Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 100 (2016) 92 – 97

Energy Procedia

3rd International Conference on Power and Energy Systems Engineering, CPESE 2016, 8-12 September 2016, Kitakyushu, Japan

A thermodynamic model of solar thermal energy assisted natural gas fired combined cycle (NGCC) power plant

Xingchao Wang*, Edward K. Levy, Carlos E. Romero

Energy Research Center, Lehigh University, USA

Abstract

A solar thermal energy assisted NGCC power plant was modeled to investigate the impact on plant efficiency, output and CO_2 emission with solar thermal energy addition. In this particular model, with 23.7 MW_{th} solar thermal energy input to the HRSG, the duct firing could be shut off, 2337.5 kg/h natural gas would be saved, and 6.2 t/hr CO_2 emission would be eliminated. However, there would also be a 4.07 MW_e loss in power from the combined cycle. Another solar input approach shows 14.35 MWe additional electricity would be generated with 35 MW_{th} solar thermal energy addition. The thermodynamic analyses in this paper demonstrated the possibilities to utilize the solar thermal energy to reduce fuel consumption and CO_2 emission, or to increase the NGCC power plant efficiency and output, while taking advantage of the already existing power plant infrastructure.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of CPESE 2016

Keywords: solar thermal energy; NGCC, hybrid power plant, integrated solar combined cycle

---

1. Introduction

Rapid increase of renewable and clean energy demand in major developing countries of the world such as China, India and Mexico has driven the development of using solar energy, wind and geothermal energy for power generation [1, 2].

Concentrating solar-thermal power (CSP) is proven to have the capability of capturing solar energy and using the captured solar energy to heat a high temperature heat transfer fluid (HTF) [3-5]. It becomes possible to utilize the solar energy to increase the efficiency or increase the output of the conventional fossil-fired power plant. Parabolic

---

* Corresponding author. Tel.: +1-610-758-6282; fax: +1-610-758-5959.
E-mail address: xiw611@lehigh.edu.

1876-6102 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of CPESE 2016
doi:10.1016/j.egypro.2016.10.138

trough, compact linear Fresnel reflector, power tower and dish-engine are the four existing CSP technologies [6, 7].

Integrating CSP into a NGCC power plant is a way to increasing plant efficiency and output, also decrease the fuel consumption and greenhouse gas emissions [8, 9].

2. Model description

2.1. Solar collection system

A CSP collection system was chosen to perform the investigation. In the solar collection system, the HTF will be heated up to 550℃ and goes into solar steam generator (SSG) to produce steam. Then, the cold HTF flows back to cold storage tank at 300℃. Table 1 shows the major technical data of the solar collection system.

Table 1. Solar collection system technical data.

Parameters	Units	Values
Technology	-	Power Tower
HTF type	-	Molten Salt
Receiver inlet temperature	℃	300
Receiver outlet temperature	℃	550
Thermal collection efficiency	%	77

2.2. NGCC power plant thermodynamic model

The model is using the design data of the NGCC power plant located in Hermosillo, Mexico, which is equipped with a 150 MW_e gas turbine cycle and a 93 MW_e steam Rankine cycle. A Heat Recovery Steam Generator (HRSG) with three pressure levels is producing steam to link the gas turbine cycle and steam Rankine cycle. Table 2 listed the major design data of this NGCC power plant.

