Energy Conversion and Management 111 (2016) 271–278

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Effects of the selection of heat transfer fluid and condenser type on the performance of a solar thermal power plant with technoeconomic approach

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A R T I C L E I N F O

Article history:
Received 26 August 2015
Accepted 24 December 2015
Available online 8 January 2016

Keywords:
Parabolic trough
CSP
Levelized cost
Heat transfer fluid
Condenser
Solar thermal
Power plant

A B S T R A C T

Renewable electricity generation systems have an increasing trend in terms of usage due to aiming to decrease greenhouse gas emissions and energy source diversification strategies of countries. Parabolic trough, Fresnel, and solar tower systems have been used to generate solar thermal electricity around the world. In this study, the effects of the selection of collector heat transfer fluid (HTF) and condenser type on a concentrated solar thermal power plant were analyzed. Net power, net electrical efficiency, and economic analysis were carried out for the selected HTFs for different collector outlet temperature cases. In the case of condenser type selection four different systems were considered; water cooled, air cooled (dry air) and air cooled with water spraying (spraying before fan and spraying before and after fan). Levelized cost of energy (LCOE) and specific investment cost were calculated. According to the results, specific investment cost and LCOE were found to be 4000 USD/kW$_{el}$ and 0.207 USD/kW h, respectively. Carbon tax/credit was also included to the calculations of LCOE and a comparison study was carried out for gas turbine, combined cycle and solar thermal power plant with thermal storage. Including carbon tax/credit to the LCOE shows that solar thermal power plant with heat storage can be competitive when compared to gas turbines.

1. Introduction

Approximately 50% of the world electricity generation has been provided by fossil fuels according to the annual energy generation reports [1]. The negative effects and greenhouse gas emissions originated from combustion in these power plants to the environment were proved by many researchers. Solar electricity generation from photovoltaics or thermal systems has gained attention due to decreasing CO_2 emissions to the limits. South part of Europe has 1700–2000 kW h/m^2 annual global irradiation which has to be utilized to generate higher exergetic product instead of hot water production. A part of this potential can be utilized in solar electricity generation with solar thermal systems or photovoltaic systems.

Parabolic trough type solar collectors (PTC) are in use today for electricity generation or solar process applications. Energy storage systems, heat transfer fluids, the material selection of reflecting and absorber surfaces, control and tracking mechanisms etc. are the main research areas related to collector characteristics [2–4]. Stirling engine applications [5,6], Kalina cycle integration of parabolic trough type collectors [7], desalination systems [8], solar geothermal heat pump systems [9] and nanofluids [10] are other research areas in parabolic collectors related to collector applications. Zhang et al. [11] reviewed CSP plants and design methodology. Comparison of linear focusing CSP technologies was performed. Linear Fresnel reflectors optical quality and thermal efficiency is lower due to incidence angle and cosine factor when compared to parabolic trough type solar collectors [12].

Energy generation cost and its reduction alternatives for solar power plants are of interest. Electricity generation cost of a solar thermal power plant with 47 MW$_{el}$ installed power was found to be 0.162 €/kW h$_{el}$ [13]. Another study, performed by Shinnar and Citro [14], showed that the electricity generation cost was around 0.08 USD/kW h, with 50 MW$_{el}$ installed power and energy storage. The annual operation for the power plant was taken 4900 h and specific investment cost was found to be 4816 USD/kW$_{el}$. It is obvious that energy storage can decrease the cost of electricity per installed capacity. However, the storage capacity and other economic factors that affect the initial cost have to be determined. The location of the power plant was investigated by many researchers in many different areas [15–20]. For instance, Boukelia and Mecibah [21] showed the potential of CSP technology in

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http://dx.doi.org/10.1016/j.enconman.2015.12.068
0196-8904/

Nomenclature

Abbreviations

DNI	direct normal irradiance (W/m^2)
D	diameter (mm)
W	width (m)
f	geometric concentration ratio (–)
L	focal length (m)
ε	emissivity
h	convective heat transfer coefficient (W/m^2 K)
η	efficiency (%)
P	pressure (bar)
x	quality of steam at evaporator outlet
C	cost
E	net electricity generation (MW h)
LCOE	levelized cost of energy (USD/kW h)
CT	critical temperature
SIC	specific investment cost (USD/kW)
WSBF	water spraying before fan
WSBAF	water spraying before and after fan

