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Thermo-economic analysis of integrated linear Fresnel reflector gas turbine trigeneration power plants

Yousef N. Dabwan^{1,2} and Pei Gang¹

¹Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei, China.

²Department of Mechanical Engineering, Sana'a University, Sana'a, Yemen.

E-mail Yousefdabwan@gmail.com

Abstract. The present work provides an economic feasibility and annual performance of integrated linear Fresnel reflector gas turbine trigeneration power plant (LFR-GTPP) that is progressively being installed to produce electricity, steam and chilled water. In order to pinpoint the best integration mode, different sizes of gas turbine and solar collector's area have been examined and presented. Thermoflow software was used for evaluating the performance of each integrated design under consideration. The optimal solar integration sizes have been determined. Moreover, reduction in CO₂ emissions due to integrating the LFR system is estimated with respect to that of the conventional trigeneration plant. For the considered trigeneration plant (that is required to produce 120.5 MW of steam, and 2500kg/s of chilled water), the study revealed that LFR-GTPP with gas turbine sizes less than 190 MWe capacities have more economic feasibility and sufficient ability for utilizing solar energy. The levelized electricity cost (LEC) for the (LFR-GTPP) varied between 4.28 US¢ and 5.6 US¢/ kWh. Furthermore, the study revealed that integrating LFR system with a conventional gas turbine trigeneration power plant in Sun Belt regions leads to a considerable avoidance in CO₂ emissions compared to the conventional trigeneration plant.

Keywords: Gas turbine trigeneration power plant; solar thermal power plants; integrating linear Fresnel reflector; thermo-economic analysis.

1. Introduction

A Linear Fresnel Reflector (LFR) based concentrating solar power technology power plant has been considered as one of the most promising technologies for utilizing solar energy. A 100MW solar thermal power plant powered by a LFR system with thermal energy storage was evaluated by Bishoyi and Sudhakar [1]. Mokhtar et al.[2] performed the thermal performance analysis of a solar water heating system based on LFR technology. Bachelier and Stieglitz [3] presented optimisation analyses in terms of LEC of several designs and configurations for direct molten salt technology plants based on the LFR system. The performance of an integrated gas turbine cogeneration power plant based on LFR technology was investigated using Thermoflow simulation software by Dabwan and Mokheimer [4].

Trigeneration for electricity, heating and cooling production systems integrated with solar energy resources have been investigated in some previous studies. For example, Wang and Yang [5] presented a hybrid-thermal power strategy of a trigeneration system driven by natural gas and solar energy. The system was used to produce electricity, space cooling/heating and domestic hot water. Tora and El-Halwagi [6] developed a systematic procedure for energy saving through the integration design of a trigeneration system powered by natural gas and solar energy. Al-Sulaiman, et al.[7, 8] performed a thermodynamic analysis of trigeneration power plant powered by parabolic trough collector (PTC) system with thermal energy storage. In another work, Zhai, Dai [9] evaluated annual energetic and exergetic efficiencies of a hybrid solar trigeneration system integrated with PTC system under Beijing



weather data (China). Zhang, Li [10] analyzed a solar-biomass hybrid trigeneration power plant for producing chilled water, hot water and electricity. In another work, Baghernejad, et al.[11] compared three trigeneration systems in terms of multi objective optimization parameters. Meng, Yang [12] proposed a trigeneration system driven by industrial waste heat and solar energy. The performance of the system was theoretically evaluated. Yao, Wang [13] proposed a new trigeneration cycle based on compressed air energy storage system. The system was evaluated in terms of energy, exergy and exergoeconomic performance. It is obvious from the literature that the application of LFR system in the trigeneration power plant for steam, chilled water and electricity generation has been rarely investigated. In addition, most of the previous research works deal with the application of PTC system for co/trigeneration power plants. Thus, this paper presents the investigation of possible design modifications required for integrating LFR to a conventional trigeneration plant for the optimal operation under Al-Hodeidah weather conditions, Yemen.

