Optimal Solar Hybridization of a Grid-Connected Gas Turbine Combined Cycle Power Plant: a Case Study

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November 22, 2021

Optimal solar hybridization of a grid-connected gas turbine combined cycle power plant: a case study

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Abstract
The world is moving toward sustainability, but it may require many years for sustainable energy systems to dominate the market. Many fossil fuel power plants are in commission right now and will be in service for decades to come. Integrating solar thermal to fossil fuel power plants can diminish emitted greenhouse gases and fuel consumption. The efficient integration of solar energy into conventional power plants plays a vital role in persuading investors and owners to provide finance on such projects. The biggest challenge facing the process of integration is the capital cost of modifications for making conventional combined cycle powerplants capable of integration. In this paper, three configurations have been proposed for adding solar thermal energy to the heat recovery steam generator (HRSG) of a gas turbine combined cycle GTCC power plant. The attempt is made to determine the best configuration of the solar cycle regarding the performance, thermodynamic efficiencies and economic indices in a way that the primary cycle faces with the least modifications and capital costs while it provides the highest cash flow and augmented power during the operation lifetime.
Keywords: First-law analysis; Exergy analysis; Economic assessment; ISCC; Optimization;

I. Introduction

Gas turbine combined cycle (GTCC) power plants are attractive in power generation as they use the residual heat of flue gas from gas turbines for generating electricity in steam turbines. In recent years integrated solar combined cycle (ISCC) systems have been offered as a method of adding solar heat to the common GTCCs. Many studies have implied the positive effect of solar integration, and some plants came into operation, the Archimede power plant in Sicily, Italy (Falchetta et al., n.d.) and Hassi R'Mel in Algeria are in service today. Moving toward the carbon-neutral economy mentioned as the primary goal of recent international and regional agreements such as Paris agreement (“Paris Agreement,” n.d.) and European Union roadmap for low carbon economy by 2050 (“2050 Energy Strategy - European Commission,” n.d.).

Availability at no cost and being environmentally-friendly have made solar energy known among the best alternatives for nonrenewable resources (Wei et al., 2016). However, due to the high cost of operation and the non-reliability of solar energy during some periods of the year, integration with fossil fuels has been suggested for the optimal operation of the systems (Ameri and Mohammadzadeh, 2018). An ISCC system is a combined cycle power plant with a solar parabolic trough cycle which provides auxiliary heat to the primary system. Many researchers have studied the concept, and some configurations have offered for improving performance and system efficiency (Borello et al., 2013).

Exergy analysis of power plants has been discussed in many studies in recent years (Dinçer and Rosen, 2012). Exergy analysis of the HRSG’s components has carried out by Mansouri et al. (Mansouri et al., n.d.). they conducted thermodynamic analyses of the HRSG in a combined cycle power plant for finding the effect of HRSG’s pressure levels on exergy efficiency. It is concluded that the increase in pressure levels has an adverse effect on exergy efficiency and increases the irreversibility of the system.

In another study (Gülen, 2015), Gülen analyzed different solar integration methods using central receivers, parabolic troughs and linear Fresnel in comprehensive second law analysis of ISCCs. He mentioned HP steam production “a clear winner” over cost and performance among other types of steam available in the system i.e. (Low pressure, intermediate pressure). Also, the parabolic trough has mentioned the most favorable option regarding its maturity and dominance in the market.

II. Research methodology

Solar cycle integrated configurations proposed for adding solar auxiliary heat to the system, to have the least capital cost of modifications some constraints have been imposed on the system.

Iran's climate has numerous advantages for utilizing solar energy. High solar irradiation and numerous sunny days are some of the mentioned climatic features. In this study, simulations and assessments have been done on the Qom combined cycle power plant in Iran. The models have been verified with the power plant’s real-time data to resemble the primary system with the highest accuracy.

Three cases developed for finding the best configuration for adding the solar auxiliary heat to the HRSG. Cases one, two, and three are designed to add solar thermal energy from parabolic troughs to an auxiliary economizer, evaporator and superheater, respectively.

Due to the cost minimization approach of the study, the following constraints met by the system.

1. Turbine inlet temperature (TIT) of the steam turbine is fixed the same as primary value due to material restrictions and the necessity to redesign steam turbines. 2. The condenser has a limited capacity so that the total flow rate of the system restricted to 119 Kg/s. The main goal of adding auxiliary heat has set to transform LP steam into HP steam. 3. The gas turbines have provided the system’s baseload while the solar auxiliary heat added to

boost power generation when the sunlight is available. 4. All developed cycles received an equal amount of heat from the solar cycle.
The first case (figure1), has been designed to increase the temperature of the feed water in the solar auxiliary economizer. In the proposed model, a portion of the feed water has been separated and went through the solar economizer and re-joined the main flow before entering the high-pressure evaporator (HPB).

