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Concentrating solar power for seawater thermal desalination☆

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HIGHLIGHTS

- Operational performance of Fresnel concentrating solar power (CSP) system.
- Cost effectiveness of a commercial solar assisted thermal desalination plant
- Impact of DNI, thermal energy storage and fuel cost on the feasibility of CSP assisted thermal desalination plant.

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ABSTRACT

Extensive pilot plant experimental studies for a period of one year were carried out to study the impact of climatic conditions on the operational performance of an innovative Fresnel solar collecting system. The solar measurements revealed that the total yearly Direct Normal Irradiance (DNI) on the tested site amounts to 1132 kWh/m^2. The thermal collector efficiency, which depends on climatic conditions such as solar insolation, ambient temperature, receiver temperature as well as heat losses, ranges from 60% to 80%. The cost effectiveness when the tested Fresnel solar collection system with solar multiple of 1.0 (limited to day time operation) is combined with a commercial thermal desalination plant is compared with one completely run by fossil fuel. The breakeven fuel cost whereby the levelized cost of water of the two cases will be equal is yielded at a fuel cost of $92/bbl. When the tested Fresnel solar collection system is run at a location with a relatively high annual DNI level (1937 kWh/m^2), the fuel breakeven cost falls to $52/bbl. This study also revealed that combining a Fresnel solar collection system with an MED thermal desalination plant under specific climatic conditions is considered more cost effective when operated without thermal energy storage.

1. Introduction

The Saline Water Conversion Corporation (SWCC) of Saudi Arabia is currently operating small scale single purpose thermal desalination plants with water production capacities ranging from 250 to 9000 m^3/day. One of the major problems that impede the cost effectiveness of a single purpose thermal desalination plant is its high fuel energy consumption. Techno-economic feasibility of small scale MSF or MED thermal desalination plants driven directly by boilers can be greatly enhanced when solar energy is employed to provide all or part of the thermal energy consumption.

A solar distillation plant may consist of one integrated system (direct solar desalination) or two separate devices, the solar collector/accumulator and distiller (indirect solar desalination). Direct use of solar energy is through the direct heating of salty water by the sun through conventional solar stills for low water production [1]. Another example of direct use of solar energy is achieved by combination of the principle of humidification-dehumidification with solar desalination using air as a heat carrier [2,3]. For relatively large water production capacities, the solar energy is indirectly used to drive thermal desalination plants by capturing solar radiation through one of the modern technologies which transform the solar energy into heat using means such as parabolic trough and linear Fresnel collectors, evacuated tube collectors and salinity gradient solar ponds [4–20]. Concentrated solar power (CSP) technology stores the energy from solar radiation in a working fluid in the form of heat. This heat can then be used directly to run a conventional thermal desalination multistage flash ((MSF), multi-effect distillation (MED), multi-effect distillation with thermal vapor compression (MED/TVC) plant. The thermal energy can alternatively be converted into electrical energy through a conventional power generation

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Nomenclature

A	total collector aperture area (m^2)
ATAN	inverse tangent value
CAPEX	total capital expenditure of solar field ($)
COSIθdI	cosine absolute value of sun's direction angle
Cp	specific heat (kJ/(kg °C))
CRF	capital recovery factor
DNI	direct normal irradiation (kW m^{-2})
DNI_{eff}	actual or effective received irradiation (kW/m^2)
ΔT	oil temperature rise (°C)
K_∥(Θ_∥)	longitudinal correction factor
K_⊥(Θ_⊥)	transversal correction factor
LCOW	levelized cost of water ($/$m^3$)
n	amortization period (years)
OPEX	total annual operational and maintenance expenditure ($)
P_{loss}	heat loss from receiver per unit length (W/m)
P_{th}	net (useful) thermal energy absorbed by the receiver (kW)
q	oil volumetric flow rate (m^3/s)
SINIθdI	sine absolute value of sun's direction angle
T_{abs}	average of inlet and outlet temperature of heat transfer fluid (°C)
TAN	tangent value
W_c	MED annual water production (m^3/year)
Z	discount rate (%)
η_0	optical efficiency at zero
η_{sy}	overall solar system efficiency (%)
η_{th}	thermal efficiency (%)
Θa	sun's measured height angle (°)
θd	sun's direction angle (°)
θII	sun irradiation longitudinal angle (°)
θL	sun irradiation transversal angle (°)
Π	numerical value of PI (3.142)
ϱ	density (kg/m^3)

plant and can then be used to run a reverse osmosis (RO), electrodialysis (ED) or mechanical vapor compression (MVC) desalination plant.