2. Problem statement and system description

In order to perform thermo-economic analyses for an integrated LFR gas turbine trigeneration power plant (LFR-GTTP), a conventional gas turbine trigeneration power plants (GTTP) was considered as a reference cycle in this study. The reference plant used to produce 340MWe of electricity (250 MWe at gas turbine + 90MWe at steam turbine), 120.5MW of industrial process steam, and 2500 kg/s of chilled water (24440 tons). In this regard, several simulations have been conducted to assess the performance of the plant with different gas turbine sizes and to determine the optimal size of the LFR solar fields that can be integrated with each gas turbine size. The schematic diagram of an integrated solar gas turbine trigeneration plant considered (LFR-GTTP) is presented in Figure 1. The schematic diagram of the conventional gas turbine trigeneration plant (GTTP) is similar to the plant in the Figure 1, but without solar integration. Thermoflow software [14] has been used to simulate both configurations (GTTP and LFR-GTTP). The objective of the current study is to investigate the possible different designs of the conventional and integrated solar gas turbine trigeneration plants for optimal operation for a constant plant steam side load (electrical, thermal and cooling load). In this regard, different gas turbine sizes for the trigeneration plants described above have been investigated.

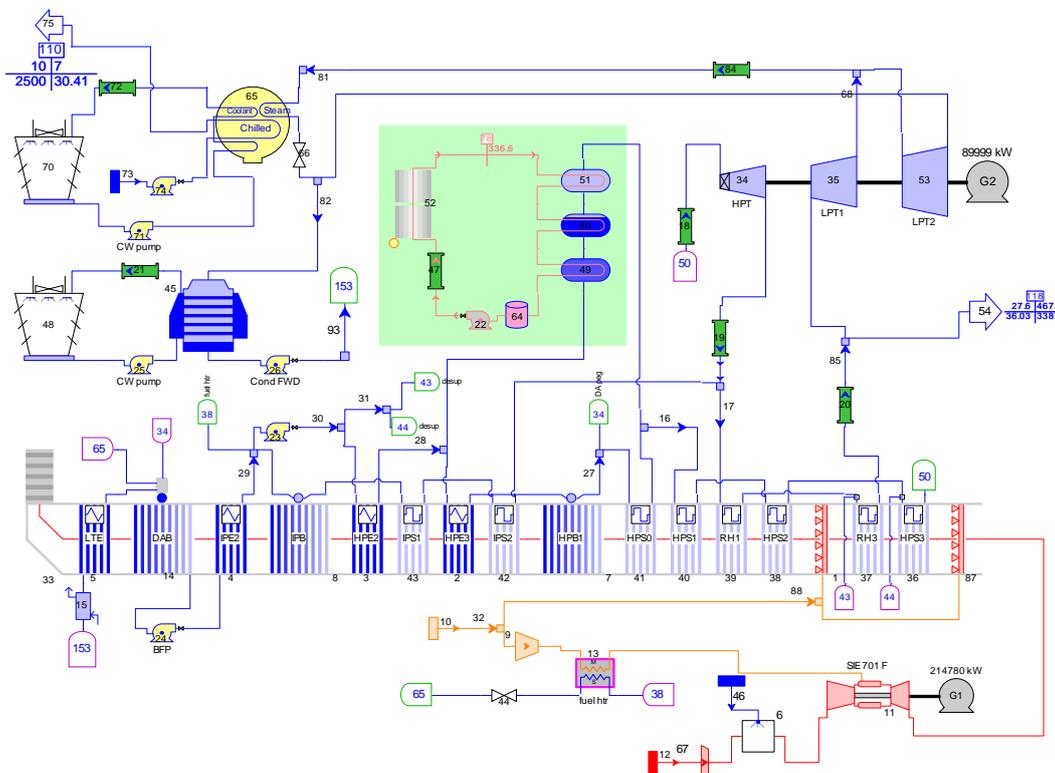


Figure 1: Schematic diagram of an integrated solar gas turbine trigeneration power plant based on LFR as simulated in Thermoflow.

The plants are originally designed to give the required electricity (at steam turbines), industrial process steam and chilled water at the required conditions for the large gas turbine size of 250 MWe. Therefore, for gas turbine sizes smaller than 250 MWe, the required plant steam side load was provided by the LFR system and/or a duct burners. The duct burners are installed in the HRSG to keep the same amount of steam at the same conditions produced when the solar generator is unavailable.

3. Performance parameters

Several thermo-economic parameters were used for evaluating the considered power plants.

