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Thermodynamic Evaluation of Repowering Options for a Small-size Combined Cycle with Concentrating Solar Power Technology

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Abstract

The increasing penetration of low-carbon technologies and enhancements in fossil-fuelled power plants efficiency are some of the most important and up to date research topics.

Renewable energy, in particular solar, has the potential of meeting the world energy needs while addressing environmental concerns, but technological advances in renewable energy electricity production are necessary to become competitive with conventional technologies.

New opportunities to increase the penetration of renewables energies, smoothing out renewables variability and intermittency problems, come out from the hybridization concept. Hybrid renewable-fossil fuel systems join the advantages of both renewable energies and programmable devices. Among all the renewable technologies available for hybridization, Concentrating Solar Power (CSP) with parabolic trough is the most diffused because of its relatively conventional technology and ease of scale-up. CSP hybrids are well established worldwide, predominantly with natural gas: the hybridization options for CSP ranging from feed water heating, reheat steam, live steam to steam superheating.

Based on a detailed thermodynamic cycle model of a reference small-size one pressure level Combined Cycle (CC) plant, the impact of CSP addition is thoroughly evaluated. Different hybrid schemes are evaluated and compared considering CC off-design operation. The goal of this study is to evaluate, from a thermodynamic point of view, three repowering options of a small-size CC with a CSP system in a hybrid system configuration and to quantify their potential benefits in terms of system's performance increase. In particular, the optimal size of CSP plant is shown for each investigated hybrid repowering options. The changes in CC steam cycle operating parameters are presented together with CC performance increase. It is shown that solar hybridization into an existing CC plant may give rise to a substantial benefit from a thermodynamic point of view.

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Keywords: Hybrid systems; Repowering; Concentrating Solar Power; Combined Cycles

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Nomenclature

CC	Combined Cycle
CSP	Concentrating Solar Power
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator

1. Introduction

Combined Cycle (CC) power plants nowadays are among the world's safest fossil-fired plants for the environment and climate [1]. Today's CC technology already achieves efficiency of around 59%, and it is still being optimized [2]. Integrating solar thermal energy into CC power plants is seen as an effective means for lower fossil fuel consumption and lower CO_2 emissions, as well as for a rational use of local and renewable resources [1, 3, 4]. In particular, great attention is paid on CSP technologies (parabolic trough, linear Fresnel, power tower and dish/engine). The integrated solar plant combined cycle concept was initially proposed by Luz Solar International. Kelly et al. [5] examined the potential of such design, finding that the most efficient method for converting solar thermal energy into electric energy is to withdraw feed water from the Heat Recovery Steam Generator (HRSG) downstream of the second stage feed water economizer, produce saturated steam, and return the steam to the HRSG for superheating.

2. Methodology

In order to evaluate the effect of the integration between CSP and CC technologies, the first step of the analysis has been the definition of the reference combined cycle plant and the evaluation of its performances with the software Thermoflex [6].For the sake of simplicity, a small-size one pressure level CC plant [7] with a nominal power of 30 MW_e has been considered. The layout, presented in Fig. 1, has been modeled in Thermoflex environment considering that the total net power of a CC is typically generated for 2/3 by the Gas Turbine (GT) cycle and for 1/3 by the steam cycle. As a consequence, the GT size has been fixed. Within the Thermoflex's library, paying particular attention to the GT cycle efficiency and to the exhaust gas temperature, the GE LM2500PE machine has been chosen. The maximum pressure of the cycle, which defines also the produced steam mass flow rate, is equal to 31.8 bar [7]. This value has been determined simulating the CC behavior on varying the steam turbine inlet pressure and evaluating the achievable performance, in order to optimize both the net power output and the net electric efficiency of the cycle. The main parameters of the selected GT are presented in Table 1, while the other operational input parameters are listed in Table 2, along with the main performance output.

