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Enhancing the efficiency of a CSP assisted MED-TVC desalination system

Amr Mohamed Mahmoud*, Ahmed S. Alghamdi, Sultan Ahmed

Saline Water Conversion Corporation - Water Technologies Innovation Institute & Research Advancement (SWCC-WTIIRA), Jubail, Saudi Arabia, email: amahmoud4@swcc.gov.sa (A.M. Mahmoud)

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ABSTRACT

Socioeconomic development in many parts of the world is hampered by a lack of fresh water for potable and industrial use. The Kingdom of Saudi Arabia (KSA) relies on seawater desalination for meeting its water needs due to low per capita water availability. Desalination technologies predominantly utilize energy produced from oil and natural gas which emit greenhouse gases (GHGs), with the current policies encouraging the integration of renewable energy. KSA with its abundant solar energy resource availability has strategized decarbonization of the water sector through process efficiency improvement and renewable energy utilization. This study looks at the effect of performance ratio (PR) on the cost of desalinated water and CO_2 emission reduction, when using a concentrated solar power (CSP) assisted multi effect distillation – thermal vapor compression (MED-TVC) desalination unit. The PRs chosen were 8.4,12,16, 20 and 24 based on the enhancement in the top brine temperature (TBT) from 65°C seen in commercial plants (PR 8) to 85°C and 95°C in the pilot studies. The techno-economic study showed that CO_2 emissions are reduced by 42% when the MED-TVC is operated at a PR of 20 when compared with a conventional MED-TVC operating at a PR of 8.4. The cost of water production is reduced by 3.3 $/m^3 when comparing CSP MED-TVC at a PR of 20 to the current commercial plant operating at a PR of 8.4. Furthermore, the solar area required to power CSP MED-TVC at a PR of 8.4 for 8 h without any Thermal Energy Storage (TES) is nearly equal to the solar area required to operate the MED-TVC at a PR of 20 with a TES of 16 h.

Keywords: Desalination; CSP; Solar; Techno economic

1. Introduction

The Kingdom of Saudi Arabia (KSA) suffers from water scarcity and is experiencing an increase in water demand for potable and industrial use. Fast depletion of ground water resources and an increased reliance on seawater desalination has led to an increase in energy consumption for potable water production. To this end, several measures have been undertaken in KSA to enhance efficiency of the water production systems and decarbonise them via efficient technology adoption and renewable energy integration into the process [1].

Nowadays, seawater reverse osmosis (SWRO) desalination technology is mainly applied to new desalination plants, as it is considered a more energy-efficient and environment-friendly process compared to thermal processes [2]. However, since this technology is very sensitive to seawater conditions (i.e., clay, metal inorganics, organics and algal blooms), its performance is directly influenced by membrane fouling, leading to an increase in the O&M cost and a decrease in plant availability due to shutdowns [3]. Therefore, it requires additional pretreatment processes for reliable operation when it is constructed in challenging seawater conditions [4].

Although most existing thermal desalination technologies have relatively high energy consumption when compared to SWRO desalination technology, those systems can be reliably operated under severe seawater conditions, while there is also a significant potential to reduce

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* Corresponding author.

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energy consumption of thermal desalination technologies [5]. Al-Mutaz describes the salient features of multi effect distillation – thermal vapor compression (MED-TVC) systems which makes it one of the most promising desalination technologies [6]. The MED-TVC system consumes lower amount of electrical energy when compared with the multistage flash (MSF) technology and conventional multi effect distillation (MED) [7–10]. During the 1990s and early 2000s, MED-TVC systems were limited in unit capacities Al-Najem et al. [11], but the 15 MIGD unit of Yanbu Phase 2 plant in Saudi Arabia set an example of a modular evaporator concept which allows building of evaporators with any unit capacity considered practical and economical [6]. A possible high-performance ratio (PR) of the MED-TVC system can result in considerable reduction of steam consumption for the same water production in a cogeneration configuration [12] and would be the preferred form of thermal desalination technology in concentrated solar power (CSP) assisted cogeneration [13].

KSA has abundant solar energy resources that may be utilized. In fact, as early as the 1960s, solar energy applications had already been explored in KSA; however, due to many obstacles the applications did not become widespread [14]. KSA, aside from being rich in terms of oil and gas reserves has also abundant resources of solar energy amounting to an average of 2,200 kWh/m^2 [15].