Solar multiple is the ratio of the produced thermal power by the LFR system to the total thermal power produced by HRSG (equal to 391.9 MW) [15-17].

$$SM = \frac{P_{th,solar}}{P_{th,total}} \quad (1)$$

Instantaneous solar share can be estimated by the ratio between the power generated by the LFR system and the total power generated by both of fuel and solar energy input at the design hour, [16-19].

$$X_{net,eng,solar} = \frac{P_{gen,solar}}{P_{gen,LFR-GTPP}} = \frac{P_{gen,LFR-GTPP} - \eta_{GTPP} * P_{fuel,LFR-GTPP}}{P_{gen,LFR-GTPP}} \quad (2)$$

Annual solar share can be estimated by the ratio between the energy generated annually by the solar energy input and the total energy generated annually by the solar energy and fuel input [16-19].

$$SS = 1 - \frac{(Annual\ fuel\ consumption / kWh)_{LFR-GTPP}}{(Annual\ fuel\ consumption / kWh)_{GTPP,reference}} \quad (3)$$

Incremental CO₂ avoidance is the annual reduction of CO₂ emissions due to integrating LFR technology [16, 17, 19], and it is defined as:

$$\Delta CO_2 = \left(\frac{E_{gen,LFR-GTPP}}{\eta_{ref}} - E_{fuel,LFR-GTPP} \right) \times f_{CO_2}, \text{ or } \Delta CO_2 (\%) = \frac{CO_{2,GTPP,ref} - CO_{2,LFR-GTPP}}{CO_{2,GTPP,ref}} \times 100 \quad (4)$$

Where, $CO_{2,LFR-GTPP}$ is annual CO₂ emissions from the LFR-GTPP, $CO_{2,GTPP,ref}$ is annual CO₂ emissions from the GTPP; and f_{CO_2} is the amount of CO₂ emissions per fuel's heating rate [20].

Levelized energy cost (LEC) can be estimated by the ratio between the total annual cost in USD\$ and the total annual energy produced by the power plant. In a trigeneration power plant, the LEC of electricity can be estimated by subtracting the total annual price of steam and chilled as per their common local market price, as follows:

$$LEC = \frac{I_{tot} * f_{cr} + OM_{ann} + F_{ann} - (thermal + cooling)_{cost}}{E_{el,ann}} ; \quad f_{cr} = \frac{K_d * (1 + K_d)^n}{(1 + K_d)^n - 1} + K_{insurance} \quad (5)$$

Where, $E_{el,ann}$ is annual total electric power (KWh), I_{tot} is total investment cost; F_{ann} is annual cost of fuel; OM_{ann} is annual cost of maintenance and operation; and f_{cr} is annuity factor; where K_d is the interest rate, $K_{insurance}$ is the annual insurance rate, and n is the depreciation period in years.

In current study, the steam and chilled water price have been assumed to be of 20% and 33% higher than that of the respective fuel price, respectively.

Solar levelized energy cost is used to assess the feasibility of integrating LFR technology to the power plant.

$$SLEC = \frac{LEC_{LFR-GTPP} - [(1-SS) * LEC_{GTPP}]}{SS} \quad (6)$$

4. Results and discussion

The simulation results of the present study are basis to figure out the optimal LFR field size that can be integrated to a trigeneration plant with different gas turbine sizes to cover the fixed plant steam side load. Figure 2 shows solar multiples for different areas of LFR solar field. The produced thermal powers by the integrated LFR gas turbine trigeneration power plant (LFR-GTPP) with different integration sizes is

plotted in Figure 3. The results show that the obtained thermal power from solar system increases with LFR field area (solar multiple) till it reaches a maximum point for each capacity of the gas turbine. After that, it remains constant. This is due to the solar field over sizing, which means that the LFR field would be operated at part load after that point. The maximum thermal power required from the LFR system takes place when the burned fuel at the duct burners is extremely-small during the daytime. That means there is no room for integrating LFR technology after these specified points; this is because the thermal content in gas turbine exhaust gasses is enough for producing electricity, steam and chilled water at the plant steam side.