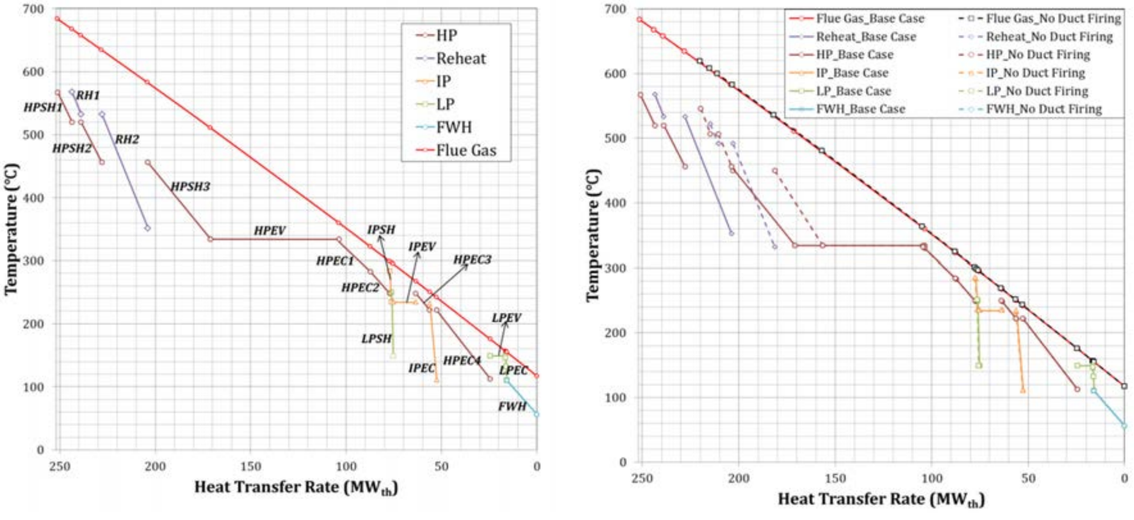

Fig. 1. HRSG Temperature Profiles. (a) left figure for Base Case ; (b) right figure for No Duct Firing Case (Solar Input1).

ASPEN Plus® is a widely used commercial power system process modelling software. The model with design data is as base case in this investigation. Figure 1a shows the heat transferred and temperatures in each component of HRSG (abbreviation definitions in Figure 1a are listed in Appendix Table A1).

Table 2. NGCC power plant design data

Parameters	Units	Values
Ambient and Plant Performance		
Ambient pressure	bar	1.014
Ambient temperature	℃	25.33
Total plant power output	MWe	239
Gas Turbine		
Natural gas, LHV	kJ/kg	47,800
Compressor inlet pressure	bar	0.98
Compression ratio	-	14.527
Compressor η_s	%	86.38
Turbine η_s	%	89.90
Gas turbine cycle output	MWe	150
Steam Cycle		
Steam turbine η_s, HP/IP&LP	%	80.83/84.72
Steam cycle output	MWe	93
Condenser temperature	℃	55.7
HRSG and Duct Burner		
Duct firing natural gas flow rate	kg/s	0.6493
HRSG flue gas inlet pressure	bar	1.83
HRSG flue gas inlet temperature	℃	683.5
HRSG flue gas outlet temperature	℃	116.5
HRSG flue gas flow rate	kg/s	389

Figure 2 is a detailed process diagram for the gas turbine and steam turbine cycle portions of the NGCC power plant with no solar thermal energy input at Hermosillo, Mexico. The HP, IP and LP steams are going out of HRSG as mass flow rate percentages and temperatures of 85.20%/565.6℃, 9.42%/281.2℃ and 5.38%/248.2℃, respectively.

The plant performance was evaluated by combined cycle efficiency as

$$\eta_{\mathrm{cc}} = \frac{W_{\mathrm{GT}}+W_{\mathrm{ST}}}{(\dot{m}_{\mathrm{NG,GT}}+\dot{m}_{\mathrm{NG,Duct\ Burner}})\cdot LHV_{\mathrm{NG}}} \tag{1}$$

where η_{cc} is combined cycle efficiency, W_{GT} is gas turbine net power, W_{ST} is steam Rankine cycle net power, $\dot{m}_{\mathrm{NG,GT}}$ is natural gas flow rate in gas turbine, $\dot{m}_{\mathrm{NG,Duct\ Burner}}$ is natural gas flow rate in duct burner and LHV_{NG} is lower heating value of natural gas.

The results presented in Figure 2 show the flow rate, temperature, pressure and enthalpy of all streams of the system. The gas turbine net power of 152.03 $\mathrm{MW_e}$ and steam Rankine cycle net power of 86.81 $\mathrm{MW_e}$ are consistent with design data.

