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Prospect of utilization of solar energy in SWCC existing multi-effect desalination satellite plants

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ABSTRACT

The shortage of drinking water source limits the socio-economic development of many areas of the world. Saudi Arabia has very limited resources in fresh water source and around 40%–50% of portable water in Saudi Arabia is produced by desalination technology which depends on using fossil energy. As the high cost of water and electricity production reflects depleting oil resources of the country which is non-renewable, solar energy would be a good alternative since Saudi Arabia has abundant free solar energy. This study investigates the feasibility of using concentrated solar power system (CSP) for thermal desalination. The study is conducted for CSP coupled with multi-effect desalination with thermal vapor compressor existed in western province Saudi Arabia in five locations with various DNI, for two cases, without storage and with 16 h storage. The total saving from coupling solar collectors to all five plants shows around 20.45 million $/y. Using of solar energy can reduce carbon dioxide emission to the environment by 420 thousand ton/y for all selected plants.

Keywords: Multi-effect desalination with thermal vapor compressor; Solar; Desalination; Cost of water (LCOW)

1. Introduction

Freshwater demand is persistently increasing as populations around the world keep growing and as existing freshwater reserves keep declining due to high consumption and pollution [1]. The worldwide capacity of desalination using renewable energy is less than 1% of that of conventional desalination due to high capital and maintenance costs associated with using renewable energy. Therefore, further techno economic evaluations are needed and are important steps to select the promising configuration before construction phase.

97% of the earth's water is available is salty water in the oceans and sea while only3% remained is fresh water. About 70% of the fresh water is frozen in the earth poles and the other 30% is ground water rivers, which used for drinking water [2]. Therefore this limited resources of fresh water is not enough to fulfill human requirement as drinking, industrial and agriculture use. Desalination can play an important solution of the scarcity of fresh water. Two main techniques are used in desalination: by evaporation or by using of a semi-permeable membrane to separate fresh water from a concentrate. Historically, seawater desalination has been the most expensive way to produce drinking water at the commercial scale because of the high capital and energy costs [3]. Fuel cost is major component of water unit cost almost 40%–50% of the water total cost. Many research works have been conducted to reduce the fuel cost by increasing efficiency and change fuel sources.

Solar energy considered as attractive source of renewable clean energy, which does not contribute to global warming. Attention has been directed towards improving

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the conversion efficiency of solar energy systems. However, desalination technologies are highly intense power consumption industry. Optimization of coupling between desalination and solar system is highly attractive to enhance the economics of desalination which have reliable and renewable source of energy. Solar desalination is in particular attractive and promising in high solar radiation intensity countries such as KSA and Gulf countries in general. There are essentially two widely known methods to combine solar and desalination systems. The solar collection sub-system is used either to collect heat using solar collectors and supply it via a heat exchanger to a thermal desalination process or convert heat to electricity using photovoltaic cells to drive pressure driven technology; membrane desalination process (reverse osmosis).

2. Materials and methods

This project will focus on analyzing the operation data of the existing multi-effect desalination (MED) units located in red sea coast of Saudi Arabia, based on solar radiation data Fig. 1 shows the solar intensity in the kingdom and plants locations.

A techno-economic analysis was conducted based on mass and energy balances for the main components of the solar desalination system and cost estimation giving the total cost of water.

The selected locations solar data is shown in Table 1 [5].

Multi-effect desalination with thermal vapor compressor (MED-TVC) desalination plants have different production capacity varied from (8,000–18,000 m^3/d) and different performance ratio (8–10) detail heat and mass balance was carried out based on actual operational data to estimate the required energy to drive the unit all over the year. Estimation of required solar field was estimated using System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) USA. An economic model developed and implemented on Excel tool by DTRI thermal team was used to evaluate the cost of water. Considering different thermal storage time (0 and 16 h storage).

2.1. Research objectives

The principal objective of the project is to conduct a feasibility study on the utilization of solar energy in thermal desalination plants in Saudi Arabia. The specific objectives can be expressed as:

To develop the appropriate design, configuration and operating conditions of solar assisted thermal desalination systems located in the Western Coast of Saudi Arabia.

To conduct technical and cost studies of the solar desalination system with and without storage for a 1-year period.

To evaluate the economic benefits of such integration.

2.2. Research methodology

The methodology of this project can be described as shown in Fig. 2.

SAM which is developed at the National Renewable Energy Laboratory (NREL), usually used to simulate solar field assisted power plants that simulate the concentrated solar power system (CSP) system by using solar data however, the solar field and related output would be extracted from SAM used as input to the generated in house excel file to calculate the specific water production cost. The procedure of calculation is shown in Fig. 2.