Subscripts

r	receiver
ref	reflector
g	glass
env	envelope
opt	optical
is	isentropic
f	fuel
c	carbon included

Algeria. Direct normal irradiance (DNI) is directly related to the thermal performance of the power plant and it also affects the initial cost and energy storage cost. Thermal performance of the parabolic trough type collectors and the effects of some parameters on collector efficiency were investigated [22,23]. An analytical approach was performed by Rolim et al. [24] to compare the results with SEGS VI. Another technoeconomic study was performed by Quaschning et al. [25] for 50 MW$_{el}$ installed power. The study was focused on efficiency, net electricity generation, and unit electricity generation cost for different DNI values. According to the results, unit electricity generation cost was found to be 0.16 €/kW h for the highest DNI value. Energy and exergy efficiency improvement with reheat in a solar thermal power plant were also investigated and a reheat temperature, 200 °C, was found to be the optimum value in case of energy and exergy efficiencies [26]. Montes et al. [27] performed an optimization study on the effects of the selection of collector surface area.

In addition, heat storage for solar thermal power plants is an important parameter for the investment and annual energy generation. Integrating a storage system increases the load factor of the power plant when solar energy is not available. However, it also increases the first investment cost and operational cost of the system. Therefore, an economic optimization study has to be performed in order to determine integrating it into the system. Heat can be stored by different methods in solar systems [28–30]. Working fluid can be used as storage media but the investment cost increases rapidly. Molten salt is another option to store the excess heat with two tank storage system [31]. An economic analysis was carried out for 12 h storage and it was reported that levelized cost of electricity (LCOE) decreases 10% and storage cost was found to be 30–40 USD/kW h$_{th}$.

As it can be seen, there are many factors that affect the performance of a solar power plant. The configurations of the components and design parameters have to be simulated in order to obtain maximum performance and minimum cost criteria. Therefore, some commercial codes or in-house codes can be found in the literature. Giostri et al. [32] compared five different solar thermal power plants with an in-house code. The results show the net overall efficiency was found to be between 15% and 17%. Abutayeh et al. [33] used IPSEpro in the modeling of a solar thermal power plant with additional spreadsheet to simulate the transient behavior of the solar system.

The motivation of this study is to investigate the effects of the selection of the heat transfer fluid and the condenser type on the levelized cost of electricity for a parabolic trough concentrating solar power plant. For this purpose, a solar thermal power plant was designed, without the heat storage system, in THERMOFLEX commercial code. Levelized cost of electricity was compared to conventional electricity generation systems. Carbon taxes were also included to the levelized cost of electricity calculations. Apart from the literature, the effects of the selection of HTF and condenser type on LCOE were investigated and a comparison study was performed to investigate carbon tax/credit included LCOE for conventional (gas turbine, combined cycle) and solar thermal power plant with and without heat storage cases.

2. System structure

Parabolic trough type solar collectors are one of the line focusing concentrated solar power (CSP) technologies. In the literature, many research studies were performed for thermal and optical analysis of the collectors [34]. A detailed thermal model of a parabolic trough collector receiver was presented by Kalogiraou [35]. In this study, the geometric structure of the collectors was not considered as a variable. Main constant input parameters for different cases are given in Appendix A. For consistency and verification of the results, an error analysis in Thermoflex with real power plant data can be found in the previous work [36].

In Fig. 1, the system structure is shown, in which solar-island and power-island are on the left and right hand sides, respectively. Thermoflex was used in the simulations and steady state cases were considered. This commercial code numerically solves any process. A solution matrix is generated according to the input values and when mass, momentum, and energy equations are satisfied the solution converges. Transient analysis and dynamic response behavior of the power plant were not considered in this study. Hot heat transfer fluid is passed from shell and tube type heat exchangers; superheater, evaporator, and economizer, and it is entered to the collectors to be heated again by solar energy. In the power-island, superheated steam is expanded in the turbine to generate electricity. Bled steam is used to preheat the condensed water before deaerator as shown in Fig. 1.

3. Results

3.1. The selection of the heat transfer fluid

The selection of heat transfer fluid (HTF) directly affects the design, equipment selection, first investment, and operational