Energy Conversion and Management 119 (2016) 203–214

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Techno-economic performance of concentrating solar power plants under the climatic conditions of the southern region of Tunisia

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ARTICLE INFO

Article history:
Received 8 February 2016
Received in revised form 31 March 2016
Accepted 9 April 2016
Available online 19 April 2016

Keywords:
Concentrating solar power (CSP)
Dry cooling system
SAM software
Levelized costs of electricity (LCOE)

ABSTRACT

This work aims to study the performance of deploying concentrated solar power (CSP) parabolic trough plants under the climatic conditions of the southern region of Tunisia "Tataouine", taking into account the consideration of the limited water availability in such desert regions. The ground meteorological data from the high precision enerMENA station; which are installed in Tataouine are used in the simulations runs. The reference solar power plant is based on parabolic trough concentrating technology and has (50 MW_e) power capacity and (7.5) hours of storage at full load. The results of the simulations are validated by the published data of the reference plant "Andasol Type", and are compared to each other. In a following step, an examination of the influence of meteorological parameters on the performances of the concentrating solar power plant for both the dry and wet cooling options is carried out. Finally, a comparative study of the power plants in study region for both economic and technical performance of the two simulated cooling options is done and compared with the reference power plant "Andasol-1" in Spain. The technical simulations show excellent results regarding the dry cooled CSP power plants and it will be taken into consideration in the future planning of new projects by cause of high DNI specifically at the study and generally in the desert region. Thus if the Andasol-1 CSP plant in southern Spain is shifted to Tataouine in southern Tunisia, and its wet cooling system is replaced with a dry one, it will have a competitive electricity output with a difference that does not exceed (9%), also water consumption will be reduced by (93.3%), and the levelized cost of electricity will be lower by (1.45%) in terms of 18.28 c€/kW h_e.

1. Introduction

The Tunisian energy market offers potential in a very favorable environment for the implementation of the concentrating solar power (CSP) and other renewable energy CSP technologies have relatively good conversion efficiency from solar radiation to electrical and thermal energy. This component has presented a considerable achievement possibility in its implementation in Tunisia and particularly in the region of Tataouine. The choice of this region in the south of Tunisia was explained by the important solar radiation direct normal irradiation (DNI). Recent studies ([1–3]) show that the south of Tunisia presents one of the most suitable attractive regions for the implementation of solar energy technologies, by having solar radiations levels above those of other regions, where CSP plants are commercially installed like in Spain. The parabolic trough presents a recent technology for the production of the electrical and thermal energy using the solar concentration which is in fact; these universal components presented are considered the most dominant market in the world. The parabolic trough presents (76.6%) of the whole market, compared with other types of conversions of the solar energy [3]. In the recent study (e.g., [4–15]), we estimated that, the parabolic trough power plants will continue to dominate the market and remain the dominant technology comparing to towers and linear Fresnel technology. Concentrated solar power technology has presented major innovative issues and applicability to West African countries as explained in [5]. A review of concentrating solar power plants in the world and their potential has been improved in [6–10]. The electrical power production by the CSP is studied in [6,7,10]. The economic and reliability benefits of CSP with thermal energy storage are explained in [8,13]. The performance and economic value of multiple concentrating solar power technologies in a production cost

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http://dx.doi.org/10.1016/j.enconman.2016.04.033
0196-8904/

Nomenclature

$A_{aperture}$	net aperture area (m^2)
A_C	the collector area (m^2)
ConcRat	the concentration ratio (kg/h)
DNI	direct normal irradiation (W/m^2)
E_{eff}	annual overall efficiency (%)
$F_R(\tau\alpha)_n$	the efficiency with solar radiation is absorbed by the plate and removed by fluid flowing through the collector (–)
I_{beam}	the amount of beam solar radiation incident on the collector surface (kJ/hm^2)
I_t	the amount of solar radiation incident on the plane of the collector surface (kJ/hm^2)
IAM	the incidence angle modifier (0.1)
LCOE	levelized cost of electricity (c€/kW h_e)
$\dot{m}_{fluid}$	the mass flow rate of fluid (kg/h)
$N_{parallel}$	the number of series collector strings in parallel (–)
N_{series}	the number of collectors in series (–)
Q_{dump}	dumped solar heat (kJ/h)
Q_u	thermal power output of the solar field (kJ/h)
R_1 and R_2	tow constant modifiers (–)
T_{amb}	the ambient temperature (°C)
T_{in}	the temperature of fluid entering the collector array (°C)
T_{max}	the maximum temperature at which fluid may exit the collector array (°C)
T_{out}	the temperature of fluid exiting the collector array (°C)
ΔT	a temperature difference (°C)
η_{col}	the collector efficiency (%)
$\eta_{overall}$	the overall efficiency (%)