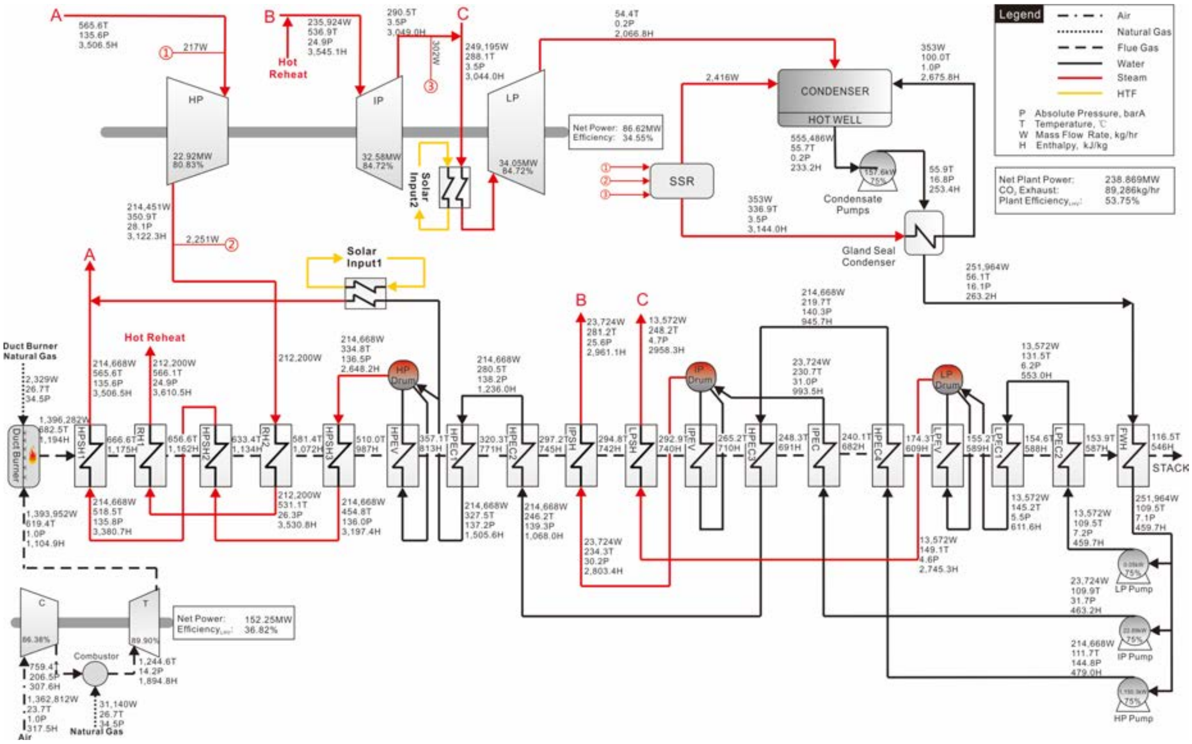

Fig. 2. Process Diagram of the 239 MW$_e$ NGCC Power Plant. (Base Case with No Solar Input, only Solar Input Locations Marked).

3. Solar Thermal Energy Assisted NGCC Power Plant

3.1. Solar Thermal Energy Integrated Strategies

The diagram in Figure 2 illustrates the complexity of the NGCC system and raises the issue of where to add the solar thermal energy such that the performance of the power plant is improved as much as possible. In this investigation, the possibilities to integrate solar thermal energy to the HRSG and the steam cycle were discussed. For the gas turbine, the potential of being added thermal energy to improve its performance is less. Therefore, only the HRSG side and steam Rankine Cycle side have been investigated.

3.1.1. HRSG Side (Solar Input 1 in Figure 2)

With solar heat available at a maximum of 550℃ and minimum of 300℃, potential location for getting highest converting rate of solar thermal energy to electric energy is HP circuits [10]. To avoid steam being generated in the economizer, which would cause a flow blockage, it is reasonable to add solar thermal energy downstream of the economizer.

The HPEV in HRSG has largest heat transfer rate and temperature difference between steam and flue gas. To withdraw saturated water then send to solar steam generator [11] will reduce the enthalpy change of flue gas passing through the HPEV and less fuel burning in duct burner.

The location of solar input 1 marked in Figure 2 shows the saturated water extracted from HPEC1 outlet goes to SSG then it is injected back to HP turbine inlet. The consequence is heat transfer rate in the HPEV decreasing (Figure 1b) leads to duct burner could be shut off as no duct firing case in this paper. However, flue gas temperature entering the HRSG, main steam and reheat steam temperatures would also decrease which will cause plant power loss as penalty.

3.1.2. Steam Cycle Side (Solar Input 2 in Figure 2)

On the steam side, the solar thermal energy source with temperature range from 300℃ to 550℃ determines the LP turbine would be the only possible location to inject solar thermal energy with feasible design. The LP turbine inlet steam with temperature of 288.1℃ would be heated to increase enthalpy then goes into a solar steam superheater. This approach will increase the LP turbine output and increase the steam quality at LP turbine outlet. The maximum level of solar thermal energy addition to the location of solar input 2 is as power boost case.

3.2. Simulation Results

To compare the impact of two different solar input approaches on combined cycle efficiency, net power output and CO_2 emission intuitively, the assumptions are made as followed:

- The flue gas temperature at the HRSG outlet and the pressure distribution in the steam cycle are fixed.
- The gas turbine conditions are the same as the base case.
- Heat transfer coefficients and heat transfer surface areas in the HRSG do not change as a result of adding solar thermal energy.

Table 3 summarizes the results for the base case, the no duct firing case (solar input 1) and power boost case (solar input 2).

