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Energy and economic analysis of the CO_2 capture from flue gas of combined cycle power plants

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Abstract

Carbon capture and storage is considered as one of the key strategies for reducing the emissions of carbon dioxide from power generation facilities. Although post-combustion capture via chemical absorption is now a mature technology, the separation of CO_2 from flue gases shows many issues, including the solvent degradation and the high regeneration energy requirement, that in turn reduces the power plant performances.

Focusing on a triple pressure and reheat combined cycle with exhaust gas recirculation, this paper aims to evaluate the potential impacts of integrating a post-combustion capture system, based on an absorption process with monoethanolamine solvent. Energy and economic performances of the integrated system are evaluated varying the exhaust gas recirculation fraction and the CO_2 capture ratio. The different configurations examined are then compared in terms of efficiency and rated capacity of the integrated system, as well as considering the cost of electricity generated and the cost of CO_2 avoided.

Keywords: NGCC, CO_2 capture, post-combustion, MEA, economic evaluations

1. Introduction

The EU's objective of reducing the greenhouse gases emissions by at least 20% in 2020 can be accomplished by promoting renewable energy resources, improving energy efficiency and implementing low-carbon technologies. In this context, carbon capture and storage (CCS) has received an increasing attention as a potential option to directly reduce the CO_2 emissions, thus limiting the global climate changes [1].

CCS technologies are based on the idea to separate the carbon dioxide produced by fossil fuel power plants and permanently store outside the atmosphere. CO_2 capture can be achieved by three main techniques: pre-combustion

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and post-combustion capture, where CO_2 is removed before or after the fuel burning, and oxy-fuel cycles where pure oxygen rather than air is used for combustion [2].

Among the post-combustion capture techniques, the most promising and mature technology is the absorption process based on a chemical solvent, such as monoethanolamine (MEA) [1]. In this case the flue gas from fossil fuel power plants is scrubbed by chemical reactions and the resulting stream of concentrated CO_2 is then compressed for transport and storage [2].The main disadvantage when applying chemical absorption process is the thermal energy requirement for dissolving CO_2 from the solvent [3]. In addition to the large energy penalty inflicted, other important challenges concern the thermal and oxidative solvent degradation, the equipment corrosion, and the environmental issues related to the disposal of the degradation products [4]. When the post-combustion CO_2 capture is applied to combined cycle power plants, these issues are aggravated by the high exhaust gas flow rates and the low CO_2 concentrations, which account for an increase of both the size of the removal system and the energy requirement for amine regeneration [5].

Hence, many studies have dealt with the problem of integrating a CO_2 capture system within combined cycles, in order to reduce the energy and economic penalties [5-9]. Traditionally the increase of the CO_2 concentration of the exhaust gases is obtained through exhaust gas recirculation (EGR), which also allows to reduce the flue gas flow rate to be treated by the post-combustion capture system. Indeed, compared to other techniques for enhancing the CO_2 concentration, such as humidification, supplementary and external firing, EGR enables the highest efficiency, due to a more efficient thermal integration of different subsystems [9].

The aim of this paper is to investigate the integration of a carbon capture system, based on MEA absorption into a natural gas fired combined cycle, based on a triple pressure and reheat heat recovery steam generator. The energy and economic performances of the integrated system are evaluated for various percentages of exhaust gas recirculation and CO_2 capture ratios. The energy analysis is performed at design conditions, using the GateCycle software [10] for the natural gas combined cycle and the ChemCAD software [11] for the CO_2 removal system, properly integrated into Excel environment by means of macros developed in Visual Basic. The economic analysis focuses on the cost of electricity (COE) and the cost of CO_2 avoided, which are evaluated through cost functions that take also into account for the impact of EGR and capture ratio on equipments capital costs.

Nomenclature

<u>Symbols</u>		<u>Acronyms</u>	
$CO_{2,\,em}$	Specific CO_2 emissions, kg/MWh	CCS	Carbon Capture and Storage
M	Mass flow rate, kg/s	COE	Cost of electricity, $/MWh
Q	Volumetric flow rate, m^3/s	EGR	Exhaust Gas Recirculation
		HRSG	Heat Recovery Steam Generator
<u>Greek letters</u>		MEA	Monoethanolamine
φ	CO_2 capture ratio, %	NGCC	Natural Gas Combined Cycle
H	Efficiency, %	TEC	Total Equipment Cost, M$
		TOC	Total Overnight Capital, M$
<u>Subscripts</u>		3RLH	Triple pressure level reheat plant
EXH	Exhaust	LPST	Low pressure steam turbine
FG	Flue gas	O&M	Operation and Maintenance
Ref	Reference (w/o CO_2 capture)	LHV	Lower heating value
S	Steam	WHTR	Water heater

