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Techno economic feasibility analysis of Linear Fresnel solar field as thermal source of the MED/TVC desalination system

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HIGHLIGHTS

- A low part of thermal energy of MED/TVC is supported by LF field without TES.
- LF field with TES could support a large amount of MED/TVC thermal energy.
- The scenario of “two LF fields” increases the amount of thermal energy storage.
- Increasing the role of solar thermal energy increases the water production costs.
- 12-fold increase in the MED/TVC scales decreases the LCOW by about 180%.

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ABSTRACT

The application of Linear Fresnel (LF) solar field was technically and economically considered as the thermal source of a Multi Effect Desalination Thermal Vapor Compression (MED/TVC) system with a water production rate of 9000-m^3/day. The analysis was made on the five years radiation data of Kish Island, located in the Persian Gulf at south of the Iran. The water production costs were considered for three different configurations of the MED/TVC/LF desalination system to determine the required sizes of LF solar field, system costs and also amount of annual fuel savings. The results of the present study shown that the water production costs of the MED/TVC/LF system is obtained as a value between 1.63 \$/m^3 and 3.09 \$/m^3 for the systems without thermal storage and with thermal storage, respectively. The thermal storage system would increase the costs of the water production by about 42% and 65% for 6 h and 12 h of thermal storage, respectively. It was found that the water production cost of the MED/TVC/LF system with 67.77% contribution of solar energy and without the thermal storage system is high (3.32 \$/m^3) as compared to the conventional fossil fuel powered MED/Desalination plants with a water production cost of 1.26 \$/m^3.

1. Introduction

Three-fourths part of the Earth surface is covered by water, but the 97% is salt water. Hence, water scarcity is a remarkable problem in many part of the world. The regions with more fresh water shortage like Middle East and North Africa (MENA) countries, are those with high solar radiation. Several methods are used to produce the fresh water such as phase change thermal process techniques (Multi Effect Desalination (MED), Multi Stage Flash (MSF) and Reverse Osmosis (RO) membrane single phase process. The MED technique needs low energy consumption as compared to MSF. AS compare to the other desalination methods, the MED method has longer operation life, lower capital cost and requires less pumping power [1]. The MED plants are integrated into thermal power plants to produce fresh water and electricity by a cogeneration system [2–5]. The combination of Concentrating Solar Power (CSP) plants and MED desalination plants is one of the alternatives to produce fresh water using both MED and RO desalination systems. G. Iaquaniello et.al [6] have investigated the integration of CSP with MED and RO desalination systems. In that work, MED is powered by the low temperature exhaust steam delivered from the back pressure steam turbine while the RO is powered by the electricity produced by the same steam turbine in addition to that generated by a conventional gas turbine integrated as a thermal backup system. The economic results of that study demonstrated that the water production cost is decreased by about 8.8% by increasing the system life time from 20 years to 30 years. A thermo-economic analysis was made on solar power assisted MED/TVC and Mechanical Vapor Compressions MED/MVC systems by Sharaf et.al [7]. Two techniques were developed in that study; in one of which the solar thermal energy is directly used as the motive steam of the MED/TVC system. In the other technique, the power generation from the Solar Organic Rankine Cycle (SORC) is

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Nomenclature

A_{field} solar field aperture area (m^2)
$C_{CAPEX}(D)$ capital annualized direct costs, $
$C_{CAPEX}(ID)$ capital annualized indirect costs, $
C_{el} electricity costs, $
C_f fuel costs, $
C_{Ins} insurance costs, $
C_L labor costs, $
CRF capital recovery factor
C_{SP} spare parts replacement costs, $
CSP concentrating solar power plant
DNI Direct Normal Irradiation, (W/m^2)
DSG direct steam generation
GOR Gain Output Ratio
h_{in} enthalpy of the heat transfer fluid at the inlet (kJ/kg)
h_{out} enthalpy of the heat transfer fluid at the outlet (kJ/kg)
HTF Heat Transfer Fluid
IAM_t transversal incident angle modifier
IAM_L longitudinal incident angle modifier
i interest rate (%)
L receiver length, m
$LCOW$ levelized cost of water, $/m^3$
L_f focal distance, m
LF Linear Fresnel solar field
$LF1$ Linear Fresnel solar field of number 1
$LF2$ Linear Fresnel solar field of number 2
$\dot{m}$ heat transfer fluid mass flow rate, kg/s
N number of project Life time
n number of effects
NGB natural gas boiler
OT Once Through configuration
P_{ev} entrained vapor pressure (kPa)
P_s discharged vapor pressure (kPa)
Q specific heat consumption, kJ/kg
$Q_{absorbed}$ absorbed solar energy, W/m^2
Q_{hl_HTF} heat transfer fluid heat loss, W/m^2
$Q_{hl_{piping}}$ heat lost from solar field pipes, W/m^2
ϕ_L longitudinal angle, degree
Q_{LFR} solar field useful thermal output, W/m^2
Q_{in} incident thermal power, W/m^2
ϕ_T transversal angle, angle
Ra entertainment ratio
T_{amb} ambient temperature, °C
$TAWP$ total annual water production, m^3/yr
TES thermal energy storage
T_{in} temperature of the heat transfer fluid at the inlet, °C
V_w wind speed, m/s

