Theoretical Utilization of High Temperature Solar Power Tower Technology in a 30 MW Cogeneration Cycle

Reza Soltani, Payam Mohammadzadeh Keleshtery, Maziyar Vahdaty, Mehdi Rahbar, and Majid Amidpour

***Abstract*—Solar-hybrid power plants that use large heliostat fields and solar receivers located on top of a tower are now in the position to deploy the first generation of grid connected commercial plants. The well-known CGAM cycle is selected to be hybridized by solar field in gas turbine section and the results are compared to the conventional fossil fired cycle in terms of technical, and economical figures. For steady power generation it is obvious that in any case a certain amount of additional fossil fuel is required to bridge the temperature gap between solar receiver and turbine inlet. The final results of this study show that by stable generation of 30 MWe in both modes, the fuel consumption and CO_2 emission decreased by 13.29% annually compared to conventional cycle. Additionally, the calculated total specific investment cost for solar-hybrid plant is substantially more than conventional one due to the fact that low CO_2 emissions and low LEC cannot be gained at the same time.**

***Index Terms*—CGAM cycle, power generation, heliostat field, solar receiver, solar-hybrid.**

I. Introduction

Solar thermal power plants can guarantee supply security by integration of thermal energy storages and/ or by using a solar fossil hybrid operation strategy. Only few technologies among the renewables offer this base-load ability. Therefore it is predicted that they will have a significant market share of the future energy sector [1].

The sun is an intermittent source of energy. Solar power plants that are operated with a solar-only operation strategy and use thermal energy storages to extend the operation to hours when the sun does not shine cannot entirely provide power on demand and account at the same time for economical aspects. Therefore those solar power plants do not have a real ability for base-load and the utilities have to provide backup power from conventional fossil fired power plants. This situation can be overcome by the use of additional fossil fuel to generate the heat in a solar-hybrid power plant [1].

In this study the 30 MW cogeneration cycle (CGAM) [2] is hybridized theoretically with a solar field consist of sun tracking mirrors and the receiver cluster on top of a tower (Fig. 1). The Mojave Desert in California is the hypothetical location of plant. The solar field is designed to harness the most available solar power. Although the capacity of the plant remains constant at 30 MWe, hybridization demands modification of the main power block equipments.

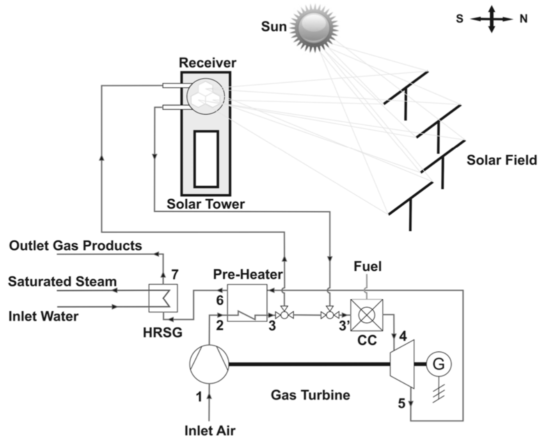

Fig. 1. Hybrid cogeneration cycle

However, total capital investment increases significantly yet, the fuel consumption and pollutant emissions reduction are the advantages of this scheme. The results of technical and economical aspects of this study are discussed in subsequent sections.

II. System Overview

The conventional fossil fired cogeneration cycle (CGAM) consists of a regenerated gas turbine and a HRSG, generating saturated steam [2]. The compressed air stream is preheated up to 850 K and turbine inlet temperature is 1520 K [2].Moreover, 14 kg/s saturated steam is generated in HRSG with regard to this fact that the outlet air temperature must remain above 400 K, owing to the presence of sulfur in natural gas, corrosive sulfuric acid can be formed when the products of combustion are sufficiently cooled [2].