2. Effects of the exhaust gas recirculation on the integrated power plant

The main drawbacks of integrating a CO_2 capture system into a natural gas combined cycle (NGCC) concern the high flow rates of flue gas to be treated and its low CO_2 concentration, resulting from the high excess air used for the combustion process. While the first aspect adversely affects the size of the capture system, the second accounts for an high amount of thermal power for the amine regeneration. As well known, the CO_2 concentration in the exhaust gas can be increased through the exhaust gas recirculation (EGR), which in turn allows a reduction of the flue gas to be treated [12]. The EGR markedly affects the size and the energy requirement of the capture system, having also non-negligible implications for the NGCC. In this study the effects of exhaust gas recirculation have been preliminary assessed for the NGCC and the CO_2 capture plant, assuming that these systems are not integrated.

2.1. EGR effects on a triple pressure and reheat combined cycle

The baseline natural gas combined cycle, simulated using the commercial software GateCycle [10], is based on a F-series General Electric gas turbine (PG9351), having a rated power of 252 MW and a LHV efficiency of 36.5% without exhaust gas recirculation. The steam turbine comprises high, intermediate and double-flow low pressure sections, a condensing system and a heat recovery steam generator (HRSG) with three pressure levels and reheat, including a preheater, 3 economizers, 3 evaporators, 3 super-heaters and a reheater.

Compared to a traditional NGCC, a fraction of the exhaust gases leaving the water preheater (WHTR) is mixed to the air at the compressor inlet. In order to reduce the temperature of the recirculated gases and the volumetric flow rate at the compressor inlet, the NGCC plant also includes a two-stage flash separator that cools the exhaust gas to a temperature of 25°C, thus allowing the separation of the excess condensed water.

As shown in Fig. 1a, increasing the percentage of exhaust gas recirculation, the CO_2 concentration in the exhaust gases increases from 4 to 8.5% for EGR=50%, while the exhaust gas flow rate drops from 615.2 to 300.8 kg/s. At the same time, the oxygen concentration in the exhaust gases decreases, with beneficial effects on CO_2 capture system, reducing the amine degradation and the corrosion phenomena related to the oxygen by-products [13].

The exhaust gas recirculation also affects the thermodynamic properties in main sections and the performances of the NGCC. In fact, the decrease of the oxygen concentration can compromise the flame stability and combustion efficiency, considering that combustors are designed for about 20% O_2 concentration. Experimental studies have shown that it is not possible to fall below 16% of the O_2 concentration at the combustor inlet, in order to avoid an excessive formation of unburned hydrocarbons [14]. Thus, the EGR ratio cannot exceed 35%, unless of technical adaptations of combustion chamber in order to allow the injection of additional oxygen [15].

The EGR has also an important effect on the oxidant temperature at the compressor inlet: it increases with the EGR (Fig. 1b), leading to a decrease of the fuel-to-oxidant ratio to achieve the established temperature in the combustion chamber. Thus, the rated power of the gas turbine undergoes a slight reduction, reaching about 246 MW for EGR=50%. At the same time, as the temperature of the exhaust gas rises from 615 to 630°C, a slight increase of steam power cycle capacity also occurs.

Due to these contrasting effects, the rated power of the NGCC has the trend shown in Fig 1c, featured by a minimum (383 MW) corresponding to a recirculation ratio close to 35%. On the other hand, the LHV efficiency slightly increases with the EGR, gaining less than 1 percentage point for EGR=50%. This aspect positively affects the specific CO_2 emissions referred to NGCC, that decrease of about 2%, reaching 377 kg/MWh (Fig. 1d).

2.2. EGR effects on the CO_2 post-combustion capture plant

In this study the CO_2 is captured from the NGCC flue gas using a chemical absorption process, based on an aqueous solutions of monoethanolamine. The CO_2 capture system is simulated using the software ChemCAD 6.3, by Chemstations [11].

The CO2 removal target depends on the absorption and desorption processes where the main parameters of both processes are strongly coupled. Consequently, the simultaneous optimization of the whole CO_2 capture process is essential to determine the best design and operating conditions in order to minimize the total cost [16]. The post-combustion CO_2 capture system is composed by two main parts: the section where the carbon dioxide is absorbed and the stripper where the solvent is regenerated. As shown in Fig. 2, the flue gas coming from the NGCC (at 40°C and 1.01 bar) is compressed and fed to the absorber, where CO_2 is absorbed by a countercurrent flow of 30 wt% MEA solution.

