclatures

BBL: barrel of oil
CAPEX: capital cost
CSP: concentrated solar power
DNI: direct normal irradiation
DT: total distillate mass flow rate kg/s
Ds: motive steam flow rate kg/s
EPC: engineering procurement and management construction cost
FT: total feed flow rate kg/s
K: yearly insurance
LCOW: levelized cost of water
LFR: linear Fresnel collector
MED-TVC: multi effect desalination unit with thermal vapor compressor
N: amortization period
OPEX: operation cost
PR: performance ratio
Q: specific heat consumption

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