Table 1
Solar radiation at different location

Location	Radiation, kWh/m²/d
Al-Wajih	2,450
Umluj	2,300
Rabigh	1,900
Al-Qunfuthah	1,600
Frasan	1,485

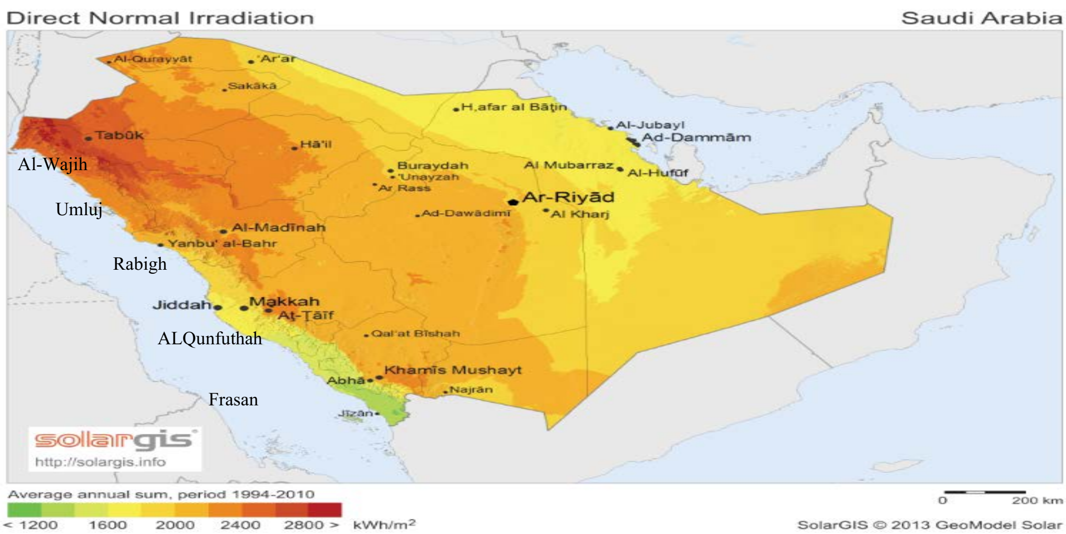

Fig. 1. Solar radiation in Saudi Arabia.

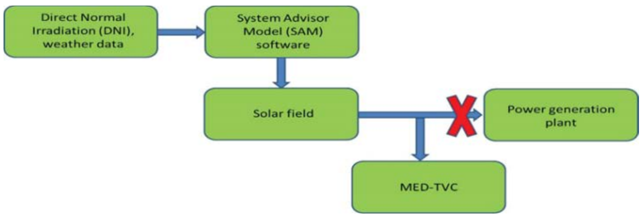

Fig. 2. Simplified diagram for the project methodology.

Table 2
Existed MED-TVC plants criteria

	Production (m^3/d)	PR	Availability
Al-Wajih	8,400	8.4	98
Umluj	12,100	9	97
Rabigh	17,600	9.4	98
Al-Qunfuthah	7,600	10	95
Frasan	7,400	7.9	98

The analysis is based on the conservation of mass and energy principles with technical specifications of the various components of the combined plant. Up to date prices for the various systems and fuels needed in the economic analysis is considered in order to have reliable results. Theoretical models based on the first law of thermodynamic for solar collector assisted MED-TVC will be developed. The solar collector will be simulated and designed by using SAM.

Several scenarios characterized by various configurations of solar collectors and desalination technologies and options on the use of storage system shall be considered and analyzed in the study. The comprehensive study will cover the following configurations:

Hybrid system Linear Fresnel assisted MED-TVC with back up fossil fuel.

Hybrid system Linear Fresnel assisted MED-TVC with thermal storage 16 h.

The proposed system can be described as in Fig. 3, which shown the hybridization of the solar system (power source) and the steam transformer which is used to produce the steam which drive the MED-TVC plant.

2.3. Mathematical model

An Excel program is used to evaluate the cost of water; it is linked between MED-TVC model and CSP model. Thermal energy required to operate MED-TVC plant calculated as in Eq. (1).

$$Q_s = \frac{\text{DT}}{\text{PR}} \times \left(H_{\text{si}} - H_{\text{so}}\right) \quad (1)$$

Then by using (SAM) the solar field area calculated based on required energy, form solar field area CAPEX of solar field calculated based on the values in Table 3. Then contingency and engineering, procurement and construction management cost (EPC) are added to the capital cost

Table 3
Capital cost for CSP system based to SAM program

	LFR (steam HTF)	LFR (molten salt HTF)
Site improvement	20 \$/m^2	20 \$/m^2
Solar field	150 \$/m^2	150 \$/m^2
HTF system	33 \$/m^2	47 \$/m^2
Storage	32 \$/kWht	32 \$/kWht

Table 4
Operation cost of solar field [8]

	LFR
Operation cost of solar field	11.2 \$/m^2
Operation cost of storage	70 \$/MWh/y

as percentage of total cost as 7% contingency and 11% EPC cost. The capital cost of solar system are calculated from following equations.