Solar thermal energy assisted cogeneration desalination systems using MED, RO and MSF have been studied, for example, [13,16–18].

An advanced MED-TVC technology with a TBT of 85°C was successfully developed and demonstrated in Changwon, Korea [19] and Jubail, KSA [20] under severe seawater feed conditions (45 g/L salinity – Arabian Gulf seawater condition) without any softening of feedwater. Higher TBT allows the plant design to have a higher number of effects and more utilization of steam produced in individual stages, leading to efficient steam consumption and improved economics. In later pilot studies, the TBT was further increased to 95°C at the Desalination Technologies Research Institute (DTRI) of the Saline Water Conversion Corporation (SWCC) [21].

Al-Wajh, Ummlujj, Rabigh, Al-Lith, Qunfuda, Farasan Islands on the West coast of KSA have standalone satellite MED-TVC plants of 1–2 MIGD capacity, which utilize steam from fossil fuel-based boilers. DTRI-SWCC conducted pilot studies on the utilization of linear Fresnel reflector (LFR) systems at Jubail [22]. As high PR MED-TVCs would significantly reduce the solar field area, CSP assisted MED-TVC systems would be a suitable option for the reduction of fossil fuel consumption and CO_2 emissions.

To this end, the main objectives of the study were: (a) impact of higher TBTs (PRs) of MED-TVC on the solar field area, (b) impact of CSP assisted MED-TVC on the cost of water production, and (c) the reduction in CO_2 emissions based on the studies undertaken for the standalone satellite MED-TVC plants.

2. Methodology

2.1. MED and MSF system comparison

A higher top brine temperature (TBT) increases the operation temperature range of a MED-TVC system, allowing to design MED evaporators with a larger number of effects, which results in the increased PR [6]. However, it increases the risk of fouling/scaling potential [23]. Calcium carbonate is a dominant form of scale in the operation range up to 85°C while magnesium sulfate deposition begins occurring beyond 85°C [24]. In the MSF process, a forced brine flow inside the heat exchanger tubes leads to relatively uniform concentrations of the brine exposed to the heat exchange surface area. The concentration of a falling film applied to the outside of the tube bundles in a MED-TVC system is influenced by several factors such as uneven feed water distribution, uneven evaporation, blocked nozzles, etc. Also, the MSF process includes a ball cleaning system to remove scales which are generated inside the tubes during operation. In a MED-TVC system, it is physically difficult to remove scales which are formed outside the tubes. For these reasons, MSF plants have been generally designed to be operated at a TBT of 112°C, while existing conventional MED-TVC plants have been designed with a TBT in the range of 65°C to prevent scale occurrence.

An economic analysis was performed to compare the levelized cost of water (LCOW) of a MED-TVC operating at a TBT of 85°C with a brine recirculation cross tube multistage flashing system (BR-CT MSF) and a conventional MED-TVC operating at 65°C. The levelized cost of water (LCOW) included the CAPEX (i.e., material, civil, erection cost, and transportation cost) and OPEX (i.e., steam, power, chemical, and O&M cost) and has been calculated for each plant based on a capacity of 50 MIGD. Furthermore, the water cost has been based on an oil price of 24 USD/barrel, 30 y plant lifetime, a discount rate of 5%. The thermo-physical properties (i.e., mass, temperature, salinity, and enthalpy) of all process streams (i.e., steam and seawater) were determined as a function of temperature, pressure, and salinity based on heat and mass balance equation of each process at the given fixed conditions (i.e., feed condition, capacity, TBT, and so on). As a result, based on the techno-economic evaluation shown in Fig. 1, the TBT 85°C MED-TVC plant shows 27% lower LCOW compared to BR-CT MSF. Furthermore, compared with a conventional TBT 65°C MED-TVC unit, its steam consumption can be considerably reduced up to 34%, leading to up to 16% reduction in the view of LCOW. Therefore, it can be suggested that TBT 85°C MED-TVC is a financially competitive and technologically reliable option under challenging seawater characteristics.

Based on that techno-economic study, high TBT MED-TVC technology integration with CSP would be economically viable, as the solar field area is reduced due to reduction in steam consumption from the MED-TVC system.

2.2. MED system with higher TBTs

An increase in the TBT of the MED-TVC would allow an increase in the number of effects. Advantages manifest in the form of an increase in the system efficiency and a reduction in the OPEX (due to higher GOR) or a reduction in the capital cost (due to reduction in the heat transfer area).

