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New improvements in existing combined-cycles: Exhaust gases treatment with amines and exhaust gas recirculation

David Borge-Diez*, David Gómez-Camazón, Enrique Rosales-Asensio

Department of Electrical and Systems Engineering and Automation, Electrical Engineering Area, University of León, Campus de Vegazana, s/n, 24071 LEÓN, Spain

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Abstract

The combined cycle plants in 2019 are upswing due to definitive closure of conventional coal-fired power plants. The price increase of a ton of CO_2, will close to 25 euros in 2019, could allow to increase their capacity factor above 50%. It has been already achieved a high flexibility imposed by the regulator of the Spanish network and possible hybridizations, in both gas turbine and heat recovery steam generator. Therefore, one step ahead directed to the reduction and treatment of the flow of exhaust gases at the outlet of the boiler during the operation is necessary.

An optimization study based on a parametric analysis of this possible reduction has been carried out, with recirculation of the exhaust gases and the treatment of them with amines in a CO_2 capture plant, both at the exit of the boiler, using real data base, to study their possible integration within the existing combined cycle.

The results obtained are very promising: firstly, with the use a 35% of exhaust gases recirculation + capture plant in existing combined cycle, the efficiency of the gas turbine improves 0.5%. Secondly, the total number of tons of CO_2 avoid per year would be around 633 kilotons (based on a capacity factor in 2019 closed to 0.41). Therefore, the saved cost in ton of CO_2 for one existing combined cycle could be around 21.4 million of euros/year. This configuration, therefore, decreases the number of trains from 2 (existing combined cycle + capture plant) to 1.36. This decreasing is traduced in costs reduction and due to it an effective technique for pollutant emissions reduction.

On the other hand, the new combined cycle will have an efficiency penalty caused by chemical absorption in the capture plant. The crossover requires approximately 30% of the middle/low steam of the turbine to obtaining 90% capture of CO_2 with the corresponding penalty of 4 points in the global cycle performance and a reduction of power close to 21% with respect to the existing cycle. All boil down to a conflict of interests between €/Mw lost vs €/ton CO_2 avoided. Clearly the rising in capacity factor and flexibility in current combined cycle plants will be decisive in future to elucidate this conflict. The results obtained are totally in contrast with other studies carried out being fully feasible for implementation in existing combined cycles.

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Keywords: Combined cycle power plant; Exhaust gas recirculation; MEA; Gas turbine

* Corresponding author.
E-mail addresses: david.borge@unileon.es (D. Borge-Diez), dgomec01@estudiantes.unileon.es (D. Gómez-Camazón), erosa@unileon.es (E. Rosales-Asensio).

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Nomenclature

Subscripts and Acronyms

$CCGT_{3PR}$	combined cycle power plant with triple pressure HRSG with reheating
PCC	CO_2 carbon capture and storage plant
EGR	exhaust gas recirculation
GT	sequential gas turbine GT26 with 2 combustor chambers: EV and SEV

1. Introduction

It is obvious that global CO_2 emissions are currently increasing dramatically due to the still excessive use of fossil fuels to service an exponential overpopulation. It is also obvious that the trend in recent years is the use of renewable and clean energy due to the taxation of "less" clean energies and the imposition, in our case in Europe is Horizon 2020, of directives aimed at meeting the objectives of 20-20-20: improvement of energy efficiency, increasing the use of renewable energies by 20% and reduction of greenhouse gas emissions by 20% to do the planet more sustainable. The challenge continues, and a new point of view is necessary [1].

Nowadays in Spain the combined cycle power plants (CCGT) are adapting: operating between load limits, possible hybridizations in both gas turbine (GT) and heat recovery steam generator, HRGS, to the new operation modes imposed by the regulator of the Spanish network, REE. Definitively CCGTs are far away from the operation mode for which were designed in the 90 s (full fixed load of 400 MW approximately). Currently higher flexibilities in these plants are being achieved and because of it another different way, directed to the reduction and treatment of the flow of exhaust gases at the output of the boiler during its operation, is necessary (since currently price of €/ton CO_2 is increasing considerably and it is also imperative to comply with the European Horizon 2020 Directive). Also, in Spain, this year 2019, most of thermal coal plants are destined to close. Due to this fact, CCGTs will be the base energy with a very upward capacity factor in the next decade before a greater inclusion and/or coexistence with renewable energies such as wind, solar or hydraulic.

Based on these concerns, technological improvements must be applied to achieve a higher reduction of emissions in existing CCGTs. The main problems concerning the integration of one CO_2 capture plant (PCC), inside one existing CCGT, are the highest penalties in electrical efficiency and power. Supported in a previous article already published that reproduces, in a reliable model, the technological improvements inside one existing CCGT [2]; our objective will be to check all process inventories and look for improvements that will lead us to optimize the energy impact of the PCC included the compression process in six stages. The main penalty is the large amount of steam required for its operation which reduces the power output of the turbines and using part of the power generated by the global CCGT. The PCC and its compression process have been simulated in HYSYS/ASPEN PLUS® and energetically integrated in the real model that reproduces the existing CCGT. A new % of exhaust gases recirculation, EGR, and partial regeneration with solar hybridization, just validated in Colmenar-Santos et al. [2], would provide an interesting possibility to increase performance and efficiency whilst decrease the energy impact of the PCC process reducing finally the emissions from the existing CCGTs.