The capital cost of MED-TVC can be calculated as unit cost equal 1,542 \$/m^3/d [6], and operation cost of MED-TVC equal 0.18 \$/m^3/d including pumping cost [7]. Table 4 used to calculate the OPEX of solar field.

Back up fossil fuel calculated from the balance energy required as number of barrels, then multiply by the oil price from 10 to 100 \$/bbl to calculate specific fuel cost \$/m^3.

Cost of water calculated from all previse information and calculation by the following method:

Find total capital investment by summation of all capital cost of integrated system

$$\text{Total CAPEX} = \text{CAPEX of solar} + \text{CAPEX of MED} + \text{CAPEX of boiler} \quad (2)$$

The LCOW calculated by using the following equation which depend of economic methods [9].

$$\text{LCOW} = \frac{\text{CRF} \times \text{CAPEX} + \text{OPEX} + \text{Backup fuel cost}}{\text{Water production}} \quad (3)$$

where (CRF) the capital recovery factor is generally used to find out the uniform annual amount 'CAPEX' of a uniform series from the known present worth at a given interest rate '*i*' per interest period (n) [10].

$$\text{CRF} = \left(\frac{z(1+z)^n}{(1+z)^n - 1}\right) + k \quad (4)$$

where z is discount rate assumed as 0.05; n is amortization period per year assumed 20 y; k is yearly insurance assumed 0.01.

3. Results and discussion

A techno economic analysis was performed for MED-TVC desalination plant based on average plant production, performance ratio and availability extracted from actual data. Fig. 5 shows the variation of water cost with oil price for each plant simulated as operated 8 h by using Linear Fresnel and the rest of the day by back up fossil fuel. Then compared with conventional plant operated by fossil fuel only, which presented as dotted line in the figure this would give a clear criterion for the economic benefits via different oil prices.

As expected, the best economic benefits are obtained when the solar radiation is high with high performance MED. Frasan was found as the worst unit for coupling solar with MED-TVC desalination unit that since it has low DNI and low performance (efficiency) plant. On the other hand, Umluj was found to be the best option for such configuration. Detail analysis is shown in Figs. 5 and 6 for different storages. However, all the plants are economically feasible almost at oil price of 25 $/bbl, except for Frasan plant, which is feasible at 45 $/bbl, which present the worst case.

Table 5 summarizes the main results at international oil price (60 $/bbl). It shows the feasibility, water cost and saving for each plant when coupled with LFR without storage.

Fig. 6 shows variation of water cost with oil price for individual plants simulated as operated 24 h by using LFR. MED-TVC plant, using of LFR for 16 h shows water cost stability at high oil price is more economically feasible than conventional MED-TVC and LFR assisted MED-TVC without storage. Additionally, in this case the plant performance is more effective and the breakeven cost starts at 30 $/bbl for the best performing plant Umluj and shows a breakeven point of around 50 $/bbl for worst plant, which is Frasan.