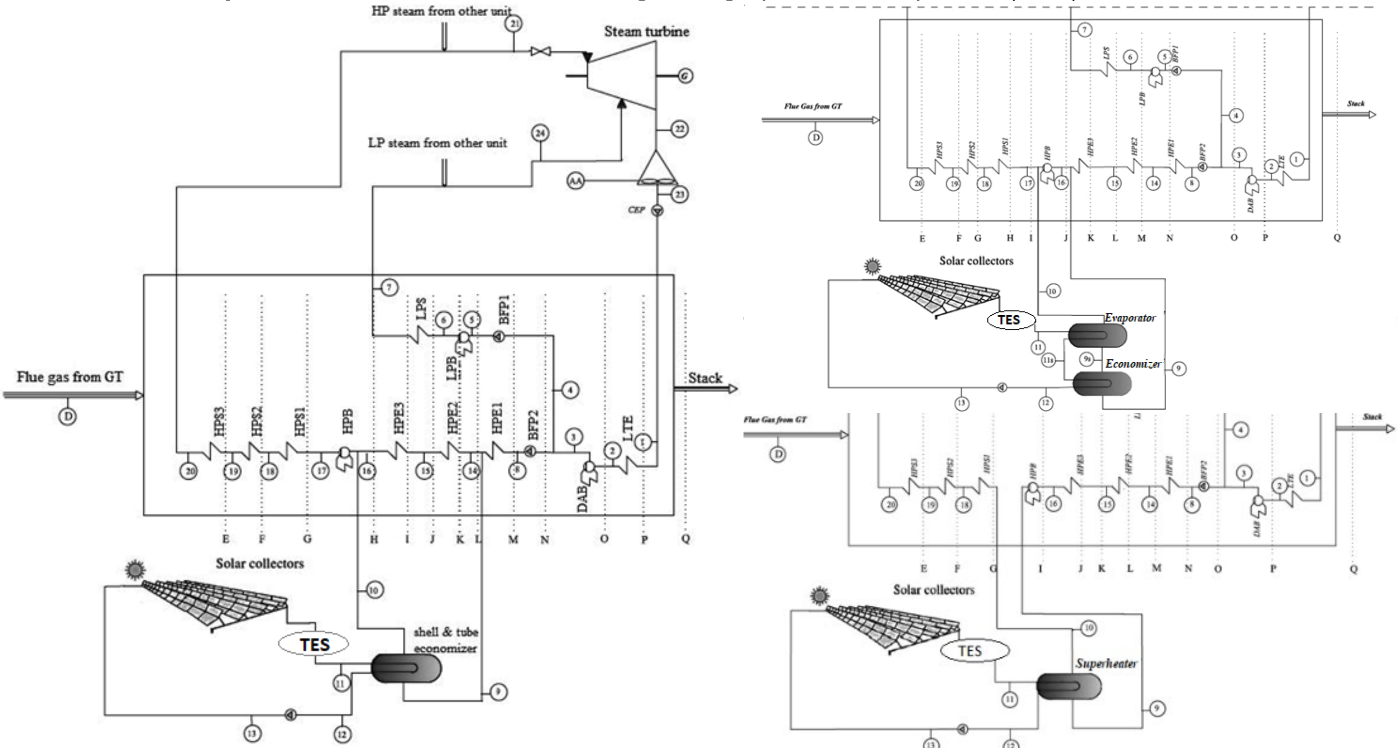

Fig. 1. Schematic diagram of the double pressure solar integrated Rankine cycle (Cases 1(left),2(right-above),3(right-below))

In the second case, the solar cycle auxiliary heat has been used in an auxiliary evaporator in which the added solar heat evaporates of a portion of feed water; subsequently, the saturated steam leaves the solar cycle and enters the HRSG's first high-pressure superheater (HPS1).
In the third case, the saturated steam flows through the solar superheater, and solar thermal heat has been used to superheat steam.

III. Thermodynamic analysis:

III.I.I First and second law analysis:

The system's energy and mass balance equations derived for every component of the system. Steady-state, Steady-flow condition assumed in evaluations, and mass flow rate and thermodynamic characteristics of the streams calculated. To find the main source of irreversibility and losses in the system,it is crucial to conduct the second law analysis on the cycle and its components. Exergy analysis includes four parts; physical, chemical, kinetic, and potential. Kinetic and potential terms can be neglected when the system does not face significant changes in speed and altitude (Akrami et al., 2018).