For example, performance is highly dependent on compression and expansion ratio, suction effect and motive pressure. Fig. 2 shows different ideal cases with the same amount of steam and a fixed steam extraction point at

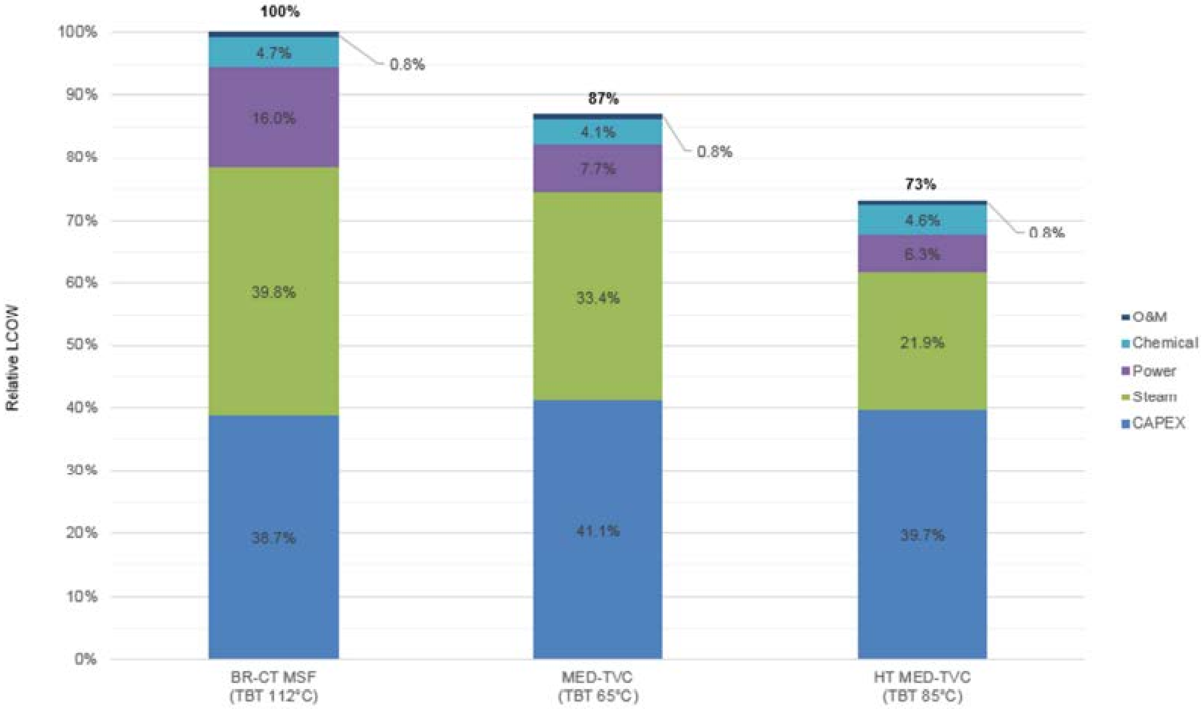
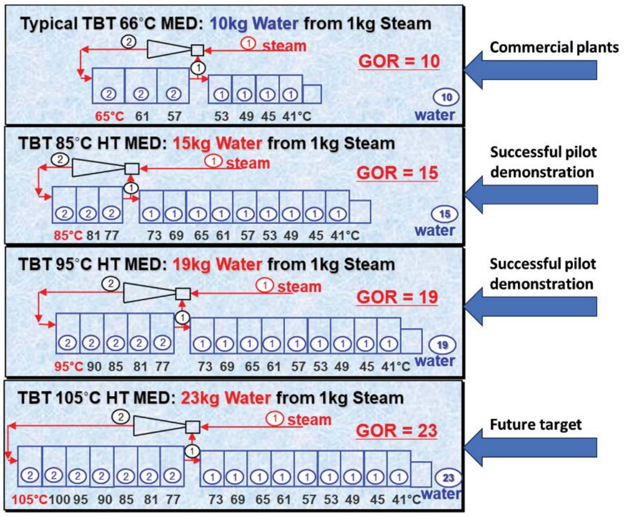


Fig. 1. Levelized cost of water (LCOW) comparison between BR-CT MSF, MED-TVC (TBT 65°C) and MED-TVC (TBT 85°C).