Subscripts and abbreviations

ET	euro trough
HCE	heat collector element
HTF	heat transfer fluid
MENA	North Africa and the Middle East
O & M	operation and maintenance
SAM	solar advisor model

model is evaluated in [9]. A comparison of different solar energy technologies is effected in [11,12]. A comprehensive thermo-mathematical analysis to analyze the performance characteristics of a parabolic trough solar under different operating conditions have been demonstrated and validated in [14]. The potential of direct solar irradiance and the performance of solar parabolic trough collector are estimated by Ouagued et al. in [15] and Balghouthi et al. in [3]. A computer program based on one dimensional implicit finite difference method, with energy balance approach has been developed by Marif et al. in [16] in order to determine the optical and thermal performances of a solar parabolic trough collector under the climate conditions of Algeria. In [17–19], the authors have presented a review of available methods for surface shape measurement of solar concentrator. They have given a detailed description of the very used techniques; the photogrammetry and the deflectometry. The most studied measurement technique was the photogrammetry, which is a method based on photographic processes and it is widely used for the 3-dimensional measurement of objects. The use of photogrammetry for the parabolic trough collector shapes' evaluations is performed in [20–23]. The technical feasibility and the economic viability of a solar thermal power plant using parabolic trough collectors are developed by Bakos and Petroglou [24]. Kalogirou [25,26] described the various types of solar thermal collectors and applications and compared the advantages and the disadvantages of concentrating collectors against conventional flat plate collectors. An energetic–economic assessment of a solar parabolic trough power plant for four typical sites in Algeria; (i) the economic feasibility of a parabolic trough solar thermal plant with the wet cooling option for power generation in the Mediterranean region, (ii) are presented in [27,28]. The technical developments of parabolic trough solar power plant with the wet cooling option and with molten salt such as heat transfer fluid (HTF) are presented, and the potential of using this HTF to reduce LCOE are discussed by Ruegamer et al. [29].

The Middle East and North Africa (MENA) regions are considered to be among the regions that benefit from the highest DNI values worldwide [30]. The MENA deserts represent favorable sites for commercial CSP implementation. However, these deserts suffer from dry and arid conditions, where water is scarce and expensive or the cost of transporting water to these sites is prohibitive. Since the wet cooling of condensed steam requires high water consumption, it brings significant extra costs [31]. Yet still, the thermodynamic laws state that the wet cooling is advantageous over the dry cooling as the steam coming out of the turbine is cooled faster and to a lower temperature with the wet cooling system [32]. The performance analysis of dry cooled thermal power cycles has been reported in the literature for a wide range of operation conditions. Liqreina and Qoaider [33] examined the impacts of the steam cooling system on the performance of parabolic trough plant. Recent studies have shown that dry cooling plant can help save water consumption compared to the wet cooling plant. Qoaider and Liqreina [34] analyzed the economics of parabolic trough CSP plants with two cooling options using a simulation software for a CSP plants. The results has shown that plants with large solar field and large thermal energy storage systems perform better and can generate power at lower costs than smaller plants in desert regions. Moser et al. [35] have analyzed the impact of dry cooling systems on technical and economic plant performances, considering several condenser layouts, different operation strategies, and economic boundary conditions. The analysis was carried out for three chosen sites with real meteorological data by means of annual simulations with hourly time steps. Zeyghami and Khalili [36] have studied the performance improvement of advanced supercritical carbon dioxide power cycles under the dry cooling conditions coupled with daytime radiative cooling. The objective is to find out the required radiative cooler area at different working conditions in order to compensate the adverse effect of dry cooling system on cycle efficiency. Furthermore, in an attempt to compensate the performance penalties associated with dry cooling, several approaches have been advanced such as the hybrid dry–wet cooling systems. Several researchers have investigated the performance of thermal power stations using hybrid wet–dry cooling systems such as Wagner and Kutscher [37] and Barigozzi et al. [38].

This present study deals with an interesting case of concentrating solar power for the production of the thermal and electrical energy. This work reveals the impact of the steam cooling system on the performance of parabolic trough plant. The current study shows that the dry cooling plant can save over (90%) of water consumption compared to the wet cooling plant, and the high solar irradiation can compensate for the efficiency losses caused by replacing wet cooling by dry cooling systems. This will be realized