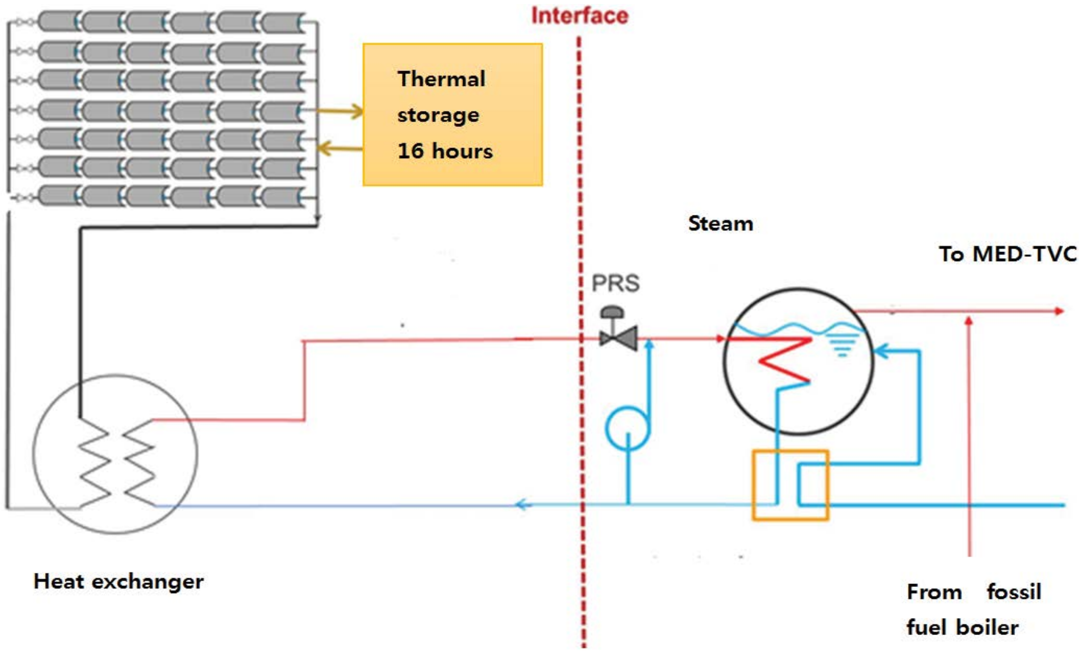

Fig. 3. Configuration of CSP coupled with MED-TVC.

Table 5
Simulation results for case LFR-MED-TVC without storage

@Oil price 60 $/bbl. CSP + MED-TVC (0 h storage)	Conventional MED-TVC	Al-Wajih	Umluj	Rabigh	Al-Qunfuthah	Frasan
Unit production, $/m^3	3.48	2.81	2.82	2.79	2.73	3.33
Gain output ratio, kg product/kg/steam	9	8.4	9	9.4	10	7.9
TBT	65	65	65	65	65	65
Motive steam pressure	8	8	8	8	8	8
Solar field area	0	49,305	65,741	106,829	54,362	57,523
Solar operational hours	0	8	8	8	8	8
Plant production	9,000	8,400	12,100	17,600	7,600	7,400
Amortization period year	25	25	25	25	25	25
Operation cost (MED + CSP), $/m^2	0.27	0.45	0.44	0.45	0.51	0.49
Carbon dioxide reduction, T/Y	0	27	34	53	21	25
Total saving million, $/Y	0	2	2.9	4.4	2.08	0.41

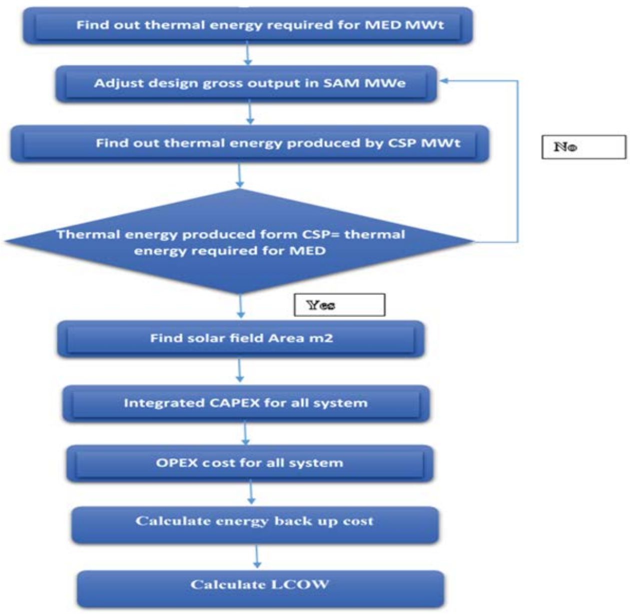

Fig. 4. Description of the general calculation procedure of project.

The cost of water and saving in \$/y is shown to be better when using 16 h storage comparing to LFR without storage.

4. Conclusions

A techno economic analysis of combination between CSP and MED-TVC was carried out for five existed MED-TVC plants located at western region of Saudi Arabia (Al-Wajih, Umluj, Rabigh, Al-Qunfuthah and Frasan). Energy consumption of MED-TVC calculated by the information from each plant based on plant capacity, performance ratio, Temperatures and pressures. Based on energy requirement, simulation was conducted to couple these plants with Linear Fresnel collector to provide a thermal energy required to run such units. SAM was used to simulate leaner Fresnel with different thermal storage capacity (0 and 16 h storage) and the coupled systems were simulated by using Excel program. All cases were compared with conventional MED-TVC (running by fossil fuel) as a reference to find out the breakeven cost with different fossil fuel price. The main issue in these plants is fuel consumption which is too high (14.3 kW/m^3).