III.II Economic Analysis:

Table 1 illustrates the fixed parameters used in the economic assessment.

Table 1. Fixed parameters in economic analysis.

Parameter	Value	Parameter	Value
Plant economic life (years)	20	Operating hours per year (full load equivalent)	7400
Average general inflation rate (%)	4.5	The unit cost of natural gas ($/GJ-LHV)	3.97
Discount rate for NPV calculation (%)	15	The unit cost of electricity ($/MWh)	55
Date of commercial operation	2019	Fixed O&M cost ($ / kWnet)	20

The following assumptions have been made in calculations:
1. Air and gases analyzed based on the ideal-gas principles. 2. Significant enthalpy losses have been observed in collectors and exhausts. Other components' losses have been neglected in the calculations due to their minimal effect. 3. The system's dead-state condition has fixed at $P_0 = 1.01$ bar and $T_0 = 298.15$ K.

IV. Results and discussions

IV.I. Exergy analysis results

IV.II. HRSG analysis

Many studies have emphasized the high exergy destruction in the HRSG; Thus, A comprehensive evaluation has done on the HRSG for finding efficiencies, losses, heat absorption, and sources of irreversibility in the system.
Figures 2 and 3 illustrate the comparison between exergy efficiency and exergy destruction of the HRSG's

components, respectively. HRSG's total exergy destruction and total second law efficiency for each case are shown in figure 4. Note that in the calculation of the efficiencies, the absorbed heat by the solar collectors has been considered as the system input heat.