Therefore, the challenge is going one step ahead to study the thermal integration of one PCC with compression station in six stages inside the existing CCGT looking for the environmental benefits that would be obtained with the decreasing in CO_2 emissions.

As previously commented, CCGT model, was obtained and validated with actual process data. The integration of the process (PCC+% EGR+ compression) was developed based on a design dataset of the CCGT in different loading points (four real points with different mass flows and percent in emissions) once validated the CCGT model with the real one. The incognita in the new configurations will be to know the quality and amount of steam that need to go to the PCC and the penalty, in the efficiency and power lost, that is obtained in the global cycle. The way to be introduced these improvements inside the existing CCGT will be discussed without risks and with the maximum guarantees of success in order that both, emissions and possible associated costs, could be optimized. This study consists of an existing CCGT with 401 MW of maximum energy power supply in which PCC-based with 30 wt% aqueous mono-ethanolamine (MEA) scrubbing technology +%EGR will be integrated.

Our goals are to demonstrate that these technical solutions are feasible and able to quantify-optimize the possible advantages. More expressly, we intend (i) to establish the dimensions of the PCC (trains number, size of the absorber and the stripper, etc.) within the existing CCGT; (ii) to study the penalties that both configurations introduce in the global cycle of the existing CCGT, and finally, (iii) to assess the new sustainability in decreasing CO_2 emissions and the performance in new configurations (CCGT with PCC and CCGT+PCC+EGR) that finally would be obtained. All these set ups are proposed maintaining the conventional layout of the existing CCGT and the same operation values in each of the four loading points studied. These improvements, together with those already contrasted and published in previous manuscripts [2], will make that the sustainability and efficiencies of these plants could be achieved and improved respectively.

In the first section, we offered an overview of the existing problem in emissions treatment inside actual combined cycles. Section 2 presents the theoretical background on which the research was based; while in Section 3 the materials and adopted methods are described. Finally, in Section 4, the results of the techno-economic study and environmental impacts of the improvements are showed and discussed, and lastly, conclusions are listed.

2. Theoretical background

The current combined cycles are evolving (were conceived to work at full load with few starts/year) with technological improvements such as the reduction of their technical minimum, regulation of the load between a technical minimum and full load, low load operation concept, etc. Because of this, they are currently more flexible and better adapted to the operation mode imposed by the regulator of the Spanish network REE. In [2], an extensive study based on the application of the latest technologies applied to current cycles to improve its efficiency has been exposed. Results: emissions-fuel consumption decreases considerably with partial regeneration in the gas turbine and the thermal efficiency with solar hybridization from renewable sources, obtained in the new CCGT, is higher than conventional solar technology. For advance one new step now will be to evaluate how to achieve a mayor post-combustion emission reduction of the existing CCGT and how would affect at its current operation. At present, an amply review of advance studies and R&D activities in exiting CCGTs with EGR) + PCC exist demonstrating the advantages over an existing and conventional CCGT [3]. As has been commented the main problems concerning the integration of one PCC plant inside one existing CCGT are high electrical efficiency and power penalty besides the cost of it. One solution for decreasing these costs is increase the CO_2 concentration at the exhaust of CCGT power plants. In this context Li et al. in [4,5], reach this by using supplementary firing and demonstrating that the specific reboiler duty on the stripping stage of the PCC plant is reduced when CO_2 concentrations in exhaust gases are higher.

Aqueous MEA solutions have been widely studied in the literature and a large amount of experimental laboratory data are able to be scaled in pilot plants. So MEA solvent is used as a benchmark solvent to compare strategies for the treatment of exhaust gases in existing CCGT on a consistent basis [6].

A lot of studies have been realized concerning the applications of EGR+PCC inside thermal plants [7–18]. Any other processes with different solvents like the MEA and any other type of post-combustion capture technology, e.g. membranes or adsorption show that the main disadvantages of chemical absorption arise from high amount of thermal energy needed to regenerate the solvent and extract the CO_2, problems with corrosion and with solvent degradation. The other improve; EGR to the gas turbine increase the amount of CO_2 in the exhaust gases but we have a limit around (35–40)% due it the decreasing in the percent of O_2 inside de combustion chambers of the gas turbine that would produce instable flame. On the other hand higher% in CO_2 composition in the air entrance would benefit the global efficiency of the GT.

This paper presents a computer-based model that compares the performance of three configurations of the existing CCGT: (i) baseline, (ii) CCGT+PCC -to reduce the CO_2 emissions-, and (iii) CCGT+PCC+%EGR (percent of exhaust gas recirculation between (35–40)% to decrease, in mayor amount, the CO_2 emissions. Comparisons between the existing CCGT versus the last one improved, in different loading points inside the normal operation, will reflect the improvements obtained of this new CCGT updated.

Our goal will be firstly, to define an optimum design for the capture plant and by the other hand, to assess the exact benefits regarding these integrated technologies in the existing CCGT (PCC and PCC+EGR).