To hybridize the CGAM cycle, the compressed air after being preheated by outlet gas products in regenerator, is heated up to about 1273 K via solar absorbers(Fig. 1). The implemented solar absorbers are pressurized volumetric type of receivers that has been demonstrated to be practical for Brayton cycle [3]. Thousands of flat mirrors in solar field track the sun light dynamically and concentrate the solar irradiance on cluster of receivers on top of the tower.

III. Thermo Dynamical Analysis

The annual average solar pre heating temperature calculated to be 1103.8 K that it fluctuates between 850 K at

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nights and 1285 K at the best solar condition in a year that is depicted in Fig. 2 which is developed via EES software.

In order to bridge the temperature gap between solar receiver outlet and turbine inlet temperature which is assumed to be fixed at 1520 K, sufficient amount of fuel must be injected in combustion chamber [4]:

$$\dot{m}_{fuel} = \frac{\dot{m}_{air} .(h_4 - h_{3'})}{LHV} \tag{1}$$

That LHV is lower heating value of methane and h is enthalpy of air stream.

For getting good comparison results, the power generated by hybridized plant decided to be 30 MWe at any condition as well as CGAM cycle. Although the turbine inlet temperature is fixed at 1520 K at either conventional and solar mode, the exergy at turbine inlet decreases because the mass fuel ratio has dropped. Therefore air intake must increase to compensate this exergy drawback that it demands compressor, combustion chamber and turbine to be modified. This problem is solved to get the best point which satisfies the generated power, highest solar pre heating temperature, lowest fuel consumption, and lowest air intake by a code developed in MATLAB. The amount of required air is calculated by assuming a control volume enclosing turbine and compressor [2]:

$$\dot{m}_{air} = \frac{M_a.\dot{W}_{net}}{(1+\lambda).(h_4 - h_5) + (h_1 - h_2)} \tag{2}$$

$$\lambda = \frac{\dot{n}_f}{\dot{n}_a} \tag{3}$$

That λ is molar fuel air ratio and M_a is molecular weight of air.

Due to increase in air intake mass the exergy of gas stream entering the HRSG rises, therefore more saturated steam in hybridized plant can be generated.

The annual average results regarding intermittency of available solar power are presented in Table I.

TABLE I: ANNUAL AVERAGE RESULTS

	Conventional Cycle	Hybrid Cycle
Generated Power (MW)	30	30
Total Fuel Consumption (ton/year)	44685	38747
Total CO_2 Emitted (ton/year)	122580	106290
m_{fuel} (kg/s)	1.64	1.12
m_{air} (kg/s)	92.7	99.22
m_{CO2} (kg/s)	4.6	3.07
m_{water} (kg/s)	14	16

During each day the available solar irradiance fluctuates that it causes change in air and fuel consumption rate second by second. The corresponding trend for a typical day is illustrated in hour basis from sunrise to sunset (Fig. 3). At one or two hours after sunrise and before sunset it is not logical to run the plant in hybrid mode because fuel consumption exceeds the conventional amount due to excess air intake and low preheating temperature. Therefore, the plant continues to operate in fully fossil fired mode at those hours.

Owing to fluctuations in solar power, deviations in power generation is inevitable in small scales (Fig. 4). Yet, the average generated power remains constant at 30 MWe annually. Moreover the solar pre heating temperature trend in day is shown in Fig. 4.