Table 3. Simulation Results of Base Case and Solar Input Cases

Parameters	Units	Base Case	Solar Input 1	Solar Input 2
Solar Thermal Energy Input	MW_{th}	0	23.70	35.00
Duct Firing Natural Gas Flow Rate	kg/s	0.6493	0	0.6385
Gas Turbine Output	MW_e	152.03	152.03	152.03
Gas Turbine Efficiency (LLV)	%	36.77	36.77	36.77
Steam Cycle Output	MW_e	86.81	82.74	101.16
Steam Cycle Efficiency	%	34.58	37.53	40.31
Total Plant Output	MW_e	238.84	234.77	253.19
Plant Efficiency (LLV)	%	53.75	56.78	57.03
CO_2 Emission	kg/s	24.80	23.08	24.78
HRSG Flue Gas Inlet Temperature	℃	684.4	621.1	683.5
HRSG Flue Gas Outlet Temperature	℃	116.5	116.5	116.7
HP Steam Inlet Temperature	℃	567.2	542.8	566.4

The no duct firing case result indicates 2337.5 kg/h is saved and 6192 kg/h less CO_2 is exhausted. It also indicates that no duct firing would reduce the steam temperature going into the steam turbines which would lead to 4.07 MWe power loss. However, the combined cycle efficiency would still increase from 53.75% to 56.78%. The temperature profile comparison between base case and no duct firing case are sketched in Figure 1b, which presents smaller temperature differences between flue gas and steam in the HPEV and HPSHs occurs. It indicates heat transfer would be more efficient in HPEV and HPSHs.

The results of power boost case with 35 MW_{th} solar thermal energy input show 14.35 MW_e more electricity was generated and the combined cycle efficiency of 57.03% was achieved. A parameter is widely used to evaluate the solar to power conversion efficiency [12]

$$\eta_{\mathrm{se}} = \frac{\Delta W_e}{Q_{solar}} \tag{2}$$

The power boost case gives 41% solar thermal energy to power conversion efficiency.

4. Conclusion

The objectives of the analyses were to determine the increase in efficiency and/or power output of the NGCC power plants as a result of the addition of a solar thermal energy. In addition, the benefit of integrated solar thermal energy at the HRSG side is to reduce natural gas consumption and to decrease greenhouse gas emission.

The other consideration needs to be emphasized is that it was assumed that the solar collectors would be added to an existing combined cycle power plant with no physical changes made to the various heat exchangers in the HRSG. If the configuration of the steam cycle were designed specifically to accommodate solar thermal input, then it is likely that larger cycle efficiencies could be obtained. However, the analysis of a solar assisted NGCC having an optimized steam cycle configuration of the hybrid these two injection strategies.

In addition, techno-economic analysis is going to be performed as future work to determine the feasibility to integrate solar thermal energy on market perspective.

Appendix A

Table A1. Abbreviation definition.

Abbreviation	Definition
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
RH	Reheat
SH	Superheater

References

[1] Twidell J, Weir T. Renewable energy resources. *Routledge*; 2015.

[2] Dincer I. Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews.* 2000; **4**(2):157-75.

[3] Hu E, Yang Y, Nishimura A, Yilmaz F, Kouzani A. Solar thermal aided power generation. *Applied Energy.* 2010; **87**(9):2881-5.

[4] Behar O, Khellaf A, Mohammedi K, Ait-Kaci S. A review of integrated solar combined cycle system (ISCCS) with a parabolic trough technology. *Renewable and Sustainable Energy Reviews.* 2014; **39**:223-50.

[5] Spelling J, Laumert B, Fransson T. Advanced hybrid solar tower combined-cycle power plants. *Energy Procedia*. 2014; **49**:1207-17.

[6] Lewis NS. Research opportunities to advance solar energy utilization. Science. 2016; **351**(6271):aad1920.

[7] Li Y, Yang Y. Impacts of solar multiples on the performance of integrated solar combined cycle systems with two direct steam generation fields. Applied Energy. 2015; **160**:673-80.

[8] Jamel MS, Rahman AA, Shamsuddin AH. Advances in the integration of solar thermal energy with conventional and non-conventional power plants. Renewable and Sustainable Energy Reviews. 2013; **20**:71-81.

[9] Zhu G, Neises T, Turchi C, Bedilion R. Thermodynamic evaluation of solar integration into a natural gas combined cycle power plant. Renewable Energy. 2015; **74**:815-24.

[10] Ugolini D, Zachary J, Park J. Options for Hybrid Solar and Conventional Fossil Plants. Bechtel Technol. J. 2009; **2**(1):133-43.

[11] McMahan A, Zervos N. Integrating steam generation from concentrating solar thermal collectors to displace duct burner fuel in combined cycle power plants. Power-Gen International. 2009.

[12] Yang Y, Yan Q, Zhai R, Kouzani A, Hu E. An efficient way to use medium-or-low temperature solar heat for power generation–integration into conventional power plant. Applied thermal engineering. 2011; **31**(2):157-62.