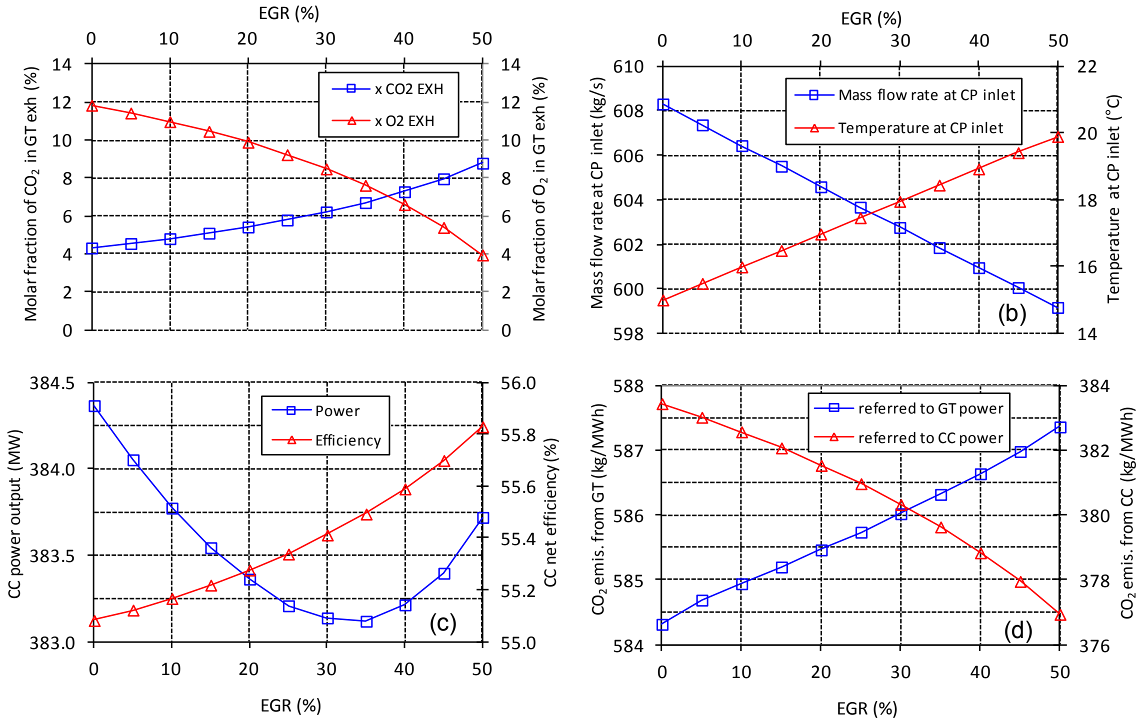

Fig. 1. Effects of exhaust gas recirculation on NGCC-3LRH without CO_2 capture system

The loaded MEA solvent exiting the bottom of the absorber is pumped through a cross flow heat exchanger where it is heated up to 122°C, by sensible heat coming from the regenerated amine. The pre-heated rich solution is then passed to the top of the stripper column, in which the CO_2 is desorbed. The regenerative section is composed by three main units: the stripper column, the condenser at the top and the reboiler at the bottom. In the stripper the rich solution meets the hot vapour from the reboiler and the CO_2 is separated from the amine. The top temperature of the stripper is set to 55°C in order to ensure the purity of the CO_2 captured over 90% in moles. The stream at the stripper top, containing carbon dioxide, steam and vapour, is partially condensed in the condenser and the gaseous CO_2 is sent to the compression section where it is compressed to 138 bar. Table 1 summarizes thermodynamic properties and composition of the main streams in the case without exhaust gas recirculation.

The regenerated solvent is cooled by the rich amine stream and finally sent back to the absorber. As shown in Table 1, there is a small amount of MEA in the lean gas; therefore, due to these losses and the degradation of the solvent, it is necessary to replenish it with a make-up stream. Moreover, the regenerated solvent is not completely free of CO_2. The level of lean solvent CO_2 loading mainly depends upon the initial CO_2 loading in the solvent and the amount of regeneration heat supplied. Hence, the regeneration heat requirement depends on the allowable level of lean sorbent loading, that has been set to 0.25 $kmol_{CO2}/kmol_{MEA}$ in all cases investigated [17].

As observed above, the main disadvantage of chemical absorption arises from high amount of thermal energy needed to regenerate the solvent in the stripping column. In this paper a correlation between the specific reboiler duty and the CO_2 concentration has been derived:

$$Y = A + Bx_{CO_2} + C/x_{CO_2} + D/{x_{CO_2}}^2 \quad (1)$$

where x_{CO_2} is the percentage concentration of CO_2 in the flue gas to be treated and the coefficients depend on the capture ratio (Table 2). As shown in Fig. 3, the reboiler duty significantly reduces at increasing of x_{CO_2} from 2% to 9%, whereas the energy savings per kg of CO_2 captured are negligible for CO_2 concentrations higher than this limit.