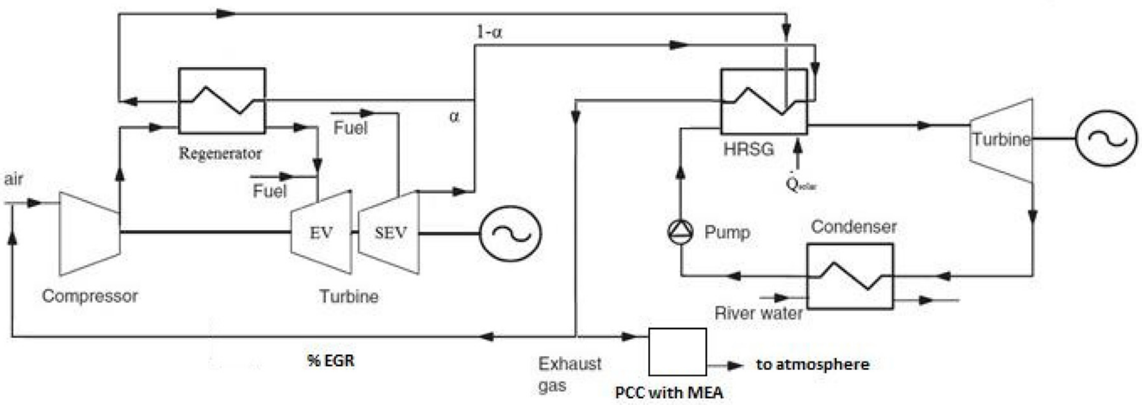

Fig. 1. Layout of CCGT with gas turbine GT24/26 with triple-pressure steam-reheat cycle.

Table 1. Exhaust gas composition at different loading points for existing CCGT and CCGT+35% EGR.

Loading point (%)	100%	88%	73%	46%
Comp. Molar Frac. (CO_2) to HRSG	0.0417	0.0423	0.0418	0.0368
Comp. Molar Frac. (H_2O) to HRSG	0.0835	0.0845	0.0832	0.0737
Comp. Molar Frac. (N) to HRSG	0.7570	0.7567	0.7570	0.7609
Comp Molar Frac. (O_2) to HRSG	0.1179	0.1165	0.1178	0.1286
Comp. Molar Frac. (CO_2) to HRSG with EGR35%	0.0653	0.0661	0.0646	0.0572
Comp. Molar Frac. (H_2O) to HRSG with EGR35%	0.0896	0.0908	0.0888	0.0794
Comp. Molar Frac. (N) to HRSG with EGR35%	0.7708	0.7704	0.7709	0.7725
Comp. Molar Frac. (O_2) to HRSG with EGR35%	0.0744	0.0727	0.0757	0.0908

3. Materials and methods

Our previous studies [2] show that compared with the existing CCGT, the improvements of regeneration in GT could increase the performance of the Brayton cycle around 2% to 3% with the reduction of gas consumption was between 6% and 9% approximately being the overall cycle efficiency loss minimal due to hybridization with steam introduced in high pressure level of the heat recovery steam generator from a source of renewable solar energy up to 50 MW. Regeneration and solar hybridization were found to contribute to increasing efficiencies depending on the loading point. Was found a loss of the net power of the new global cycle but considerably lower than if heat from a renewable source is supplied to the cycle (7.5% with regeneration only and of 1% with regeneration and hybridization). In Fig. 1, it is possible to see these previous improvements simulated and two new ones proposals (PCC+%EGR).

Starting with the data obtained of exhaust gases of our existing CCGT in different loads; this paper shows the results of exhaust gases composition, after having been used an EGR close to (35–40)%. It was obtained in a validated computer-based model for the existing CCGT in four different loading points which represents the actual trends (the complex model elaborated simulates all infinite loading points); associated with other simulation program HYSYS/ASPEN for the simulation of the PCC. The three configurations compare the efficiency of the new CCGT: (i) baseline (existing CCGT), (ii) CCGT+PCC -to decrease the CO_2 emissions-, and (iii) CCGT+PCC+ (35–40)% EGR to reduce mainly the CO_2 emissions and show the new exhaust gas compositions in the gas turbine (GT).

The thermal integration is performed using the power plant models integrated with capture. It starts from the knowledge of the concentrations of the exhaust gases at the outlet of the three pressure levels boiler for each of the proposed configurations, that is, CCGT and CCGT + (35–40)% EGR. Table 1 shows these concentrations after the contrasted simulation.

It will be significant to demonstrate that these improvements are achievable, added to the already commented like regeneration/hybridization, quantifying-optimizing all advantages. For it will be necessary, already has been commented, to establish for one part the dimensions of the PCC (trains number, size of the absorber and the stripper,