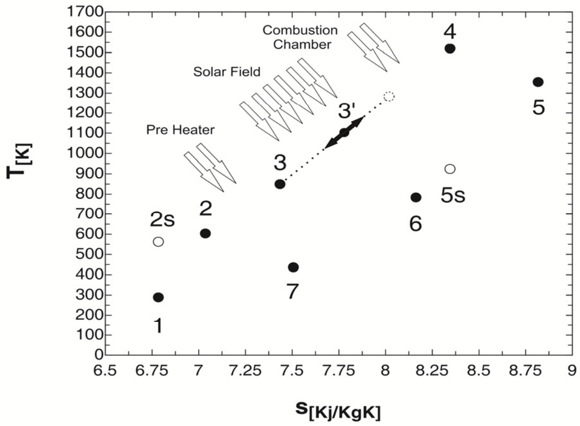

Fig. 2. Hybridized brayton cycle

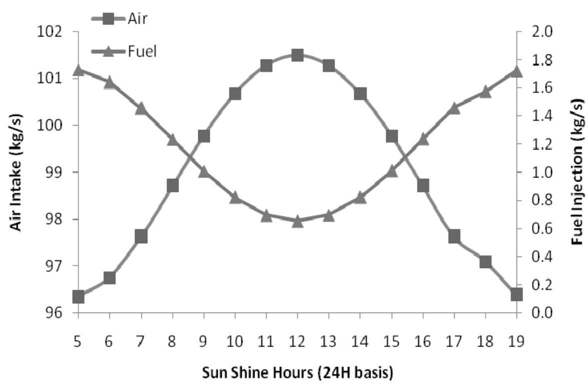

Fig. 3. Fuel and air consumption trend during a day

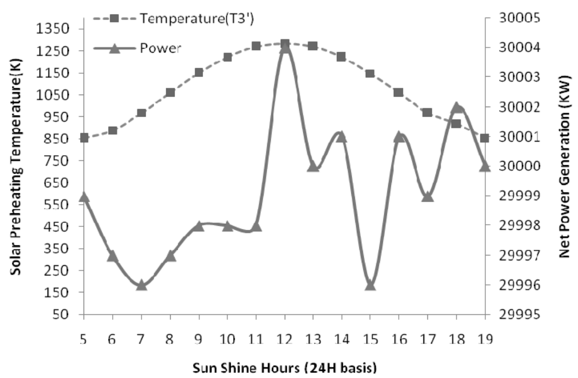

Fig. 4. Net power and receiver temperature

IV. SOLAR FIELD DESIGN

Solar power harnessed by solar field is totally intermittent, because of several factors playing role in it like sky clearance for beam radiation (τ_b) that is function of altitude of the plant and cosine efficiency (η_{cos}) which is function of sun, each mirror and receiver position. Field power can be calculated as follows [5]:

$$P_{solar} = \sum_{i=1}^{n} I_{b,h0} . \tau_b . A_{eff,i} . \eta_{shading} \tag{4}$$

$$I_{b,h0} = [1 + 0.034\, Cos\, (\frac{360\, N}{365}).I_{SC}\, .Sin\, \alpha\,] \tag{5}$$

$$A_{eff,i} = A_{mirror} . \eta_{\cos, i} \tag{6}$$

That $I_{b,h0}$ is normal solar irradiance at the edge of atmosphere, $\eta_{shading}$ is shading efficiency of field, I_{sc} is solar constant that is equal 1353 W/m^2, N is number of days from 1st January, α is solar altitude angle (Fig. 5), and A_{eff} is effective reflector area. Moreover, sky clearance factor is calculated by Hottel's equation [5].

The cosine efficiency varies for each single mirror during a day. In order to calculate the cosine efficiency the vector method is employed. Solar vector (SV) and reflector vector (RV) are unit vectors (Fig. 5) that RV for each mirror is different based on its position. SV is calculated as follow:

$$\overrightarrow{SV} = (Cos\alpha \times Sina_s, Cos\alpha \times Cosa_s, Sin\alpha) \tag{7}$$

That $\eta_{\cos}$ becomes the size of ... vector:

$$\eta_{\cos} = Cos\theta = \left| \frac{\overrightarrow{RV} + \overrightarrow{SV}}{2} \right| \tag{8}$$

Besides, other factors affect solar power absorbed by air stream in receiver [6] that the absorbed power becomes:

$$P_{absorb} = P_{solar} . \eta_{refl} . \eta_{receiver} . \eta_{blocking} \tag{9}$$

