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Energy, exergy and exergo-economic analysis of different water desalination technologies powered by Linear Fresnel solar field

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ABSTRACT

The integration of Multi Effect Desalination (MED) unit with and without Thermal Vapor Compression (TVC) system into the Linear Fresnel Rankine Cycle (LFRC) was investigated for different seawater temperatures when it is located at the regions with different solar radiation levels. A comparison was made between the fresh water costs of the dual purpose LFRC/MED (or LFRC/MED/TVC) plants and the case when the MED and MED/TVC systems use direct steam of the LF solar field to produce fresh water (LF/MED & LF/MED/TVC). The water production costs of the described dual purpose plants were compared with that of the LFRC/Reverse Osmosis (RO) plant (LFRC/RO). An exergo-economic analysis was performed to determine the water unit costs of the plants. The results show that the fresh water costs of the LF/MED and LF/MED/TVC configurations are higher than that of the dual purpose plants. Also, it was shown that the fresh water cost is more affected by solar radiation level rather than seawater temperature of a region. It was also found that at fuel prices of 0.23\$/m^3, the water production costs of fuel based dual purpose plants would be equal to that of the plants with solar thermal source.

1. Introduction

Most of the power plants that are located next to the sea use Once-Through (OT) cooling method by running a large amount of water through the condenser in a single pass and discharging it back into the sea. In these cases, the efficiency of the plants is depended on the sea water temperature. The integrating of the Multi Effect Desalination (MED) unit to the steam power plants are one of the alternatives to produce water and electricity. The water production rate and efficiency of dual purpose (electricity/water) plants are highly depended on the seawater temperature. The higher seawater temperatures results in higher required heat transfer areas of the MED desalination unit to produce specific amount of fresh water [1]. More than half of Iran's international border of 4430 km is coastline, including 740 km along the Caspian Sea in the north and 1700 km along the Persian Gulf and adjacent Gulf of Oman in the south (Fig. 1). Iran has started to decrease the fuel price subsidy and therefor the application of renewable energy technologies have been received great attention during the recent years by Iran government. Due attention to high annual Direct Normal Irradiance (DNI), especially in south of Iran, solar energy appears as the most appropriate technology to be used as thermal source of the power plants to reduce the fossil fuel consumptions in Iran. MED and RO technologies are two major desalination technologies that are used in Iran. Please refer to [2] to find the water desalination technologies and capacities that have been installed in Iran until 2014. Among all desalination plants in Iran, Qeshm water-power cogenerating is the only dual purpose plant that utilizes the waste heat of a gas turbine to produce the fresh water in a MED system with water production rate of 18,000 m^3/day.

Several research works have been conducted on MED and MED/TVC performances under different operational conditions [3–11]. The integration of MED and MED/TVC units with solar Rankine cycles (SRC) plants was investigated by Fiorenza et al. [12]. In that research, MED and RO desalination systems with different capacities were considered to be powered by Photovoltaic panels and solar thermal power plants, respectively. The water production costs of the PV/RO and SRC/MED plants were determined as 2.05\$/m^3 and 2\$/m^3, respectively. The application of SRC/MED and SRC/RO plants for the Persian Gulf, Mediterranean Sea and Red sea were investigated by Fichtner and DLR [13]. The water and electricity costs of two dual purpose plants were found to range from 1.8\$/m^3 to 2.1\$/m^3 and 0.21\$/kWh to 0.24\$/kWh, respectively. Sharaf et al. [14] investigated two techniques for

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Nomenclature

BPE	Boiling Point Elevation
C_{CAPEX}	capital annualized direct costs, $
COE	cost of electricity, $/kWh
COW	cost of water, $/m^3$
CRF	capital recovery factor
C_r	compression ratio
CSP	concentrating solar power plant
DNI	Direct Normal Irradiation (W/m^2)
D_r	entrained vapor mass flow rate (kg/s)
D_s	motive steam mass flow rate (kg/s)
DSG	direct steam generation
GOR	Gain Output Ratio
i	interest rate (%)
LF	Linear Fresnel solar field
MED	Multi Effect Desalination
$\dot{m}$	mass flow rate, kg/s
N	number of project life time, year
NEA	non-equilibrium allowance
NGB	natural gas boiler
PB	power block
P_d	discharge vapor pressure (kPa)
P_r	entrained vapor pressure (kPa)
P_s	motive steam pressure (kPa)
PTC	Parabolic Trough Collector
Q	specific heat consumption, kJ/kg
Ra	entertainment ratio
RC	Rankine cycle
RO	Reverse Osmosis
SA	specific area of MED evaporators (m^2/kg/s of D)
S_{Mcw}	ratio of distillate to cooling seawater mass flow rate
T_C	condenser temperature (°C)
T_f	temperature of feed seawater (°C)
TVC	Thermal Vapor Compression
T_{SW}	seawater temperature (°C)
T_{MS}	motive steam temperature (°C)