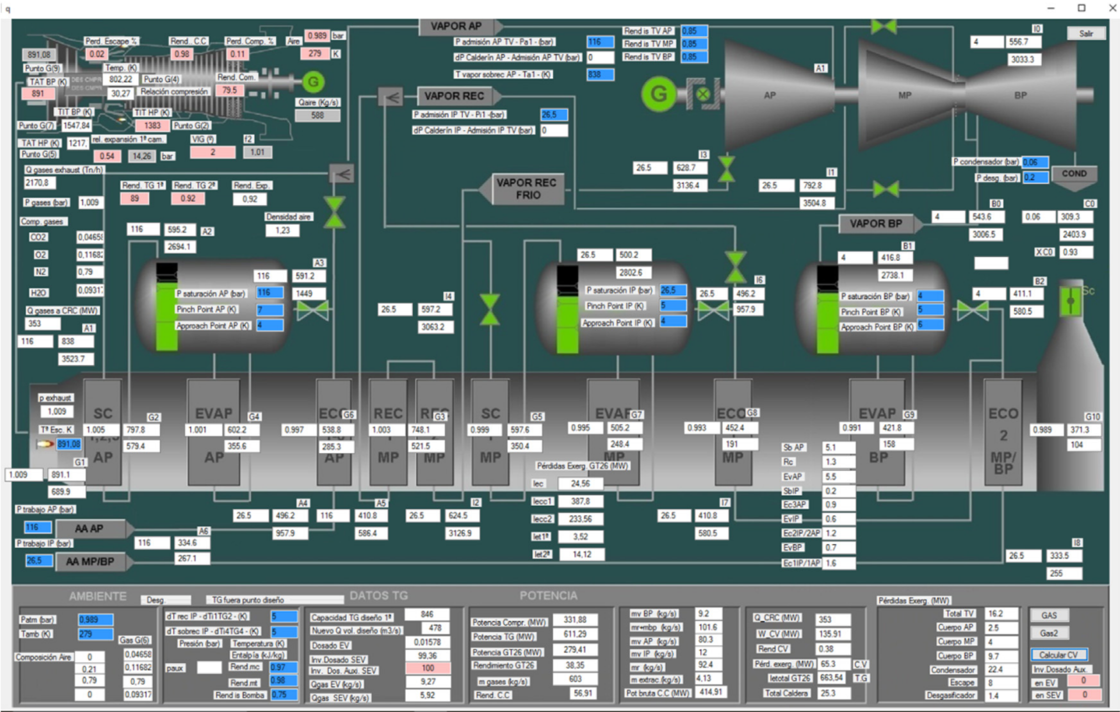

Fig. 2. Simulation model of existing CCGT Group 3 Castejón of Navarra (Spain) in loading point 401 MW.

etc... within the existing CCGT) and on the other hand studying the penalties that both configurations introduce in the global cycle of the existing CCGT evaluating possible future investments in the existing cycles. Finally, assessing the new sustainability in decreasing CO_2 emissions and the performance in new configurations (CCGT with PCC and CCGT+PCC+EGR) that last would be obtained. All this is proposed maintaining the conventional design of the existing CCGT using real data from the existing CCGT.

A scheme of the existing CCGT consisting in a triple-pressure steam-reheat cycle, $CCGT_{3PR}$, with one sequential combustion gas turbine is showed in Fig. 2. The theory applied for the modelling in different loading points of charge was presented and widely contrasted in detail by Colmenar-Santos et al. [2].

The mainly parameters defining the gas turbine and the boiler and the rest of input data and assumptions for Rankine and Brayton cycle are defined in detail following these previous work. With the exhaust gases composition obtained in each loading points one thermodynamic optimization was applied in to the PCC with the application of one multiparametric analyses and comparative study minimizing the penalty in thermal efficiency of the new combined cycle with only PCC or PC C+35%–40% EGR. Process flow diagram for MEA with 30 wt%, based in chemical absorption process, is simulated in HYSYS/ASPEN PLUS and showed in Fig. 3.

The flue gas temperature that enters in the absorber is 32 °C, previously it is necessary to make a reduction in the output temperature of the HRGS around 100 °C, and is brought into direct contact with the solvent. A temperature of 40 °C at the inlet of the absorber is considered for the solvent MEA. The flue gas temperatures at the inlet and at the outlet of the absorber column are similar (46 °C on the top in clean gases) to maintain the water balance in the system. The rich solvent coming out of the absorber is reheated in the lean-rich heat exchanger and enters to the top of the stripper column where it is thermally regenerated maintaining a temperature close to 118 °C and (1.85 to 1.9) bar in the reboiler (maximum allowable regeneration temperature is around 120 °C to prevent polymerization of the MEA [19]). The lean-rich solvent heat exchanger is designed based on to obtain at the inlet of the stripper one lean-rich solvent temperature close to 95 °C to 100°C. The stripper is designed to achieve a fixed molar CO_2 recovery ratio and the number of equilibrium stages is consequently defined. The CO_2 recovery ratio is set to control the lean solvent CO_2 loading at which the stripper column operates, and its value is selected to bring the specific heat consumption to a minimum. Finally, the CO_2 capture rate in the global plant is near to 90%.