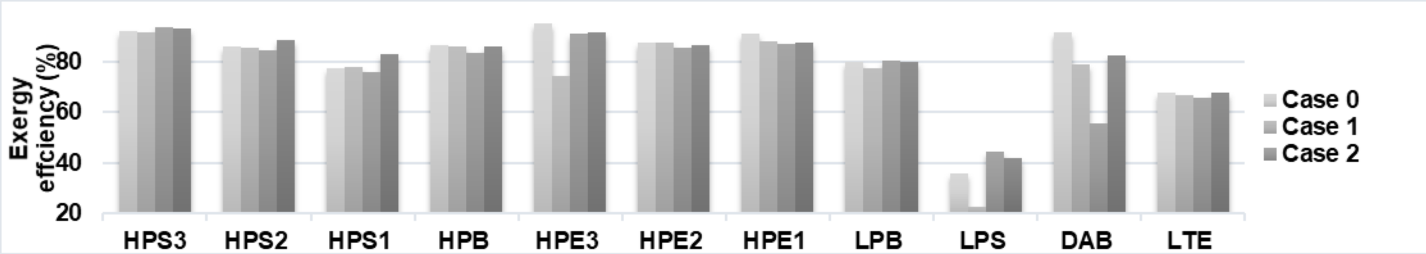

Fig. 2. Exergy efficiency for the HRSG components

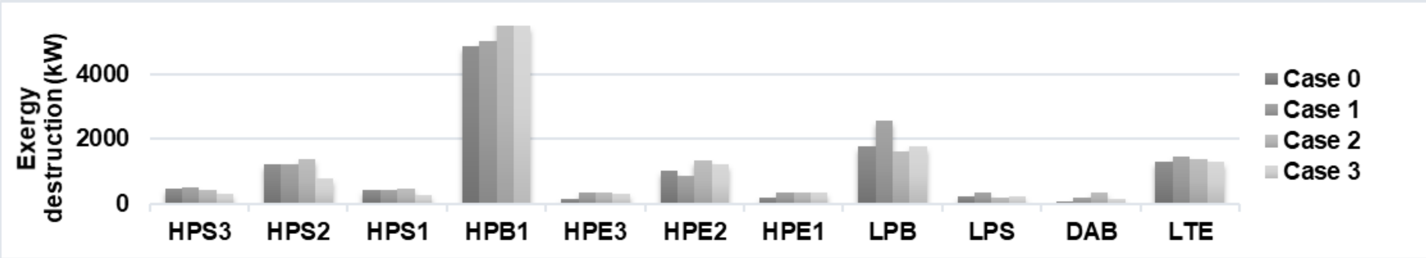

Fig. 3. Exergy destruction of the HRSG components

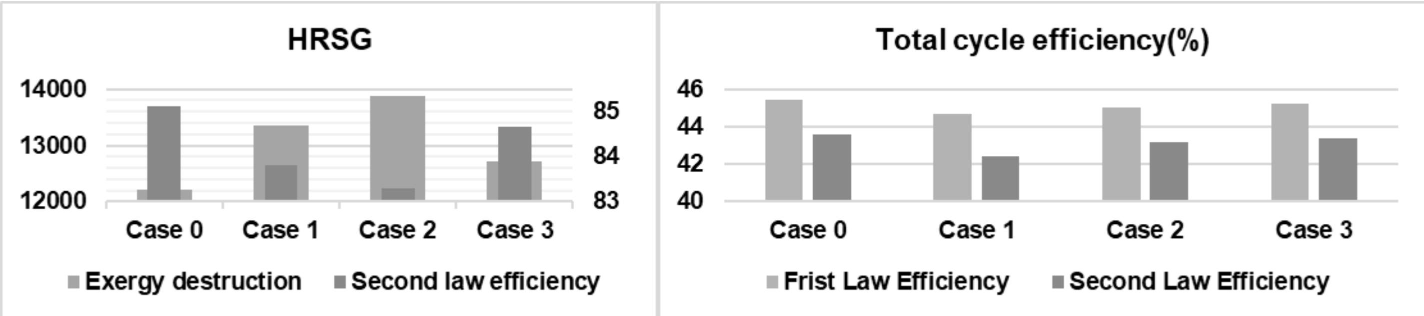

Fig. 4. Exergy destruction and Second law efficiency of the HRSG and total cycle efficiencies.

To find irreversibilities in the HRSG, the amount of absorbed heat should be calculated for each component. The amount of absorbed heat by the water/steam in the HRSG's components has shown in figure 5 for each case.

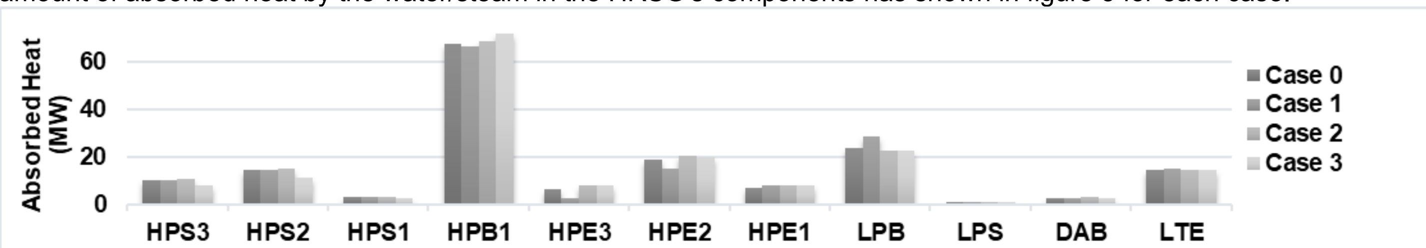

Fig. 5. Absorbed heat by the HRSG components

It is evident that the HP evaporator (HPB), and the LP evaporator (LPB) absorbed the highest flue gas heat compared to other components; therefore, the two elements have the most significant irreversibility in the HRSG. In case 1 auxiliary heat provided by the solar cycle is utilized in an economizer; therefore, a portion of the flue gas heat is conserved for the next sections, including the LP part; Consequently, the LP section received high-temperature flue gas and pinch point increased in LPB. Therefore, the LP steam generation increased. Table 2 compares the total energy and exergy parameters of cases.

Table 2. Energy and exergy parameters of the cases.

Parameter	Unit	Case 0	Case 1	Case 2	Case3
Gross power output of the plant	**MW**	**294.68 2**	**297.344**	**299.49**	**300.86**
Net electric efficiency	**%**	**45.43**	**44.69**	**45.01**	**45.22**
Overall exergy efficiency	**%**	**43.55**	**42.43**	**43.16**	**43.37**
Annual electricity exported	**GWh**	**2324**	**2350**	**2367**	**2378**
Annual CO2 emission	**kilo tonne**	**1035**	**1035**	**1035**	**1035**
Specific CO2 emission	**kg/kWh**	**0.445**	**0.44**	**0.437**	**0.435**
HP mass flow rate	**kg/s**	**89**	**93.27**	**97.67**	**98.68**
LP mass flow rate	**kg/s**	**23**	**25.8**	**19.81**	**20.57**
Total mass flow rate	**kg/s**	**112.13**	**119.07**	**117.48**	**119.25**

The same phenomenon happens in case 3 for the HPB, where the flue gas with a higher temperature passes HPB and increases pinch point; Consequently, the mass flow rate of HP steam increases. Higher thermodynamic efficiencies and better performance are calculated for this case.