*GOR: Gain Output Ratio = Product water [kg]/ Steam consumed [kg]
**PR: Performance Ratio = Product water [kg] x 2,326 [kJ/kg] / Energy input by steam [kJ]

Fig. 2. Increase in the GOR with the same amount of steam (different heat transfer area is assumed).

77°C, with varying heat transfer coefficient in each case. Here we have assumed an entrainment ratio of 1. However, entrainment ratios up to 1.27 and more have been seen in commercial MED plants.

Assuming 1 kg steam as motive steam and 1 kg as steam extracted by TVC, a total of 2 kg steam would be directed to the first effect. By neglecting the losses, each kg of steam would produce 1 kg of vapor, each top effect (before the TVC) would produce 2 kg vapor and 1 kg after the TVC. Thus,

$$\begin{aligned}\text{GOR} &= \text{Number of top effects}\\ &\quad\times\left(1+\text{Extracted vapor to TVC}\right)\\ &\quad+\text{Number of bottom effects}\end{aligned}$$

Furthermore, an increase in the PR will also lead to lower CO_2 emissions, as lower amount of steam needed in the high PR scenario would lead to lower amount of fossil fuel being burnt. Fig. 3 shows the amount of CO_2 emissions that can be offset at Al-Wajh using a high PR energy efficient MED-TVC system. Combining the high PR MED-TVC system with CSP would further reduce CO_2 emissions and contribute to the decarbonisation of the desalination sector.

2.3. Proposed system, design philosophy and calculation procedure

Fig. 4 shows the interface and integration between the solar field and the MED-TVC system. The system includes a provision for thermal energy storage for 0–16 h for covering the cloudy period or non-solar hours during the diurnal cycle. There are three loops, one covering the solar field, the second one covers the steam transformer, and the third loop covers the MED-TVC system. Separation of loops is necessary to prevent contamination of water in the MED-TVC loop.

The thermal energy required to operate the MED-TVC plant is calculated using Eq. (1).

$$Q_s = \frac{m_d}{\text{PR}} \times \left(h_{si} - h_{so}\right) \tag{1}$$

where m_d is the total mass flow rate of distillate (kg/s), PR is the performance ratio, h_{si} (kJ/kg) and h_{so} (kJ/kg) are the

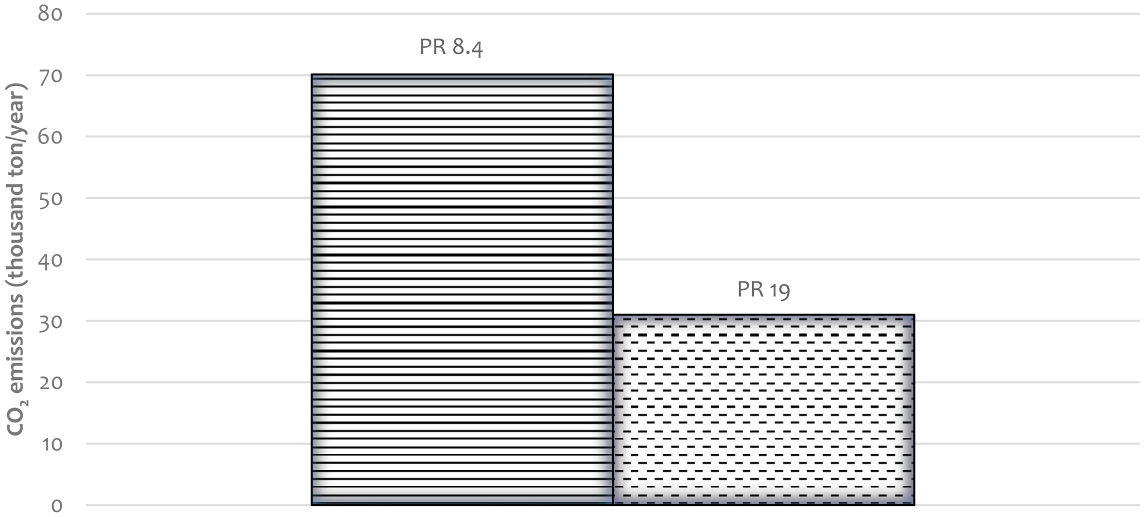


Fig. 3. Reduction in CO_2 emissions possible at Al-Wajh by adopting a high PR energy efficient MED-TVC system in comparison with the existing MED-TVC system.