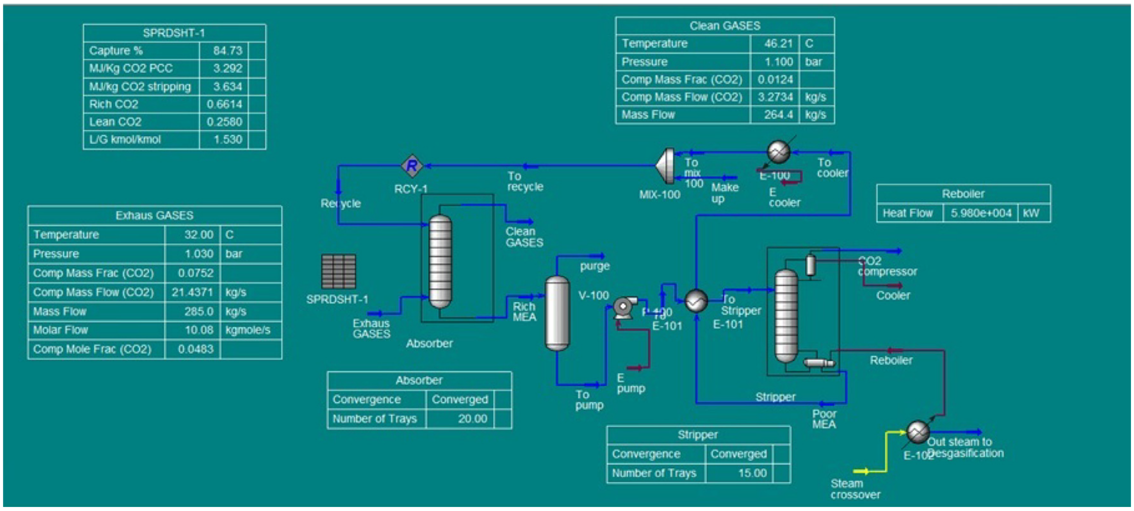

Fig. 3. Scheme of one train of exhaust gases in existing CCGT+35% EGR+PCC plant simulated in HYSYS/ASPEN +.

The steam generated in the reboiler strips off the CO_2 from the solvent. The steam phase leaving the top of the stripper column is condensed at approximately (40 to 45) °C. The condensed liquid is separated from the gas phase in a flash vessel and recycled back to the stripper at the top stage (reflux ratio used 1.1). The CO_2-rich gas, with a CO_2 concentration close to 95%vol, is compressed, liquefied and pumped up to (80 to 100) bars for transport and storage with purity close to 99%. The regenerated solvent (lean solvent) returns to the absorber at the first stage, after being cooled down to 40 °C, firstly in the lean-rich heat exchanger and then in the lean solvent cooler. The optimization of the PCC integrated inside the existing CCGT was carry out amply publicized works [15,20].

The thermal energy is supplied in the reboiler by one crossover using an extraction of steam from IP/LP pressure bodies coming from the steam cycle previous to the expansion in the LP turbine. Conditions of the extraction, at the outlet of the IP-LP, are close to 4 bars of pressure being necessary determinate the mass flow that go to the PCC depending of the loading points and the configuration with or without ERG (35–40)%.

For each configuration e.g., CCGT+PCC and CCGT+PCC+%EGR with a CO_2 concentration set in the exhaust gases and a flow rate fixed in 285 kg/s (one train to obtain reasonable columns diameters in both absorber and stripping), the minimum specific reboiler duty, in MJ/kg CO_2, is evaluated carrying out a sensitivity analysis of the lean solvent flow rate entering the absorber. The conditions in the stripper are set to achieve the lean solvent CO_2 loading resulting in the required CO_2 capture efficiency in the absorber to achieve an overall CO_2 capture level close to 90%. A fixed CO_2 capture level is considered with the intent of comparison the different configurations.

The research is proposed in these four points: 173, 284, 348 and 401 MW. These loading points were selected to cover the complete range of actual operation in existing CCGTs (164 to 401 MW approximately). The analysis of the exhaust gases at these four loading points will make it possible to identify tendencies like new efficiencies, consumptions and losses within the new configurations improved providing essential information for the final decision of their possible application. With these simulation programs, all data base can be easily adapted using mass and energy balances providing an almost optimal design strategy and gave us total security in the results obtained.

The input data and assumptions for PCC simulations, including CO_2 compression station, are summarized in Table 2, Table 3 and in Section 4 Discussion and results. With these simulations, it will be possible to assess the feasibility of the technological improvements. Indicate that the results obtained in the simulation of the PCC, within the existing combined cycle, contrast perfectly within the values obtained in previous studies. The compression process in six stages supposes a penalty in the auxiliary energy in the global plant adding a value close to 4% (the normal value use to be the 2% close to (8 to 10) MW.

It was commented that our obtained simulated results with real data base show that, compared with the existing CCGT, the improvements regeneration in GT+ hybridization (with steam introduced at the high-pressure level of the boiler from a source of renewable solar energy up to 50 MW) could increase the performance of the Brayton cycle

Table 2. Simulation summary between existing CCGT+PCC versus CCGT+EGR (35–40)%+PCC.