Greek symbols

a_s sun elevation angle, degree
η_{opt} optical efficiency
$\eta_{endloss}$ end loss efficiency
θ_i the angle of incidence, degree
θ_z Zenith angle, degree
γ_s Azimuth angle, degree

used to power on the vapor compressor of the MED/MVC process. The both techniques were considered to produce the amount of 4545 m^3 water per day. The results of that study shown that the water production costs of the MED/TVC and MED/MVC systems are about 1.5 $/m^3 and 2.1 $/m^3, respectively. In another research Sharaf et.al [8] considered different configuration of MED systems without the TVC part to produce 100 m^3 of fresh water per day. In that work also two techniques were investigated. In the first one, the solar output thermal energy is directly utilized to the first effect of the MED process via evaporator of a heat exchanger. In the second technique, the exhausted energy from the organic Rankine cycle (ORC) turbine is used in the first effect of the MED process. The water production cost for the first technique were obtained as 5.47 $/m^3 for parallel feed MED, 12.87 $/m^3 for forward feed MED and 7.13 $/m^3 for backward feed configuration of MED process. The other technique was shown to have the higher costs of 13.75 $/m^3 and 8.31 $/m^3 for forward feed and backward feed configurations, respectively. However, the parallel feed configuration of the second technique was obtained as lower than the first technique by water production cost of 5.05 $/m^3. They have also applied their two techniques for the parallel feed MED configuration with water production capacity of 5000 m^3/day. As the result, the water production costs for the first and second techniques were obtained as 1.62 $/m^3 and 1.87 $/m^3, respectively. Different combinations of desalination techniques integrated into the solar power (CSP) plant were considered by Palenzuela et.al [9]. In that research the low-temperature (LT-MED) plant was considered to feed by the steam at the outlet of the turbine replacing the condenser of the Parabolic Trough (PT) solar power cycle. The described system was compared with the combination of CSP with a RO plant. Also, a novel configuration of MED/TVC system was considered in which the exhaust steam of the CSP plant is used as entrained vapor and steam extracted from the turbine is utilized as the motive vapor of the TVC ejector. In that research, the water production rate and the electricity generation of the CSP plant were considered as 36,000 m^3/day and 55 MWe, respectively. The results of that research shown that for the solar thermal energy contribution of 54%, the water production costs would be 0.91 $/m^3 and 1 $/m^3 for LT-MED (and LT-MED/TVC) and RO configurations, respectively. In the economic calculations of that research, the unit costs of solar land improvement, solar field, Heat Transfer Fluid (HTF), and thermal storage system were considered as 15 $/m^3, 150 $/m^3, 90 $/m^3 and 35 $/kWht, respectively. A techno economic analysis was made on two different configurations of hybrid MED/RO and single RO desalination units powered by two different thermal sources (conventional steam plants and concentrating solar power plants) and under different fuel price scenarios by Moser et.al [10]. The results of that study revealed that the water production cost for hybrid MED/RO (with 12 effects of MED) and single RO units are 0.85 $/m^3 and 0.8 $/m^3, respectively, for the fuel price scenario of 0.8 $/barrel, when the thermal source of the desalination units is supported by the conventional power plant. Also, for the desalination units powered with solar power plants, the water production costs were obtained as 1.22 $/m^3 and 1.10 $/m^3 for the hybrid MED/RO (with 12 effects of MED) and single RO units, respectively. Table 1 shows the cost and water production capacity specifications of the described CSP/MED/RO desalination systems.

Most of the previous studies on the MED desalination systems considered the influence of different physical characteristics and internal operational conditions of desalination system on its performance. There is no considerable number of research works that deal with the integration of MED desalination systems with Linear Fresnel solar field. In all of the reference articles [1–10], the Parabolic Trough (PT) solar collectors are used as the thermal source of the desalination systems. Most of the previous researches considered the hybrid MED/RO desalination systems in which the MED desalination unit works as the condenser of the solar power plants. The application of Liner Fresnel (LF) solar fields as the thermal source of the MED desalination process has not been reported in the previous research studies. Because the fixed receiver of LF solar field includes a simple piping system without moving junctions, water could be used as Heat Transfer Fluid (HTF) and operate under high temperatures. The output water steam generation from the LF field could be directly utilized as the motive steam of the MED/TVC desalination system. As compare to the PT solar field the LF field can use cheaper flat glass mirrors and lighter metal support structure so that the assembly process of LF field is more simplified and its production costs are low as compare to PT solar field. The tight spacing and ground location of the mirrors and fixed receiver entail