CSP collectors developed and tested so far can be broadly divided into two categories: Line focus collectors and point focus collectors [21]. Line focus collectors include both the parabolic trough (PT) and Linear Fresnel (LF) types which use a single axis tracking system and can yield moderate temperatures up to 400 °C, while point focus collectors include parabolic dish and central receiver collectors with dual-axis tracking systems generating temperatures as high as 1000 °C or more. CSP technology offers two main advantages [21]. First, all CSP technologies can be combined with thermal energy storage systems. Second, CSP plants can be operated with fossil fuel backup (hybrid operation). The use of thermal energy storage systems and/or hybrid operation provides the possibility of continuous 24 h operation of solar assisted desalination plants.

A number of studies have been reported comparing between parabolic trough and linear Fresnel applications [22–32]. Lined focused parabolic and linear Fresnel solar concentrators [22] both consist of a long reflector, which act as the only concentrator aligned on a north–south axis. One advantage of these systems is the tracking which is primarily only in one dimension. The reflector is rotated to track the sun's movement and it's reflected solar energy is concentrated along a focal line and captured by receiver tube containing a heat absorbing fluid that absorbs the concentrated heat. One-axis solar concentration provides a simple operation and highly reliable system to reach maximum operation temperatures about 400 °C. Normally, medium concentration ratios between 15 and 40 are attainable; therefore, one-axis sun tracking is required [23]. Synthetic oils are used as heat transfer fluid in conventional solar PT collectors, which limits the top temperature. Nevertheless, the synthetic oil may be replaced by water in order to generate steam directly into the absorber pipe and temperatures up to 400 °C may be allowed. Direct steam generation (DSG) offers the potential for higher performance of the plants and for cost reduction [24]. Parabolic trough collector (PTC) using DSG has identical collector structures as for thermal oil. On the other hand, linear Fresnel collectors (LFC) with DSG use a potentially cheaper design mainly due to the use of flat mirrors and structural advantages, however with a lower optical efficiency. DSG avoids the costs of heat transfer fluid and the central oil heated steam generator. The DSG system is not without its technical challenges, with the risk of overheating tubes and potential flow instabilities [25]. Sophisticated controls are required to accommodate the use of the two-phase flow of water and steam.

Compared with parabolic troughs, linear Fresnel collectors suffer from lower optical efficiency [26]. However, the low-profile setting of the linear Fresnel collector poses no mechanical difficulty to maximize the collector geometrical concentration ratio (the ratio of mirror aperture to receiver aperture), which enables high temperature output. The high temperature output would give rise to high power cycle efficiency and accordingly a great reduction of storage system cost. The low-profile setting of the mirrors also leads to a lower wind load requirement and thus lower-cost mirror assembly design. Further, it will also help in lowering the O&M cost for a power plant. The fixed receiver assembly greatly reduces the risk of heat transfer fluid (HTF) leakage and the resulting maintenance labor. A comparison has been made between the optical performance of parabolic trough collectors and linear Fresnel reflectors using multi-tube receivers and secondary [27]. The results reveal that PTC efficiency is higher than the efficiency of LFCs, either with multi-tube or secondary reflector receiver. This was due to the fact that PTCs conform a perfect parabola with its aperture perpendicular to the impinging beam, in the transversal plane, at all moments. However, LFC are characterized by a simpler configuration: narrower mirrors, and thus lighter structure, fixed receiver, and leakages avoidance. Comparison of the annual performance and economic feasibility of Integrated Solar Combined Cycles (ISCC) using two solar concentration technologies: parabolic trough collectors and linear Fresnel reflectors, is reported [28]. Results show that the thermal contribution is higher with PTC, but LFR may improve the economic feasibility of the plant.

Existing commercial CSP plants are mainly used for electricity generation rather than water production. The National Renewable Energy Laboratory (NREL) [33], has compiled data on concentrating solar power (CSP) projects around the world that are either under operational, construction, or development stage. CSP technologies include parabolic trough, linear Fresnel reflector, power tower, and dish/engine. The majority of solar assisted power generation plants are using parabolic trough collectors with planned electricity generation per plant in the range 1800 to 175,000 MWh/year and are equipped with thermal storage system of molten salt (60% sodium nitrate, 40% potassium nitrate). There are seven operational solar power projects which are employing Fresnel solar collectors with plant generated electricity in the range of 2000 to 280,000 MWh/year and the majority of which are without storage. Around 24 concentrating solar power (CSP) projects that are either operating or under construction use power tower systems and molten salt for storage. Only one CSP project is under construction that uses dish/engine systems with at turbine capacity of 1 MW and without storage system.

A number of parabolic collector desalination demonstration plants have been implemented and tested [6]. At the plataforma Solar de Almeria, Spain, a parabolic trough collector field was connected to an MED plant with a water thermal storage system. At the second phase of the project, a double-effect absorption heat pump was coupled with the solar desalination plant. Subsequently, the thermal energy