Loading point (%)	100	88	73	46
Number of trains for EGR 35%	1.36	1.21	1.07	0.84
Number of trains without EGR	2.09	1.86	1.64	1.29
Number of trains for EGR 40%	1.25	1.12	1,0	0.78
Steam necessary crossover 35% EGR+ PCC (kg/s)	31.01	27.66	24.39	19.2
% steam crossover with 35% EGR+PCC	30.08	26.83	23.66	18.63
% performance reduction in CCGT with 35% EGR +PCC	4.67	4.16	3.67	2.88
Performance reduction in CCGT with EGR 35% + PCC	2.46	2.19	1.93	1.52
% power reduction in CCGT with EGR 35% +PCC	13.61	12.13	10.69	8.4
Steam necessary crossover without EGR + PCC (kg/s)	47.71	42.55	37.53	29.54
% steam crossover without EGR+PCC	46.27	41.26	36.39	28.65
% performance reduction in CCGT without EGR + PCC	7.19	6.41	5.65	4.45
Performance reduction in CCGT without EGR + PCC	3.79	3.37	2.98	2.34
% power reduction in CCGT without EGR + PCC	20.99	18.71	16.49	12.96
Energy compression/kg CO_2 PCC (MW/kg) 35% EGR	0.62	0.55	0.49	0.39
Energy compression/kg CO_2 PCC (MW/kg) without EGR	0.96	0.85	0.75	0.59
Energy compression/kg CO_2 PCC (MW/kg) 40% EGR	0.57	0.51	0.45	0.36

Table 3. Important input data obtained in CCGT+PCC and CCGT + PCC + 35%EGR simulation in HYSYS/ASPEN +.

SIMULATION existing CCGT+PCC (30% wt MEA)		SIMULATION existing CCGT+PCC (30% w MEA) + 35% EGR	
Loading point (%)	100%	Loading point (%)	100%
Absorber/train		**Absorber/train**	
Mass flue gas IN (kg/s)	285	Mass flue gas IN (kg/s)	285
CO_2 conc. (wt%)	6.5	CO_2 conc. (wt%)	10.1
CO_2 conc. Flue gas clean (wt%)	1.24	CO_2 conc. Flue gas clean (wt%)	4.16
Absorber efficiency (%)	84.73	Absorber efficiency (%)	61.17
MEA solvent/recycle T^a (°C)	40	MEA solvent/recycle T^a(°C)	40
Flue gas IN T^a (°C)	32	Flue gas IN T^a (°C)	32
Absorber column pressure (bar)	1.2	Absorber column pressure (bar)	1.2
Lean solvent loading (molCO_2/molMEA)	0.26	Lean solvent loading (molCO_2/molMEA)	0.23
Rich solvent loading (molCO_2/molMEA)	0.66	Rich solvent loading (molCO_2/molMEA)	0.49
Lean solvent molar flow rate (kg/s)	324	Lean solvent molar flow rate (kg/s)	186.2
Diameter (m)	10.06	Diameter (m)	9.90
Packing height (m)	19.99	Packing height (m)	19.9
Packing	Mellapak 250Y	Packing	Mellapak 250Y
N^o trays	20	N^o trays	20
Stripper/train		**Stripper/train**	
Stripper pressure (bar)	1.8	Stripper pressure (bar)	1.8
Pressure steam saturated crossover (bar)	3	Pressure steam saturated crossover (bar)	3
Steam specific consumption (kg/kg CO_2)	1.39	Steam specific consumption (kg/kg CO_2)	1.38
Specific reboiler duty (MJ/kg CO_2)	3.634	Specific reboiler duty (MJ/kg CO_2)	3.61
Reboiler pressure (bar)	1.9	Reboiler pressure (bar)	1.9
Reboiler temperature (°C)	117.4	Reboiler temperature (°C)	122
Diameter (m)	4.34	Diameter (m)	4.11
Packing height (m)	11.58	Packing height (m)	11.36
N^o trays	15	N^o trays	18
CO_2 compression/train		**CO_2 compression/train**	
CO_2 purity (% wt)	99.7	CO_2 purity (% wt)	96.84
Compression: 6 stages pressure ratios	5/2/2/2/2/2	Compression: 6 stages pressure ratios	5/2/2/2/2/2
CO_2 final pressure (bar)	110	CO_2 final pressure (bar)	110
Specific compression work (kJ/kg CO_2)	404.8	Specific compression work (kJ/kg CO_2)	356.5
N^o trains	2.1	N^o trains	1.4

around 2% to 3% attached with the reduction of gas consumption (between 6% and 9% approximately) being the overall cycle efficiency loss minimal. Other results obtained in the previous study: regeneration + solar hybridization could contribute to increasing efficiencies depending on the loading point. Other important factor obtained in the

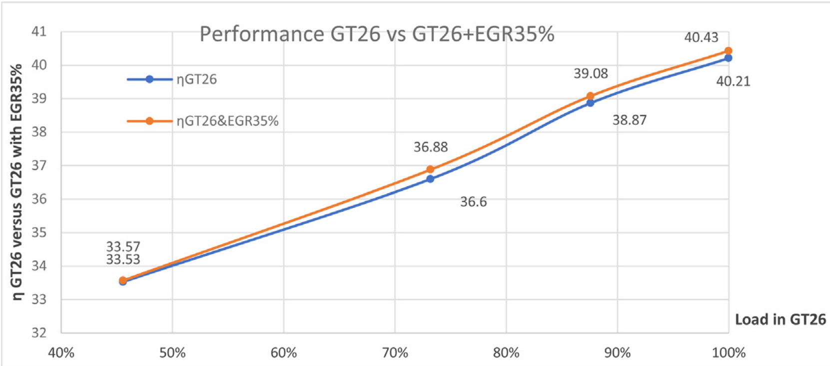

Fig. 4. Comparison of performance between existing CCGT vs CCGT with exhaust gas recirculation in gas turbine GT26.

simulation was the loss of the net power of the new global cycle: 7.5% with regeneration only and of 1% with regeneration and hybridization. Considering these results, our challenge is looking for the reduction at minimum for the gases with the most economic treatment before coming out to atmosphere once generated in the existing CCGT.