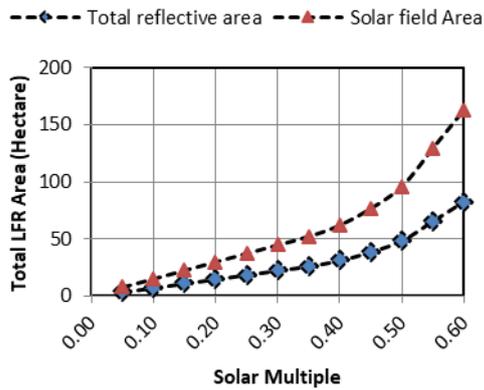


Figure 2. Solar multiples versus areas of the LFR field

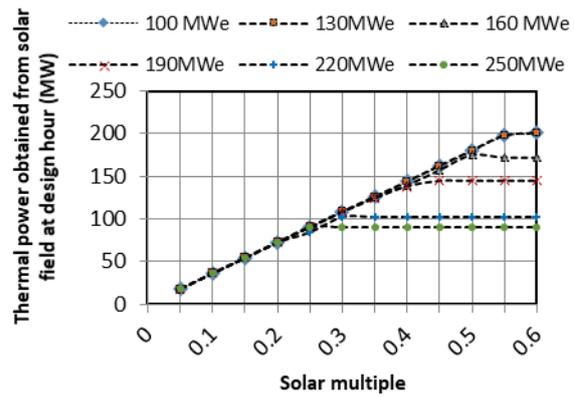


Figure 3. Obtained thermal power from the LFR field versus the solar multiple.

Figure 4 shows the variation in the instantaneous solar shear of the proposed plant (LFR-GTPP) for different values of gas turbine size and solar multiple. From the results, it is clear that an increase in the solar multiple consequently increase the instantaneous solar shear for each gas turbine size. The instantaneous solar shear reaches a maximum value for each gas turbine size. Beyond that, it remains constant. This is attributed to the area of LFR field, which is not fully used beyond that maximum value as mentioned earlier. The annual solar shear (the annual percent) of the energy produced by the LFR-GTPP due to solar integration has been plotted in Figure 5. According to the Fig, the plant with large gas turbine size, 250MWe, does not required much energy from the solar integration (about 4%). whereas, the plant with small gas turbine capacity, 100 MWe, has a small instantaneous solar shear value (about 12.2%).

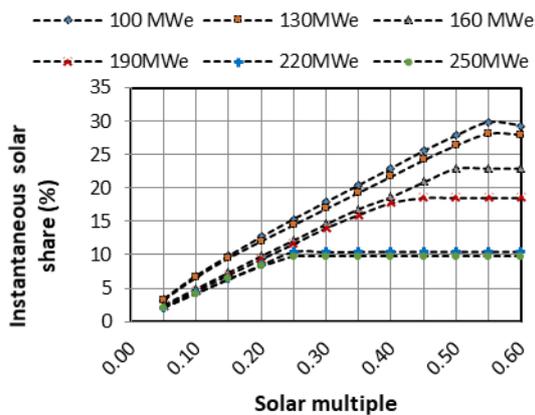


Figure 4. instantaneous solar share

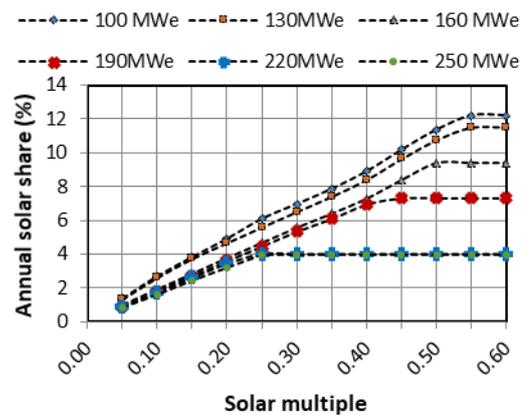


Figure 5. Annual solar share

The economic evaluation of the proposed power plants has been carried out by using LEC and solar SLEC. Figure 6 shows the LEC of the LFR-GTPP with different sizes of the solar field and gas turbine. As shown, the LEC of the plant with different gas turbine sizes slightly increased when solar multiple increases. Figure 7 shows how the SLEC of the plant with different gas turbine sizes vary in response

to rise in solar multiple. From the Figure, it can be observed that SLEC reaches a minimum value for each gas turbine size. Beyond that, it increases. This is due to the over sizing of the LFR area, which is not usable after that value. The optimal solar integration occurs when the burned fuel at the duct firings is extremely small during the daytime. It implies that after the minimal value of SLEC, there is no room for integrating LFR system, where the recovered energy in the HRSG is enough for producing electricity, chilled water and steam. Optimum solar integration sizes (solar multiples) were determined at the minimum values of SLEC (Figure 7), which are 0.5, 0.5, 0.45, 0.40, 0.25, and 0.25 for gas turbine capacities 100, 130, 160, 190, 220, and 250 MWe respectively. Figure 8 presents LEC of both configurations of the GTPP and the LFR-GTPP with different gas turbine sizes. The results indicate that solar integration with trigeneration plant results in a minor increase in the LEC compared to that of the conventional trigeneration plant. This is because the simulation site is located in a high solar radiation level in a Sun Belt country (Yemen), which makes a specific size of LFR system producing maximum possible thermal energy. Since the solar integration of LFR to the trigeneration plant leads to a negligible increment in the LEC, it results in a significant avoidance in emissions of CO₂. Therefore, LFR-GTPP could be represented as a promotion solution to the environmental problems caused by emissions of CO₂. Figure 9 presents the annual CO₂ avoidance, which is the annual reduction of CO₂ emissions due to integrating LFR system. As shown, the maximum avoidance of the annual CO₂ emission takes place when the LFR integrated to 100 MWe gas turbine (110.34 k-tonne of CO₂), and this avoidance decreases while gas turbine capacity increases until it reaches 45 k-tonne of CO₂ at 250 MWe gas turbine capacity.