IV.IV. Economic results

The economic analysis was performed on the cycle, considering fixed-parameters given in Table 1, the results of the economic analysis are shown in Table 3.

Table 3. Outcomes of the economic analysis.

CCPP configuration	Total investment (USD*1000)	Specific investment (USD per kW)	Levelized cost of electricity (USD/kWh)	Years of payback of equity (years)	Net present value (USD)
Case 1	282,682.4	974	0.0466	3.93	95,513,000
Case 2	282,495.5	964.5	0.0461	3.786	102,281,100
Case 3	281,654.9	959.6	0.046	3.6	103,422,400

It is evident in Table 3; Among solar configurations, case 3 has shown better values in the evaluated indices.

V. Conclusions

In this study, a comprehensive thermodynamic analysis carried out for finding the best configuration of the solar cycle in a grid-connected combined cycle. To have a minimum modification in the primary system, a set of constraints met by the system. Qom combined cycle power plant in the dry and hot region of Iran has been simulated. Thermodynamic and exergy analyses have carried out for each configuration, and the best option has been chosen regarding the overall performance, efficiencies, and economic indices.

Solar auxiliary heat in cases one, two, and three have been utilized in an auxiliary economizer, evaporator, and superheater, respectively.

The results show by adding solar cycle auxiliary heat closer to the high-pressure superheaters of the HRSG, flue gas heat will be conserved for the later sections such as HP evaporator with the most absorbed heat. Pinch point increases and the HP evaporator recovers more heat. Consequently, the mass flow rate of HP steam increases. Higher efficiencies and a better overall performance observed in case 3.

The solar thermal heat augmentation results in a 2.7 MW, 4.8 MW, and 6.18 MW boost in the net power for cases one, two, and three, respectively. Exergy analysis showed that cases one, two, and three have an exergy efficiency of 42.43%, 43.16%, and 43.37%, respectively. Therefore, case three has the highest efficiency and the best performance among other proposed configurations. Also, the same case stands ahead in economic assessment

References

2050 Energy Strategy - European Commission [WWW Document], n.d. URL https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy (accessed 10.13.18).

Akrami, E., Khazaee, I., Gholami, A., 2018. Comprehensive analysis of a multi-generation energy system by using an energy-exergy methodology for hot water, cooling, power and hydrogen production. Appl. Therm. Eng. 129, 995–1001. https://doi.org/10.1016/J.APPLTHERMALENG.2017.10.095

Ameri, M., Mohammadzadeh, M., 2018. Thermodynamic, thermoeconomic and life cycle assessment of a novel integrated solar combined cycle (ISCC) power plant. Sustain. Energy Technol. Assessments 27. https://doi.org/10.1016/j.seta.2018.04.011

Borello, D., Corsini, A., Rispoli, F., Tortora, E., Borello, D., Corsini, A., Rispoli, F., Tortora, E., 2013. A Co-Powered Biomass and Concentrated Solar Power Rankine Cycle Concept for Small Size Combined Heat and Power Generation. Energies 6, 1478–1496. https://doi.org/10.3390/en6031478

Dinçer, I., Rosen, M. (Marc A.., 2012. EXERGY : Energy, Environment and Sustainable Development. Elsevier Science.

Falchetta, M., Mazzei, D., Crescenzi, T., SolarPACES, L.M.-P. of the, 2009, undefined, n.d. Design of the Archimede 5 MW molten salt parabolic trough solar plant.

Gülen, S.C., 2015. Second law analysis of integrated solar combined cycle power plants. J. Eng. Gas Turbines Power 137. https://doi.org/10.1115/1.4028741

Mansouri, M., Ahmadi, P., … A.K.-E.C. and, 2012, undefined, n.d. Exergetic and economic evaluation of the effect of HRSG configurations on the performance of combined cycle power plants. Elsevier.

Paris Agreement [WWW Document], n.d. . United Nations Treaty Collect. URL https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=_en&clang=_en (accessed 10.13.18).

Wei, W., Sun, K., Hu, Y.H., 2016. Direct conversion of CO2 to 3D graphene and its excellent performance for dye-sensitized solar cells with 10% efficiency. J. Mater. Chem. A 4, 12054–12057. https://doi.org/10.1039/c6ta04008j