3.1. Existing CCGT versus CCGT with EGR close to (35–40)%

The improvement in the performance in the gas turbine GT26 with the EGR about (35–40)% can be appreciated in Fig. 4.

Depending on the loading point the improvement is noticeable and close to 0.5%. The changes in the exhaust gases composition, coming out from HRSG, depend on the% of EGR that come back to the GT. For example, the CO_2 gas concentration in final exhaust gases rise close to 6.5%vol from approximately 4.8%vol in the existing CCGT at loading point of 100% (close to 11% for 40% EGR).

By this increasing in CO_2 concentration in exhaust gases finally the high electrical efficiency penalty caused by chemical absorption will be reduced. However, the oxygen concentration decreases in the first chamber from 21%v to 16.6%v being a serious problem for the complete combustion and the maintenance of one stable flame when a mayor EGR 35% is realized (the limit determined by the manufacturers is around 16%v [21]). The EGR close to (35–40)% could be the maximum for it. On the other hand, the oxygen decreasing could bring other advantages: decreasing in NOx formation (reducing the oxygen concentration in the combustion air may be advantageous with respect to the formation of NOx). Moreover, one rising in %EGR means a decreasing in number of trains necessaries in the PCC plant. Others results obtained, because of increasing CO_2 concentration in the new exhaust gases, are the decreasing quantitatively on the energy demand in the reboiler of MEA-based chemical absorption. Finally, the decrease of O_2 concentration in the PCC causes a less degradation of amines which could lead to corrosion problems. Hence, a % of EGR could also minimize the need for chemical inhibitors or process modification involving the regeneration of the amine in the reboiler.

3.2. Existing CCGT with PCC versus CCGT with EGR 35%+ PCC

Taking in account both, the exhaust gases concentration in the existing CCGT and the CCGT with EGR, one train of 285 kg/s was simulated in HYSYS/ASPEN + (approximately the half of the total exhaust gases produced). For these exhaust flow rates, the maximum diameters in the absorption and stripping columns are obtained taking in to account [22,23], being necessary to divide the flow of exhaust gases into several trains in order to be treated correctly.

The main results obtained of the simulation are showed in Tables 2 and 3. A summary of these tables is firstly: use a 35% of EGR decreases the number of trains from 2 to 1.36 and secondly when increasing it from 35% to 40% decreases from 1.36 to 1.25. This decreasing is traduced in costs reduction and due to it an effective technique for pollutant emissions reduction. On the other hand, we have the efficiency penalty caused by chemical absorption.

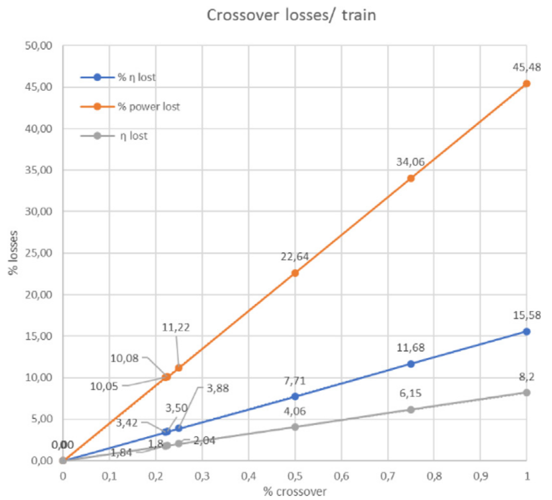

Fig. 5. Graphic % crossover versus % losses in performance and power in global cycle existing CCGT + 35% EGR+PCC.

This penalty is high in the Rankine cycle because is necessary to use a great% of the steam from IP/LP for the crossover. Therefore, for a 100% load point (full load and maximum exhaust gas flow and high CO_2 concentration) the existing combined cycle with EGR + PCC requires approximately 30% of the steam of the IP/LP turbine to the capture of 90% of CO_2 with the corresponding penalty of 2.46 points in the performance of the global cycle and a reduction of power close to 14% with respect to the power of the steam turbine output without PCC. Without EGR, the penalty at this point would be greater, with around 4 points being the loss of the overall performance of the cycle and a loss of power in the Rankine cycle of approximately 21%.

As previously mentioned, the results for the existing cycle are within the range of the values obtained in other similar ones with other types of thermal power plants being totally validated for their construction at present (e.g. columns size and diameters).

It is necessary to indicate that for the configuration 35% EGR + PCC the concentration of carbon CO_2 barely changed at the different points of loading, maintaining around 6.5%vol. That is why in the following Table 3 only the simulation values for the loading point of full load is showed. For the configuration of the cycle with only PCC in the remaining loading points, the values obtained are approximate or lower than those obtained for the point of full load and are not shown in order not to complicate the manuscript too much.

Finally, in Fig. 5 losses of performance and power in global cycle in new existing CCGT +35%EGR + PCC are showed. For one% of penalty crossover necessary at full load (approximately 30%) the total number of tons of CO_2 avoids per year would be around 366 kilotons (using a capacity factor in 2018 close to 0.22).

