Optimal integration of solar energy with fossil fuel gas turbine cogeneration plants using three different CSP technologies in Saudi Arabia

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HIGHLIGHTS

• This article presents a techno-economic feasibility of ISGCP.
• The CSP technologies considered include ST, PTC and LFR.
• Thermo-economic comparative analyses have been conducted to find the optimal LEC.
• The optimization process also includes CO2 emissions for each ISGCP configuration.
• The optimal configuration was found to be the integration of LFR with the steam side of ISGCP.

ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form 28 September 2015
Accepted 8 December 2015
Available online xxxx

Keywords:
Gas turbine cogeneration plant
Integrating solar thermal technology
Parabolic trough collector
Fresnel reflector
Solar tower
Thermo-economic analysis

ABSTRACT

The present work provides an investigation of the technical and economic feasibility of integrating Concentrating Solar Power (CSP) technologies with cogeneration gas turbine systems that are progressively being installed in Saudi Arabia to produce electricity and steam. In this regard, different designs of hybrid solar/fossil fuel gas turbine cogeneration systems have been proposed. The proposed designs consider the possible integration of three main Concentrating Solar Power (CSP) technologies, which are namely, Solar Tower (ST) systems, Parabolic Trough Collector (PTC) system, and Linear Fresnel Reflector (LFR) systems with conventional gas turbine cogeneration systems. These three CSP technologies were assessed for possible integration with a gas turbine cogeneration system that generates steam at a constant flow rate of 81.44 kg/s at $P = 45.88$ (bar) and temperature of $T = 394^\circ$C throughout the year in addition to the generation of electricity. THERMOFLEX with PEACE simulation software has been used to assess the performance of the integrated solar gas turbine cogeneration with three different CSP technologies for different gas turbine sizes under Dhahran weather conditions. The three CSP technologies to be integrated individually to the gas turbine cogeneration plant are; parabolic trough collectors and linear Fresnel reflectors to the steam side and the solar tower to the gas side of the plant. Thermo-economic comparative analysis have been conducted for all possible configurations of the integrated solar gas turbine cogeneration plant to reach at the optimal levelized electricity cost (LEC). The optimization process also includes CO2 emissions for each integrated solar gas turbine cogeneration plant (ISGCP) configuration for each the three CSP technologies in comparison with the integration of CO2 capture technology to the conventional plant. The simulation results revealed that the optimal configuration is the integration of LFR with the steam side of a gas turbine cogeneration plant of 50 MWe, which gives a LEC of $5.1 \text{US} \$/kW h with 119 k ton reduction of the annual CO2 emission. Moreover, the results indicate that the proper location to apply optimal integration configuration in Saudi Arabia is at Jazan city.

1. Introduction

Cogeneration is the simultaneous generation of heat and power from the same source. Cogeneration provides higher efficiency compared to that of conventional power plants which leads to a significant reduction in fuel energy consumption [1–3]. The recent
investigations of cogeneration focused on novel configurations of cogeneration plants using fossil fuels as the source of energy [4–11]. Recently, developed designs and technologies developed up to 2011 for heat and power cogeneration plants that utilize renewable energy sources including solar energy have been reviewed and reported by Raj et al. [12], Pearce [13] and Basrawi et al. [14] explored the utilization of solar energy via hybrid PV and combined heat and power cogeneration and trigeneration plants. Rheinländer and Lippke [15] investigated the use of solar tower technology for cogeneration of electricity and desalinated water. Nia et al. [16] experimentally investigated the use of Fresnel lens and thermolectric module to produce electricity and preheat water. Häberle et al. [17] investigated and reported the thermal and optical performance characteristics of the Solarmundo Fresnel collector using CFD simulations. Their simulation results revealed that the thermal output of the Fresnel collector is about 70% of that of parabolic trough of the same aperture area. However, this reduction in the thermal performance is overcompensated by a considerable reduction in the manufacturing and installation cost that leads to a reduction in the electricity production cost of about 10% using Fresnel linear reflectors compared that produced using parabolic trough collectors. Gharbi et al. [18] conducted a comparative investigation on the performance of linear Fresnel linear reflectors with respect to that of parabolic trough collectors. Morin et al. [19] varied the operation and maintenance cost as well as the performance reflecting different designs of linear Fresnel reflectors in order to estimate the optimal solar field for a power plant in comparison with that required parabolic trough field. Their study revealed that the Fresnel linear reflector cost should range between 78 and 216 €/m² in order to achieve a cost-effectiveness with that of parabolic trough collectors of 275 €/m². Quoilin et al. [20] investigated and optimized the performance of a small solar powered organic Rankine cycle for off-grid power generation. He developed a model that can size each component of the cycle for optimal operation. Zhang et al. [21] presented the theoretical analysis of a solar powered Rankine cycle that uses the supercritical Carbon dioxide to generate electric power and heat. Their numerical simulation showed that the system could achieve an electric power efficiency of 11.4% and heat power efficiency of 36.2%. The intermittant 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. 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 has been investigated and reported by Prengle et al. [22], Li et al. [23] used the multi-objective optimization to optimize the thermo-economic performance of a solar parabolic dish Brayton gas turbine system. Lindenberger et al. [24] has further developed and applied the dynamic energy, emissions, and cost optimization model (deeco), to analyze and optimize a district heating system for 100 houses which has reduced the CO₂ emissions by 33% via providing 80% of the heat demand but with a cost increase of 120%. This system uses compression and absorption heat pumps, condensing boilers, solar collectors, and seasonal storage system that provides the annual heat and power demand. Similarly, Buoro et al. [25] 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. The development of the PTC systems by universities and institutes for research purposes is well documented in the literature [26–31]. In these 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) was conducted by Forristall [32]. Direct steam generation in PTC system was investigated by many researchers [33–37]. Their studies were focused on generating steam directly through PTC system 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 [38–41]. Dersch et al. [39] and Montes et al. [41] examined the integration of the solar field with combined cycles. 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. Alrobai [38] 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.
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