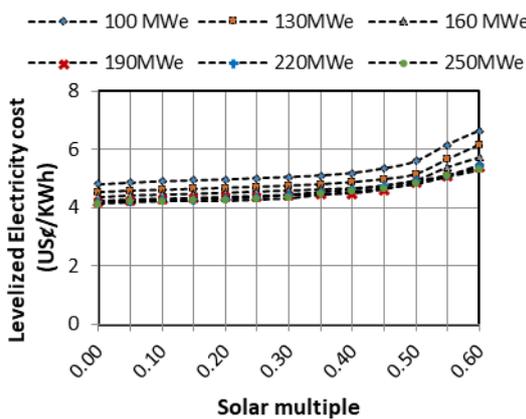


Figure 6. LEC for different integration sizes

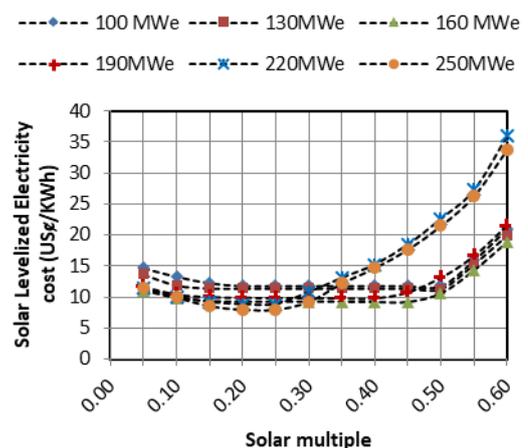


Figure 7. SLEC different integration sizes

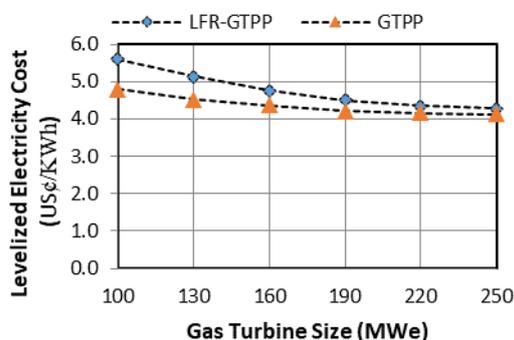


Figure 8. LEC for both configurations of GTPP and LFR-GTPP (at optimal integration).

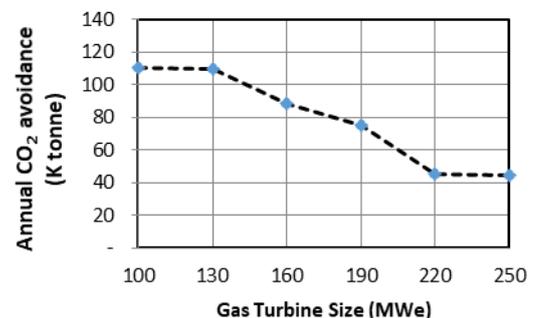


Figure 9. Annual CO₂ avoidance for utilizing LFR technology in the trigeneration power plant.

5. Conclusions

Solar energy is the most abundant source of energy on the earth and introducing integrated LFR with gas turbine trigeneration power plants offers stable and clean power plant for producing electricity, industrial process steam and chilled water. The annual and instantaneous solar shares as well as the

annual reduction in CO₂ emissions are higher when the LFR technology integrated to the gas turbine trigeneration power plant with small gas turbine generation sizes (less than 190 MWe). Moreover, integrating LFR technology with a conventional gas turbine trigeneration power plant results in a minor increase in LEC compared to the conventional trigeneration plant. The LEC for the integrated plant varied between 4.28 US¢ and 5.6 US¢/ kWh, while this integration leads to a considerable reduction in CO₂ emissions compared to the conventional trigeneration plant.

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