For draw conclusions indicate that for example this year 2019 in which, as already mentioned, there has been the general closure of most of the conventional coal plants, the existing CCGT in study have closed the year with a factor of capacity close to 0.41%. Therefore, the study of integration of the PCC within the existing CCGT can be promising with more ton of CO_2 that will be avoided (price between (25 to 30) €/ton) and therefore almost double the costs CO_2 emissions avoided than in 2018 (approximately 21.4 million of euros/year). With these numbers and the new upward trend integration could be totally feasible.

This reduction in costs is important in the configuration CCGT+35% EGR+PCC but must be considered the important reduction in steam inside the existing HRSG for the regeneration in the PCC. Important to say, see [2], that this reduction could be perfectly supported by the introduction of solar thermal power from renewable sources. With EGR approximately the 35% is reutilized again in Brayton cycle and the rest would go to the PCC for be treatment in several trains.

It is necessary to say that a greater exhaustive economic evaluation must be taking in to account. As has been succinctly predicted in this technical-quantitative study, currently the price ton of CO_2 makes the operation of conventional (more polluting) plants unfeasible and this makes that CCGTs become more relevant in future years: with much more capacity factor values, more flexible with the network operator, and higher efficiencies in GT and steam cycle. It is certain that the implementation of these technological improvements will far exceed the costs of investment. Indicate succinctly that results obtained in our simulation, in line with studies already carried out regarding specific investment [24–27], an existing CCGT with PCC + CO_2 compression in six stages would double the initial cost in €/kW installed. In this value was not the sale price of compressed CO_2 whose output would be around 1358 €/ton CO_2 (200 bar) which would help alleviate the great investment that should be done.

One of the advantages offered by the integration of EGR in existing CCGT+ PCC is the reduction in CO_2 emissions. This is even more important if we consider that the elevate price of CO_2 emissions ton is rising. Existing CCGTs are the most efficiency technology with elevate performances close to 60%. Future work should be focused on the introduction of these technological improvements on the currently operating CCGTs. A priori the studies are promising, and these techniques could become an attractive alternative in the quest of achieving improved performance and energy efficiency for the year 2020 in existing CCGTs.

4. Conclusions

Coal power plants will be destined to close during the next few years. Existing CCGTs, more sustainable and efficiency technologies based on the use of natural gas, generate less pollution and for it will be the reference in the next years. In this document exhaust gas recirculation and CO_2 capture plant have been considered like one step forward to improve the global emissions in one existing CCGT. The thermal integration, with real data base in different loading points, is performed using models already proved and validated [2]. All with the objective of reducing CO_2 emissions at the atmosphere looking for increasing the sustainability and efficiency of existing CCGTs.

Results are very promising: firstly, with the use a 35% of EGR+PCC in existing CCGT the efficiency of the GT26 improve 0.5%. Secondly, the total number of tons of CO_2 avoid per year would be around 366 kilotons (using a factor capacity in 2018 close to 0.22). Therefore, with upward price of ton CO_2 and the increasing in capacity factors, the avoid cost in ton of CO_2 for one existing CCGT would be around 21.4 million of euros/year.

This configuration, % EGR+PCC, therefore, decreases the number of trains from 2 (existing CCGT+PCC) to 1.36. This decreasing is traduced in costs reduction and because of it an effective technique for pollutant emissions reduction.

Results obtained in simulation model and carbon capture plant are in contrast totally with other studies carried out being fully possible to be implemented in existing CCGTs.

On the other hand, the improved CCGT will have an efficiency penalty caused by chemical absorption in the PCC. The crossover requires approximately 30% of steam coming from middle/low pressure bodies obtaining CO_2 capture close to 90% with the corresponding penalty of 2.46 points in the performance of the global cycle and a reduction of power close to 14% with respect to the power of the steam turbine output without PCC. Without anyone percentage of EGR in gas turbine, the penalty at this point would be greater, with around 4 points being the loss of the overall performance of the cycle and a loss of power in the Rankine cycle of approximately 21%.

These improvements, EGR+PCC, could be promising alternatives to be integrated in existing CCGTs just now the price of ton CO_2 is rising (will close to 25 €/ton in 2019) and on the other hand these most efficiency technologies are moving away definitively the old technologies based in coal. Other important detail to take into account is that the new CCGT with PCC + CO_2 compression in six stages would double the initial cost in €/kW installed. In this value was not the sale price of compressed CO_2 whose output would be around 1358 €/ton CO_2 (200 bar) which would help alleviate the great investment that should be done.

This study is a new step forward to improve the sustainability and maintenance the actual efficiency of these plants taking in to account other studies who advocate for regeneration and hybridization for example. These improvements could have a positive influence and could mitigate the decreasing in CO_2 emissions to the atmosphere. All boil down to a conflict of interests between the €/MW lost vs €/ton CO_2 avoided/savings. Clearly the actual rising in capacity factor and sustainability in existing CCGTs will be decisive in future to elucidate these conflicts.

These studies and simulations based on real data base of the existing CCGT in different loading points are promising and seem to offer a powerful tool to draw conclusions in possible future investments in actuals CCGTs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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