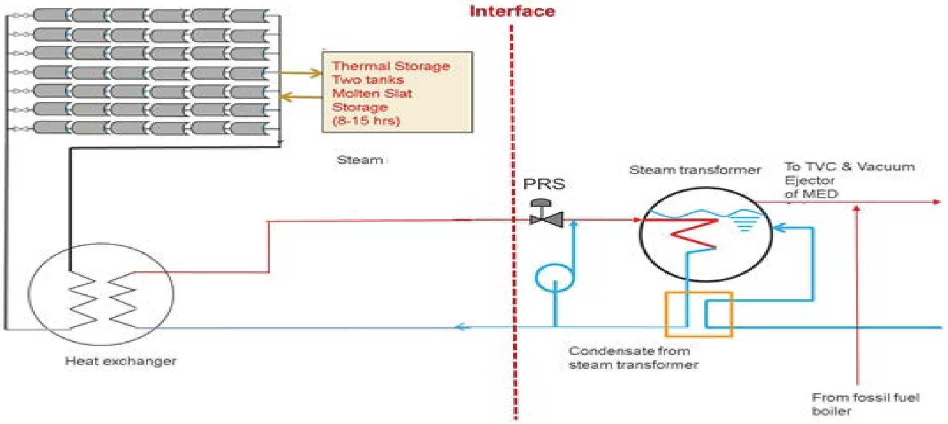


Fig. 4. Schematic diagram of the proposed system.

enthalpies of the steam coming in and the condensed steam going out of the MED-TVC system, respectively.

System advisor model (SAM) developed by the National Renewable Energy Laboratory (NREL), USA was used for assessing the solar field area and thermal energy output by the solar field. The gross output in SAM was adjusted until the thermal energy output matched the thermal energy required by MED-TVC. The thermal energy estimated by SAM was used in a software developed in-house using Microsoft Excel to estimate the techno-economics and the levelized cost of water (LCOW). The methodology used in the assessment of the CSP assisted MED-TVC system is shown in Fig. 5.

2.4. Site selection for study

The MED-TVC system at Al-Wajh on the West Coast of Saudi Arabia was chosen for study. It produces 8,400 m^3/d water with a GOR of 8.4. The solar radiation available is 2,450 $kWh/m^2/d$. More details about the plant can be found in [25]. The PRs that were considered in the analysis were 8.4, 12, 16, 20 and 24. These PRs were based on previous experimental and pilot studies at DTRI, SWCC in Jubail, KSA.

2.5. Techno-economic analysis

A techno-economic study was conducted to determine the levelized cost of water (LCOW) for the CSP assisted MED-TVC system and the apparent reduction in CO_2 emissions. All the data used in the techno-economic study was derived from the actual operation and maintenance data at SWCC's plants. Solar collector data is generated using pilot data.

The CAPEX of solar field was calculated based on the values given in Table 1. The total direct cost is a sum of the total cost of the solar field and the contingency cost, which is considered to be 7% of the cost of solar field. The total solar field cost is calculated as the sum of the total direct cost, and the EPC and owner cost, which is 11% of the total direct cost. The capital cost of solar system is calculated from following equations.

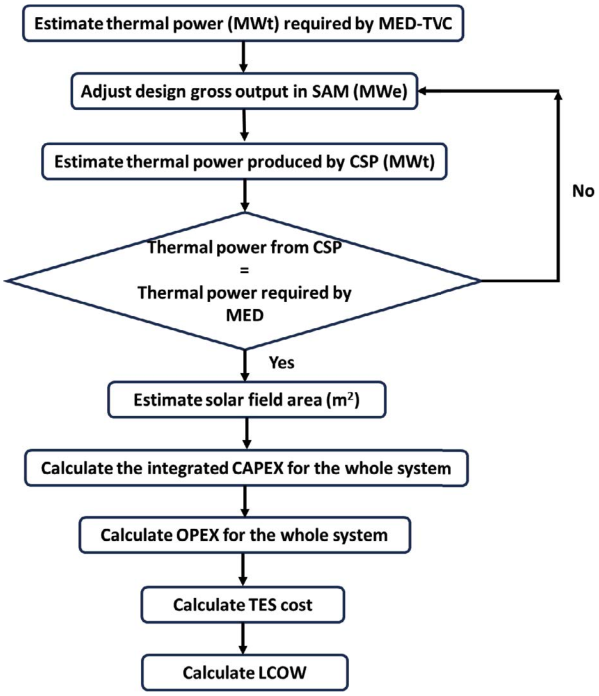


Fig. 5. Description of the calculation technique of the model.

