Applied Energy 141 (2015) 131–142

Contents lists available at ScienceDirect

Applied Energy

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

Development and assessment of integrating parabolic trough collectors with steam generation side of gas turbine cogeneration systems in Saudi Arabia

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HIGHLIGHTS

- Thermo-economic performance analysis for an ISGCP has been conducted.
- The annual solar share increases when the gas turbine generating capacity of the ISGCP decreases.
- The annual CO_2 avoidance increases with the decrease of the gas turbine generating capacity.
- Optimal integration of PTC in ISGCP results in a minor increase in the LEC.
- Optimally integrated PTC in ISGCP is more economic than CO_2 capturing technologies.

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 10 December 2014
Accepted 12 December 2014
Available online 2 January 2015

Keywords:
Gas turbine cogeneration plant
Carbon capturing
Integrating solar thermal technology
Parabolic trough collector
Solar thermal power plants
Thermo-economic analysis

ABSTRACT

Integrating solar thermal technologies with gas turbine cogeneration plants reduces fuel consumption and consequently results in a considerable reduction in gas emissions. These technologies are expected to play an important role in solving the global environmental and energy problems. The present work provides a detailed investigation of the technical and economic feasibility of integrating a Parabolic Trough Collector (PTC) system with gas turbine cogeneration system. In this regard, different generating capacities of gas turbine and areas of solar collectors have been examined and presented for a hybrid solar gas turbine cogeneration system that produces electricity and process steam at a rate of 81.44 kg/s at 394 °C and 45.88 bar. Thermoflex with PEACE simulation software has been used to assess the performance of each proposed integration design option. Optimum solar field size for each considered gas turbine generating capacity (size) has been identified. Also, the reduction in CO_2 emissions due to the integration of PTC systems has been calculated as percentage of the CO_2 emissions from the conventional system for each gas turbine generating capacity size. The results indicated that hybrid solar gas turbine cogeneration systems with gas turbine generating capacities less than 90 MWe demonstrate a negligible increase in the levelized electricity cost (LEC), which was between 5 US¢ and 10 US¢/kW h. It was demonstrated also that integrating a PTC system with a gas turbine cogeneration system of less than 110 MWe generating capacity has more economic feasibility compared to CO_2 capturing technologies.

1. Introduction

Cogeneration process includes the production of electrical power and heat simultaneously from the same fuel source [1]. Cogeneration is a more efficient way to reduce fuel consumption and as a result, the efficiency of a cogeneration plant is higher compared to that of conventional power plants which leads to a significant reduction in fuel energy consumption [2–4]. To increase the efficiency of a cogeneration plant, the design and proper operation of a Heat Recovery Steam Generator (HRSG) is the key component. Some studies had focused on this specific research area in conventional power plants using conventional technologies [5–9]. Many of the recent investigations on cogeneration focused on new applications and novel configurations of cogeneration plants using fossil fuels as the source of energy [10–17]. Wu and Rosen [18] assessed and optimized the economic and environmental impacts of cogeneration based district heating, cooling and electric services

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http://dx.doi.org/10.1016/j.apenergy.2014.12.027
0306-2619/

Nomenclature

$CO_{2,\ GCP,Ref}$	annual emissions of CO_2 from the gas turbine cogeneration power plant
$CO_{2,\ ISGCP}$	annual emissions of CO_2 from the integrated solar gas turbine cogeneration power plant
CSP	concentrating solar power
E_{ann}	annual total generated power
E_{in}	energy input
η_{ref}	net efficiency of the reference power plant
F_{ann}	annual fuel consumption cost
f_{cr}	annuity factor
f_{co_2}	amount of CO_2 emissions per heating rate of fuel
GCP	gas turbine cogeneration plant
$h_{inlet,SF}$	enthalpy of water at input of solar collector field
$h_{outlet,SF}$	enthalpy of water at the output of solar collector field
HRSG	heat recovery steam generation
ISGCP	integrated solar gas turbine cogeneration power plant
I_{tot}	total investment cost
LEC	levelized electricity cost
LHV	lower heating value of fuel
$\dot{m}_{fuel}$	fuel mass flow rate
$\dot{m}_w$	water flow rate through solar collector field
OM_{ann}	annual operation and maintenance costs
PTC	parabolic trough collector
$P_{fuel,\ GCP}$	power generated from fuel only of the integrated solar
$P_{fuel,ISGCP}$	power generated from fuel only of the integrated solar gas turbine cogeneration
$P_{gen,ISGCP}$	total power generated from the integrated solar gas turbine cogeneration power
$P_{th,solar}$	thermal power produced by the solar field
Q	heat rate
Ref	reference cycle
SLEC	solar levelized energy cost
SM	solar multiple
SS	annual solar share
W	power