After the definition of the reference case, the integration between the combined cycle and a solar field has been considered. The aim of the study has been the analysis of the behaviour of a CC plant operating in off-design when the repowering with a solar field occurs. A preliminary evaluation on hybridization systems has been carried out by varying the solar thermal contribution to the steam production and considering several configurations

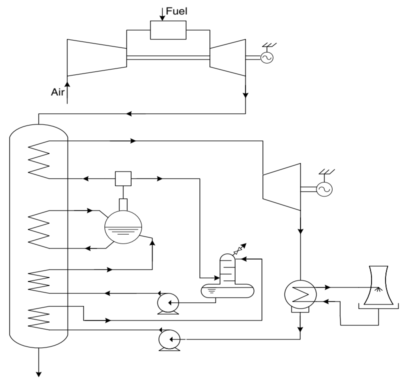

Fig.1 – Reference CC layout

Tab.1 – Gas Turbine characteristics

Manufacturer & Model	General Electric LM2500PE
Shafts	2
RPM	3000
Pressure Ratio	19.5
Exhaust Temperature	529°C
Air Flow	68 kg/s
Power	21822 kW_e
LHV Efficiency	35.5 %

Tab.2 – CC operating parameters

ΔT Pinch Point	8	°C
ΔT Approach Point	23	°C
ΔT Subcooling	5	°C
Net Power Output	30 639	kW
Net Efficiency	50.41	%
Turbine Inlet Mass Flow Rate	8.74	kg/s
Turbine Inlet Pressure	31.8	bar
Steam Turbine Inlet Temperature	510	°C
Auxiliary Systems Power	522.7	kW
HRSG Exhaust Gas exit Temperature	145	°C
HRSG Heat Exchange Power	29 309	kW
Condenser Pressure	0.06	bar

. In order to evaluate the criticalities of the components operating in off-design mode, the following three different cases are presented:

Case 1 - The first hybrid configuration – presented in Fig. 2.a – considers that the water feed leaving the high pressure economizer is split into two streams: the first one goes to the HRSG evaporator, while the other one is sent to the solar field. Thus, inside of the solar collectors the stream, starting from a saturated liquid condition, is transformed into saturated steam. The produced saturated steam, after the mixing with the saturated steam leaving the evaporator, is finally sent to the HRSG super-heater (following the extraction/bleeding for the deaeretor).

Case 2 - In the second configuration, as it can be seen from Fig. 2.b, the flow is split before the high pressure economization. Thus, at the inlet of the solar field there is a sub-cooled liquid stream. The remaining part of the plant is unmodified compared to the Case 1.

Case 3 - This last configuration, shown in Fig. 3, differs from the Case 2 because here the solar field produces superheated steam with a temperature equal to 500 °C. This superheated steam is mixed with the stream coming from the HRSG super-heater and sent to the steam turbine. In the presented figure, the solar field is composed of two different components, in order to represent separately (as modeled in Thermoflex environment) the fluid vaporization and superheating.

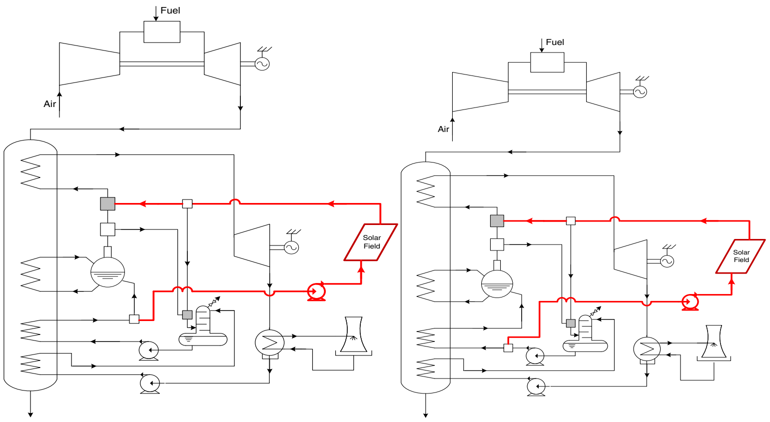

Fig. 2 (a) Case 1 schematic layout of the hybrid system; (b) Case 2 schematic layout of the hybrid system

Table 3 – Solar field main parameters [6]

	Evaporative Section	**Superheating Section**
Reflector type	Fresnel	Fresnel
Optical efficiency (0 degrees incidence)	67%	64.7%
Reflector cleanliness factor	0.95	0.95
Reflector end loss factor	0.9875	0.9848
Receiver outside diameter	70 mm	70 mm
Receiver wall thickness	4.191 mm	4.191 mm
Receiver inside diameter	61.62 mm	61.62 mm
Receiver tube material	TP321H	T22
Reflector unit width	16 m	16 m
Reflector aperture width	12 m	12 m
Reflector focal length	7.4 m	7.4 m
Geometric concentration	171.4	171.4
Ratio between reflector focal length and aperture width	0.6167	0.6167