Table 1
Costs used in solar field CAPEX calculation

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

$$\text{Totel direct cost} = \text{Totel cost of solar field} + \text{Contingency cost}\left(7\%\text{ of the cost of solar field}\right) \quad (2)$$

$$\text{Totel solar field cost} = \text{Totel direct cost} + \text{EPC and owner cost}\left(11\%\text{ of the totel direct cost}\right) \quad (3)$$

The capital cost of MED-TVC can be calculated as a unit cost equal to 1,542 $/m^3/d [26], and operation cost of MED-TVC equals 0.18 $/m^3/d including pumping cost [27]. Table 2 was used to calculate the OPEX of solar field.

The back up fossil fuel needed was calculated from energy required to fulfil production needs in terms of number of barrels. The number was then multiplied by the oil price which was varied from 10 to 100 $/bbl to calculate the specific fuel cost $/m^3.

The Levelized Cost of Water (LCOW) was calculated using the aforementioned information and the following methodology.

$$\begin{aligned}\text{Total CAPEX} = {} & \text{CAPEX of solar plant}\\ & + \text{APEX of MED-TVC system}\\ & + \text{CAPEX of boiler}\end{aligned}$$

Table 2
Operational cost of the solar field and storage

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

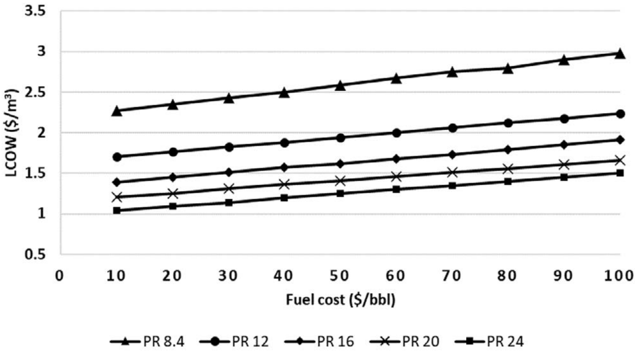


Fig. 6. Variation of LCOW with oil price at Al-Wajh for different PR and 16 h TES (full capacity powered by solar).

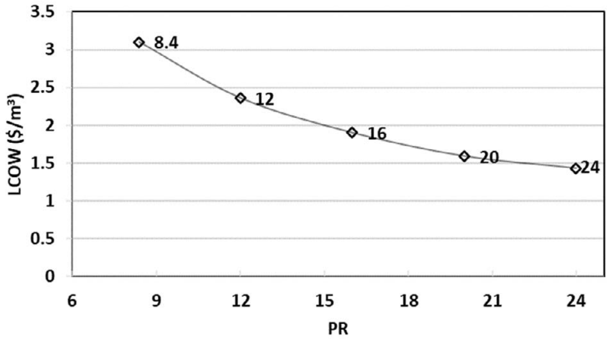


Fig. 7. LCOW variation at Al-Wajh with performance ratio for 0 h TES.

The LCOW was calculated using the following equation:

$$\text{LCOW} = \frac{\text{crf} \times \text{CAPEX} + \text{OPEX} + \text{Backup fuel cost}}{\text{Annual water production}} \quad (4)$$

The capital recovery factor (crf) is generally used to find out the uniform annual amount of CAPEX of a uniform series from the known present worth at a given interest rate *i* for a period *n*.

$$\text{crf} = \left(\frac{z\left(1+z\right)^n}{\left(1+z\right)^n - 1}\right) + k \quad (5)$$

where z is discount rate assumed as 0.05, n is amortization period assumed as 20 y, and k is yearly insurance assumed as 0.01.