Using of LFR coupled with MED-TVC is feasible average of breakeven cost for all plants is 25 \$/bbl. for zero-hour

Table 6
Simulation results for case LFR-MED-TVC with 16 h storage

@Oil price 60 \$/bbl. CSP + MED-TVC (16 h storage)	Conventional MED-TVC	Al-Wajih	Umluj	Rabigh	Al-Qunfuthah	Frasan
Unit production, \$/m^3	3.48	2.41	2.1	2.35	2.6	2.97
Gain output ratio, kg product/kg/steam	9	8.4	9	9.4	10	7.9
TBT	65	65	65	65	65	65
Motive steam pressure	8	8	8	8	8	8
Solar field area	0	158,021	195,645	3461,41	173,256	195,645
Solar operational hours	0	24	24	24	24	24
Plant production	9,000	8,400	12,100	17,600	7,600	7,400
Amortization period year	25	25	25	25	25	25
Operation cost (MED + CSP), \$/m^2	0.27	0.86	0.77	0.88	0.98	1.09
Carbon dioxide reduction, T/Y	0	70	93	136	54	67
Total saving million, \$/Y	0	3.3	6.09	7.25	2.44	1.37

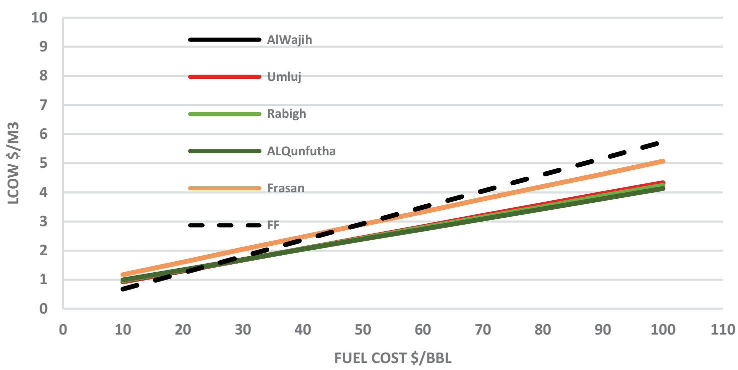

Fig. 5. Variation of water cost without storage.

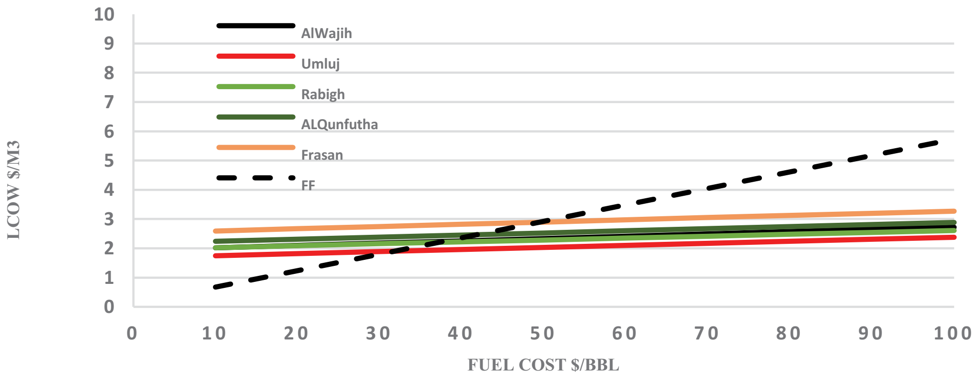

Fig. 6. Water cost vs. oil price 16 h storage.

storage case except Frasan plant at 50 $/bbl. For 16 h storage the difference appear in breakeven cost between each plants. The lower breakeven cost was shown in Umluj plant where higher performance ratio and very high DNI breakeven cost of 32 $/bbl compared to Frasan which has low performance and low DNI and shows the higher breakeven cost 50 $/bbl. The results also show that using of 16 h storage is more feasible than other cases when the LCOW calculated based on unsubsidized fuel cost (60 $/bbl), and using zero-hour storage is more feasible when fuel cost from 25 to 40 $/bbl. According to the results including fuel transportation cost the using of 16 h storage is more feasible than other cases in all fuel cost from 35 to 100 $/bbl and the total saving from coupling solar collectors to all five plants shows around 20.45 million $/y. Also, the main side effect of using fossil fuel is pollution and the results show that using solar energy can reduce carbon dioxide emission to the environment by 420 thousands ton/y for all selected plants.

Next step would be a validation test for different solar collector and to select the most efficient and cost effective scheme to be coupled with actual plant in selected SWCC plant. The project is in progress. Such technology, coupled with high efficient thermal MED would be a breakthrough in thermal desalination.

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