desalination. In one technic the direct steam of the solar field was used to feed a MED/TVC unit. In another technique the electricity generated from the SRC plant was considered to be used as the power source of an MED unit with Mechanical Vapor Compression (MVC) system. The water production costs of the first and second techniques were found to be as 1.5$/m^3 and 2.1$/m^3, respectively. The integration of MED and RO units with SRC plants was investigated by Iaquaniello et al. [15]. The authors considered a case in which the low pressure output steam of the plant is used as thermal source of the MED unit. Also, the RO unit was assumed to be fed by the electricity generated from the SRC plant. That research has shown that increasing the lifetime of the described systems from 20 years to 30 years would result in decreasing the water production cost by about 8.8%. Moser et al. [16] investigated two desalination systems of RO and MED/RO powered by the fuel based and solar based steam plants. Different fuel price scenarios were used in the economical calculations of that research. The results of that study shown that the water production cost of the RO and RO/MED systems with fuel based steam power plants would be 0.85$/m^3 and 0.80$/m^3,respectively. However, for the solar based power plants the water production cost were determined to be 1.22$/m^3 and 1.1$/m^3 for RO and RO/MED systems, respectively. Different combinations of the RO, MED and MED/TVC systems with SRCs were investigated by Palenzuela et al. [17]. In that research, the SRCs were assumed to cool down by three cooling methods of dry, wet and once through. The results of that work shown that only for high salinities of seawater and high cooling temperatures of the SRC condenser, the SRC/MED has lower water production costs as compared to the SRC/RO plant. The integration of a MED/TVC unit with SRC plant was studied by Delgado et al. [18]. The output steam of high pressure and low pressure steam turbines (4540 kPa and 362 kPa, respectively) of SRC plant were considered to be used as the motive steam of the MED/TVC unit. The fresh water production rate of 10,000 m^3/day with sweater temperature of 26 °C was considered in that research. The integration of the MED/TVC unit with different water production rates into a fuel based steam Rankine cycle was studied by Tamburini et al. [19]. The steam extracted from the steam turbines of the plant at different suction pressures were considered to feed the MED/TVC unit. The results of that study revealed that the efficiency of the plant (38%) would be decreased to 21% when the high pressure steam of the 4880 kPa is extracted from the high pressure turbine of the plant to produce 36,000 m^3/day of fresh water in the MED/TVC unit. A comparison between the Parabolic Trough Collector (PTC) base and LF base dual purpose SRC plants was conducted by the authors of the present study [20]. The results of that work shown that the water and electricity production costs of the LF/MED plant is approximately 10% and 25% lower than that of the PTC/MED plant. Also, it was shown that because of the higher thermal efficiency of the PTC solar field as compared to the LF, the electricity and water production costs of both plants would be equal, if the capital cost of the PTC solar field would be decreased to 66% of its first cost assumption (420$/m^2). In another research, the authors of the present paper investigated the application of the LF solar field direct steam as the heat source of the MED/TVC [21]. The results of that paper shown that the water production costs of the LF/MED/TVC system varies between 1.63$/m^3 to 3.03$/m^3 for the cases with no Thermal Storage System (TES) and 15 h of TES, respectively. The energy and exergy analysis of a polygeneration system was performed by one of the authors of the present paper (Calise et al. [22]). The described system includes Concentrated Photovoltaic Thermal (CPT), biogas heater, absorption chiller and an MED unit. An exergo-economic analysis was used in that work to determine the fresh water, electricity, heating and cooling costs of the so-called system. In another research by Calise et al. [23], a polygeneration system comprising geothermal well, PTC, Organic Rankine Cycle (ORC), MED and absorption chiller was investigated to determine the water, electricity, cooling and heating energy costs of the system. An exergo economic model was used in that research work to determine the production costs of different products of the system. In that work, the cumulative exergy analysis of the plant for two periods during the cold and hot seasons was applied instead of the instantaneous exergy analysis.

As it can be seed from the literature review, there are valuable research works that address the integration of MED and RO systems with SRC plants. However, to the best of our knowledge, the water production costs of dual purpose SRC/MED, SRC/MED/TVC and SRC/RO plants have not been reported to be compared with that of the MED and MED/TVC plants feed by direct steam of the solar field. Also, the detailed investigation on the integration of MED/TVC unit into the SRC plants has not been vastly investigated. Only in two references of [18,19] the detailed analysis of SRC/MED/TVC plants were reported. As it has been shown in [18], the described plant was considered at a specific seawater temperature and for a specific water production rate. Also in [19], a fuel based Rankine cycle was considered and the GOR of the MED/TVC plant was assumed to be constant for a specific seawater temperature. However, the seawater temperature has an important effect on the GOR of the MED/TVC plant and consequently on the water production cost of the plant. In the present paper, three different seawater temperatures corresponding to the Mediterranean Sea, North Australia coastlines and Persian Gulf seawater temperatures were considered in the calculations of the MED and MED/TVC plants. No