systems compared with convention systems. Raj et al. [19] presented a comprehensive review of recently developed designs and technologies developed up to 2011 for heat and power cogeneration plants that utilized renewable energy sources including solar energy. The two main technologies to use solar energy to empower cogeneration plants are the solar concentrated solar power (CSP) and photovoltaic (PV) technologies. Pearce [20] and Basrawi et al. [21] explored the utilization of solar energy via hybrid PV and combined heat and power cogeneration and trigeneration plants. Rheinländer and Lippke [22] investigated the use of solar tower technology for cogeneration of electricity and desalinated water. Nia et al. [23] experimentally investigated the use of Fresnel lens and thermoelectric module to produce electricity and preheat water. The intermittent nature of the renewable energy sources in general and the solar energy in particular, motivated researchers to investigate possible integration of energy storage technologies with solar assisted heat and power cogeneration technologies. Prengle et al. [24] studied the configuration and thermo-economic performance of central receiver solar assisted cogeneration plant that uses ammonium hydrogen sulfate cycle as a basis for chemical storage to produce heat and electricity on day-night demand. Li et al. [25] used the multi-objective optimization to optimize the thermo-economic performance of a solar parabolic dish Brayton gas turbine system. Lindenberger et al. [26] has further developed and applied the dynamic energy, emissions, and cost optimization model (deeco), to analyze and optimize a district heating system that uses compression and absorption heat pumps, condensing boilers, solar collectors, and seasonal storage system that provides the annual heat and power demand for 100 houses. Compared with the conventional systems that consume the electricity from the grid, the solar assisted cogeneration systems could provide 80% of the heat demand and reduce the CO_2 emissions by 33% but with a cost increase of 120%. Similarly, Buoro et al. [27] optimized a solar assisted distributed cogeneration system that comprises a solar thermal plant with a long term storage, combined heat and power units and compression chillers to minimize the average costs of the useful heat provided by the system.

In our present study, solar energy is integrated with the gas turbine cogeneration system in the steam generation side. Thus, parabolic trough solar collectors (PTC) is a preferred technology since the temperature levels achieved by this technology is quite enough for steam generation with high collector's efficiency. The development of the PTC systems by universities and institutes for research purposes is well documented in the literature [28–33]. In those studies, the focus was on the PTC assessment without considering its integration with a gas turbine cogeneration system. A thermodynamic analysis of thermal gains and losses through the heat collection element (HCE) had been conducted by Forristall [34]. Direct steam generation in PTC system had been investigated by many researchers [35–39]. Their studies were focused on generating steam directly through PTC systems without integrating it with gas turbine power plants. However, relatively recent research proved that solar assisted power plants are among the best energy production options that can be used to preserve the quality and accessibility in energy production while reducing fuel consumption [40–43]. Integrating a gas turbine cogeneration plant with a solar system to overcome the fluctuation of incident solar radiation is one of those promising strategies to guarantee a stable power supply from a solar thermal power plant. Alrobaei [40] identified and investigated the thermo-economic performance of concentrating solar cogeneration power plants. His results had shown that the integrated gas turbine solar cogeneration power plant was the most effective technology in terms of thermo-economy and environmental sustainability for the cogeneration of power and water desalination systems. Dersch et al. [41] and Montes et al. [43] examined the integration of the solar field with combined cycles. To the best knowledge of the investigators of the present study; none of the published studies considered the effect of variation of solar multiple, gas turbine size, or annual solar share on the performance of solar assisted cogeneration plants; and no study considered the integration of the parabolic trough solar collectors with a cogeneration system for power and steam production. This was the motivation of the current study. Hence, the main objective of this present study is to investigate possible design modifications needed to integrate an actual conventional gas turbine cogeneration plant with parabolic trough solar collectors for optimal operation under local weather conditions.

An actual conventional gas turbine cogeneration plant at Ras-Tanura, Saudi Arabia, has been selected as an example. The gas turbine of the actual plant is originally sized such that it can produce electricity of 150 MWe and its exhaust gases have thermal contents enough to produce a constant flow rate of steam of 81.44 kg/s at 394 °C and 45.88 bars [44]. The main objective of this study is to investigate possible design modifications and integration of this gas turbine cogeneration plant with parabolic trough solar collectors for optimal operation under Saudi weather conditions. In this