3. Results and discussion

Fig. 6 shows the variation of the LCOW with the fossil fuel cost for different values of PR. Al-Wajh plant was

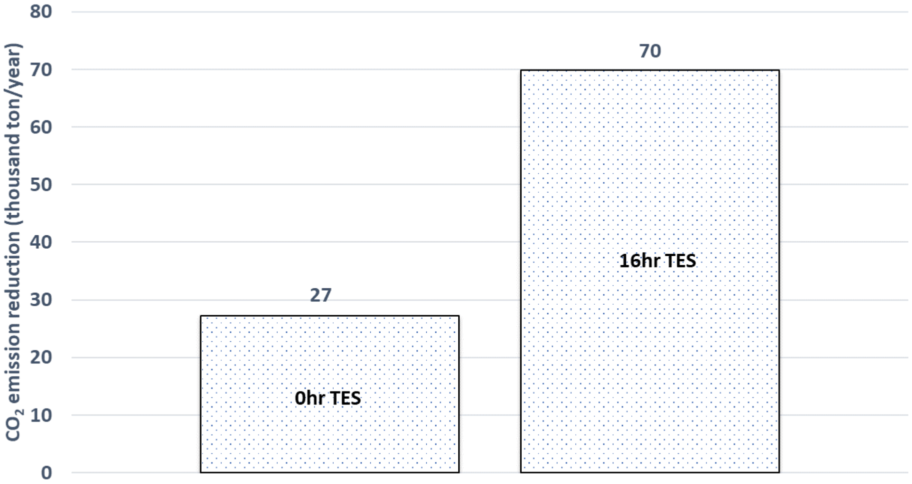


Fig. 8. Reduction in CO_2 emissions at 0 h TES and 16 h TES at Al-Wajh for a PR 8.4 MED-TVC system.

considered as the reference plant with 16 h of thermal energy storage (TES). As the PR increases, the LCOW decreases significantly.

Fig. 7 shows the reduction in LCOW with an increase in PR at unsubsidized fuel cost (60 \$/bbl) for the 0 h TES case. The LCOW decreased from around 3 \$/m^3 at PR 8.4 to less than 1.5 \$/m^3 at PR 24. The reason behind the decrease is that the plant working under high PR requires lower amount of energy (steam) and this is reflected in the solar collector area and the LCOW. Using 16 h storage is more feasible when the oil price is unsubsidized (60 \$/bbl). This indicates that coupling high energy consuming desalination plants with CSP is feasible.

Fig. 8 shows the CO_2 emissions that are offset using 0 and 16 h thermal energy storage (TES) at Al-Wajh. This indicates that higher TES leads to higher reduction in CO_2 emissions due to lowering of dependency on fossil fuel back-up system.

4. Conclusions

Techno-economic analysis of different combinations of CSP and MED-TVC was carried out for the MED-TVC plant at Al-Wajh located on the West coast of Saudi Arabia. The energy consumed by the MED-TVC was calculated using the information available from the plant, namely the plant capacity, performance ratio, temperatures and pressures. Based on the energy consumed, simulations were performed to couple the plant with LFR system to provide the required thermal energy to run the standalone MED-TVC system. System advisor model (SAM) was used to simulate the LFR CSP system with different TES capacities, that is, 0 and 16 h. The coupled system was simulated using an in-house Microsoft Excel program, with all the cases being compared with the existing conventional MED-TVC (run using fossil fuel) to find the breakeven cost at different fossil fuel prices. The main issue in the existing plant is that the fuel consumption is very high (14.3 kWh/m^3).

As per the results obtained, using LFR CSP system coupled with MED-TVC is feasible based on the Direct Normal Irradiation (DNI) and performance ratio of the plant. The average breakeven cost is 25 \$/bbl for the 0 h TES case. However, as 25 \$/bbl is not the actual international fuel price, 60 \$/bbl was also considered in the calculations.

An increase in the PR of the MED-TVC, which is possible with the adoption of high TBT MED-TVCs was considered for Al-Wajh. Higher PR values 12, 16, 20 and 24 were considered in the analysis apart from the current PR of Al-Wajh plant, which is 8.4. The results show that the LCOW decreases by more than 50% as the PR is increased. Using a TES of 16 h is more feasible than other cases when the LCOW is calculated based on an unsubsidized fuel cost of 60 \$/bbl. Using 0 h TES is more feasible when the fuel cost ranges between 25 and 40 \$/bbl. Furthermore, CO_2 emissions equivalent to 84,000 tons/y can be offset. The area required to power CSP MED-TVC at PR 8.4 for 8 h in this study is nearly identical to the area required for 16 h TES for PR 19.

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