All of these cases consider the hybridization only of the steam cycle; therefore while, the topper cycle's conditions (i.e. net power output, exhaust gas temperature and mass flow rate) are the same of the reference case, bottomer steam cycle is operating in off-design conditions. The thermal contribution from the solar field increases from Case 1 to Case 3; as a consequence, the size of the solar field – which will be one of the results of the simulations – is different for the various cases.

For what concerns the solar field, it can be modeled in the Thermoflex environment with commercial collectors available in the internal software library. For this analysis the Linear Fresnel collectors produced by Novatec Solar [8] have been chosen, due to the operating fluid (water) and to the high obtainable temperature (higher than 500 °C). Two different models are proposed for the saturated steam generation and for the superheated steam production, whose characteristics are listed in Table 3. Finally, for what concerns the solar irradiation, it has been estimated with the software for the city of Bologna, the 22nd of June at midday and imposing clear sky conditions.

After the definition of the solar field characteristics, the three hybridization cases have been simulated with the purpose of identifying the maximum mass flow rate's increase supportable by the steam cycle. In fact, the wish of maximizing the mass flow rate sent to the solar field and, consequently, the thermal power produced with the collectors must be balanced with *i*) the desire of maintaining the optimal HRSG thermal exchange of the reference case, *ii*) the pump's capability to increase the working mass flow rate without reaching critical situations, *iii*) the expander and condenser original components, thus typically means to limit to 10% the maximum increase in steam mass flow rate on the respect of the design value.

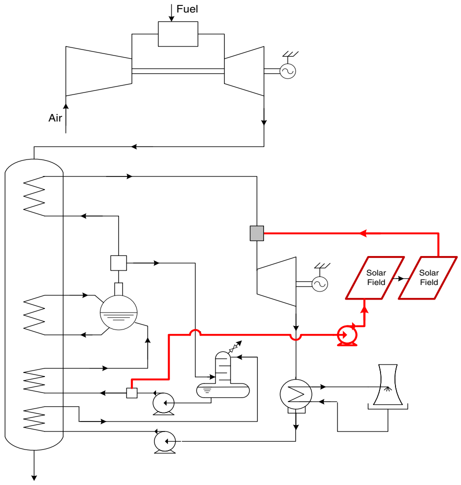

Fig.3 – Case 3 schematic layout of the hybrid system

3. Results

The main results of the simulations are listed in Table 4 for each of the three integrated plant, along with the reference case (small-size 1 level CC without solar integration).

The maximum mass flow rate to the solar field has been determined considering the limitations due to turbine, condenser and pumps operation and, contemporarily, with the purpose of maintaining the HRSG thermal exchange (i.e. the chimney exhaust gas temperature) as much as possible close to the value of the reference case. As it can be seen from Table 4, for all the analyzed cases, the net power output increases when the hybridization between CC and CSP occurs, being maximum for Case 3.

Table 4 – Main results of the analysis

		Reference Case	**Case 1**	**Case 2**	**Case 3**
Maximum mass flow rate to the solar field	kg/s	-	2.2	2.0	1.6
Net power output	kW	30 639	32 032	32 094	32 236
Net efficiency (without solar field contribution)	%	50.41	52.70	52.80	53.04
Net efficiency (with solar field contribution)	%	-	49.48	49.01	49.16
Steam turbine inlet mass flow rate	kg/s	8.74	10.13	10.19	10.19

Steam turbine inlet pressure	bar	31.8	36.5	36.8	37.0
Steam turbine inlet temperature	°C	510	500	500	509
HRSG exhaust gas temperature	°C	145	141	149	147
HRSG thermal exchange	kW	29 309	29 583	29 015	29 132
HRSG effectiveness	[-]	0.75	0.76	0.74	0.74
Net thermal power from the solar field	kW	-	3951	4705	4799

Moreover, particular attention can be paid on the hybrid cycle efficiency definition. In fact, two different net efficiencies can be defined when considering the integration of the CC with the solar field:

- Net efficiency without the solar field contribution: this efficiency is calculated considering, as thermal power introduced into the cycle, only the thermal power related to the combustion. This parameter, plotted in Fig. 5 for the three analyzed cases as function of the mass flow rate sent to the solar field, is always higher than the efficiency of the CC stand-alone reference case. In particular, the third is the case with a higher slope, while the lower increase is seen for the Case 1.
- Net efficiency including the solar contribution: in the evaluation of the heat introduced into the cycle, also the solar energy absorbed by the collectors has been considered. Starting from the reference case's efficiency value, this parameter decreases with the increase of the mass flow rate to the solar field (see Fig. 6). The higher penalization is seen for the Case 3, the lower for the Case 1.

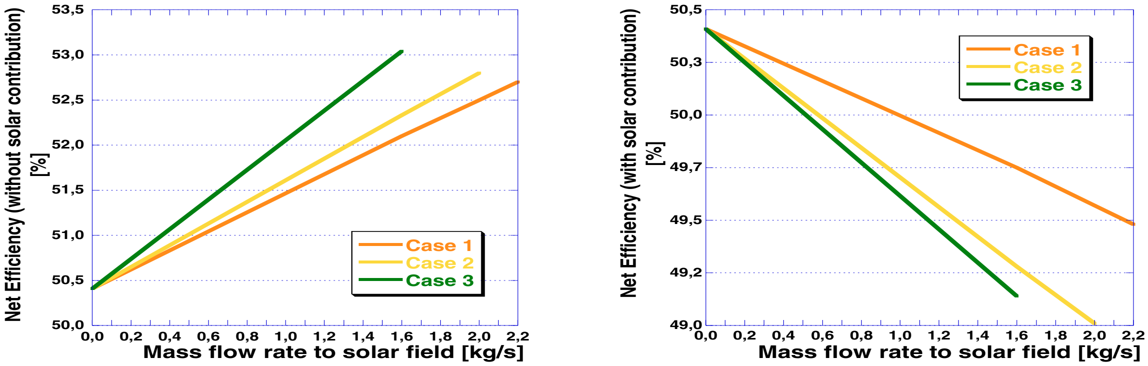

Fig.4 (a) Net efficiency trend (without considering the solar contribution) for the three analyzed cases; (b) Net efficiency trend (considering also the solar contribution) for the three analyzed cases

The interruption – appearing in Figures 5 and 6 – in net efficiency trend for different values of mass flow rate to solar field depending on the considered case, is clearly due to the different upper limits to the solar field mass flow rates imposed by the repowered steam cycle.

No substantial differences can be seen in the turbine inlet pressure and mass flow rate if considering the hybridization cases, but a clear increase is seen on the respect of the reference case.

Finally an estimation of the solar field parameters (surface area and efficiency) has been made, as reported in Table 5, fixing the value of the mass flow of each collector equal to 300 kg/sm^2. From the Table, it can be noted that the surface area increases with the net thermal power from the solar field (i.e. passing from Case 1 to Case 3, see Table 4), while the collector efficiency is similar for all the investigated cases, except for what concerns the superheating section. This evidence is due to the different collector model addressed to the superheating process.

Table 5 – Solar collectors main parameters

		Case 1	Case 2	Case 3	
Surface area	m^2	21 288	24 962	31 082	
Collector efficiency	%	61.21	61.38	61.48*	58.51**

*Economization and evaporation section

**Superheating section

4. Concluding remarks

The aim of the study has been the thermodynamic analysis of the integration between a small-size one pressure level combined cycle and a concentrating solar power plant. A CC reference case has been modeled with the software Thermoflex and its repowering has been analyzed considering three different cases for the solar hybridization: (*i*) evaporation, (*ii*) economization and evaporation, (*iii*) economization, evaporation and superheating. For each case, the maximum mass flow rate's increase supportable by the steam cycle has been identified and the performances of the system have been evaluated. The results shows that the repowering of the CC always allows to increase the net power output. Moreover, for all the considered cases, it can be seen an increase in net efficiency when considering only the thermal power related to the combustion as introduced heat; on the other hand, an efficiency decrease occurs when considering also the solar energy absorbed by the collectors. Finally, an evaluation of the solar collectors main parameters has been presented.

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