That η_{refl} is reflectivity factor of heliostat, $\eta_{receiver}$ is heat transfer efficiency in utilized receivers, and $\eta_{blocking}$ is blocking factor of field. In order to cancel the blocking and shading, appropriate distances are calculated among mirrors and tower. As the height of tower increases, blocking factor decreases [7]. Additionally, blocking and shading do not take place in designed field layout. By assuming power generation via solar and no fuel consumption, the solar share factor (SS) can be defined which is share of sun in power generation:

$$SS(\%) = \frac{\dot{W}_{net-solar}}{\dot{W}_{net}} \times 100 \tag{10}$$

The reflectivity coefficient of mirrors (η_{refl}) assumed to be 0.9 based on variety of heliostat manufacture catalogues and receiver heat transfer efficiency ($\eta_{receiver}$) for utilized REFOS type volumetric receivers is 0.58 [6]. Table II presents data regarding solar field equipments and annual solar condition.

V. Economical Analysis

In order to analyze operation of hybrid cycle economically the TRR (Total Revenue Requirement) method [2] is employed which estimates total required income of plant in each operation year. 20 years of operation with capacity factor of 0.85 is allocated. The plant design assumed to start in 2010 and in January 2012 economic operation of plant begins. Purchased equipment costs (PEC) for modified power block is calculated based on economic model of cogeneration cycle [2]. Unit cost of electricity with regard to generated net power, unit cost of steam, and escalation rate of USA can be calculated within 20 years of economic life in levelized form which is so called levelized electricity cost (LEC). Besides, input economic data was for year 1994 [2] that is escalated to each year of operation. Further detailed economic data are presented in Table III.

TABLE II: Solar Field Design Data

Parameters	
Site location specification	Mojave, California 34.86 ˚N, 116.88˚W Altitude: 700 m
Tower (m)	150
Field (m×m)	800×1500
Heliostat (m×m)	4×4
Number of heliostats	8000
η_{refl}	0.9
$\eta_{receiver}$	0.58
Average effective solar irradiation time (hour)	9.76
Annual average solar share (%)	40.99

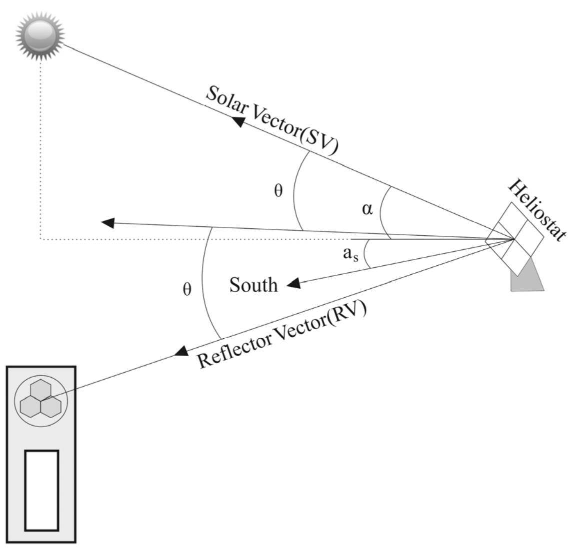

Fig. 5. Solar-field vector model

TABLE III: Economic Data

	Conventional Cycle	Hybrid Cycle
Unit cost of steam ($/Kg)	0.04	0.04
Unit cost of fuel ($/Mj-LHV)	0.003	0.003
Average nominal escalation rate	0.03	0.03
Specific total investment ($/KWe)	2474	6294.9
Specific CO_2 avoidance investment ($/Kg-$CO_2$)	-	0.22
LEC ($/KWe)	0.13	0.26
Return on investment (year)	2.39	3.17

VI. Conclusion

However specific investment and cost of electricity generated by hybrid cycle is rather high, it has been paid special attention by governments of developed countries, because hybridization of conventional fossil fired cycles with renewable energies especially solar is the best way to generate power steadily without being affected by intermittency of these sources. Naturally by commercialization of this new technology the final cost of electricity will decline in not too distant future. Moreover, decrease in dependency on fossil fuels and positive environmental effects are main advantages of so called hybrid-fossil cycles.

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