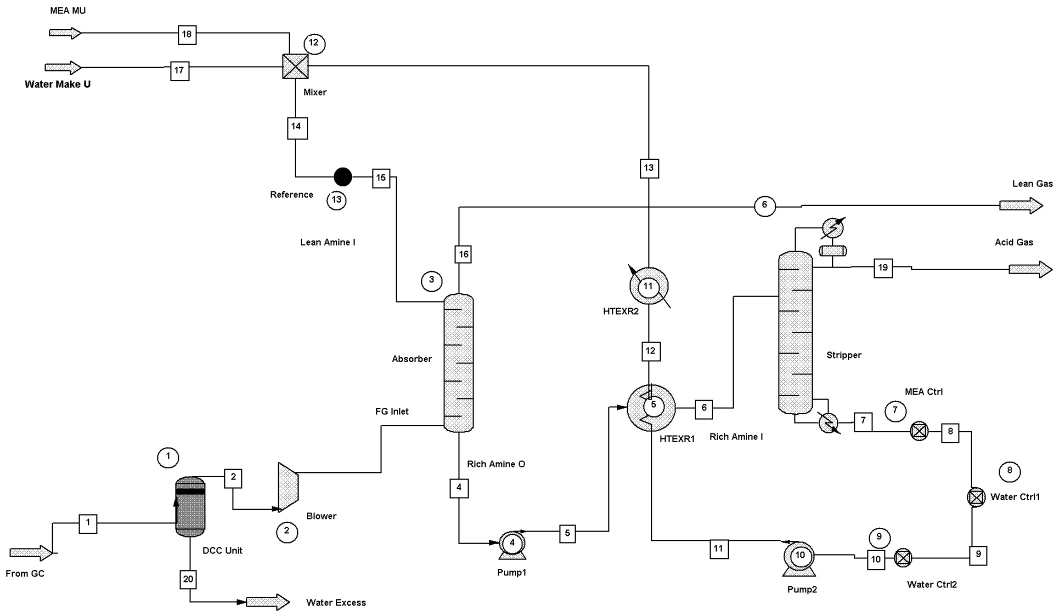

Fig. 2. Layout of the CO_2 capture plant

3. Energy performances of NGCC with CO_2 capture

In the study case, the thermal power for amine regeneration is provided by a steam extraction at the crossover pipe between intermediate and low pressure steam turbines at 4.8 bar and 234°C, as shown in Fig. 4. The steam extracted leaves the reboiler as saturated liquid; then it goes back into the steam cycle upstream the preheater (WHTR).

The effects of CO_2 capture ratio (φ) and exhaust gas recirculation (EGR) on the specific reboiler duty are highlighted in Fig. 5: the φ ratio mainly affects the steam mass flow rate to be extracted and the NGCC efficiency penalties, while EGR fraction the size of the CO_2 capture system and its energy requirements. As shown in Fig. 5, for a capture ratio up to 85%, the specific reboiler duty is almost constant, stating at about 3 MJ/kg; further increasing the CO_2 capture ratio, the reboiler duty substantially rises, exceeding 4.2 MJ/kg at φ=95% in the case without exhaust gas recirculation.

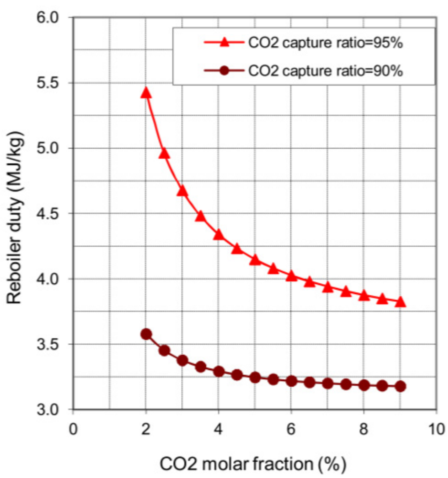

Fig. 3. Reboiler duty vs. the CO_2 concentration for different CO_2 capture ratios

Table 1. Main properties of streams without EGR

	FLUE GAS	LEAN GAS	ACID GAS
Temperature, °C	25	49	55
Pressure, bar	1.01	1.01	2.50
CO_2 Capture ratio, %	90	90	90
Lean CO_2 loading, $kmol_{CO2}/kmol_{MEA}$	0.25	0.25	0.25
Total mass flow rate, kg/s	615.2	605.2	37.6
Monoethanolamine, %	0.00	0.10	0.00
Water, %	4.59	8.98	2.69
Carbon Dioxide, %	6.61	0.67	97.30
Nitrogen, %	74.26	75.47	0.01
Oxygen, %	13.28	13.50	0.00
Argon, %	1.26	1.28	0.00

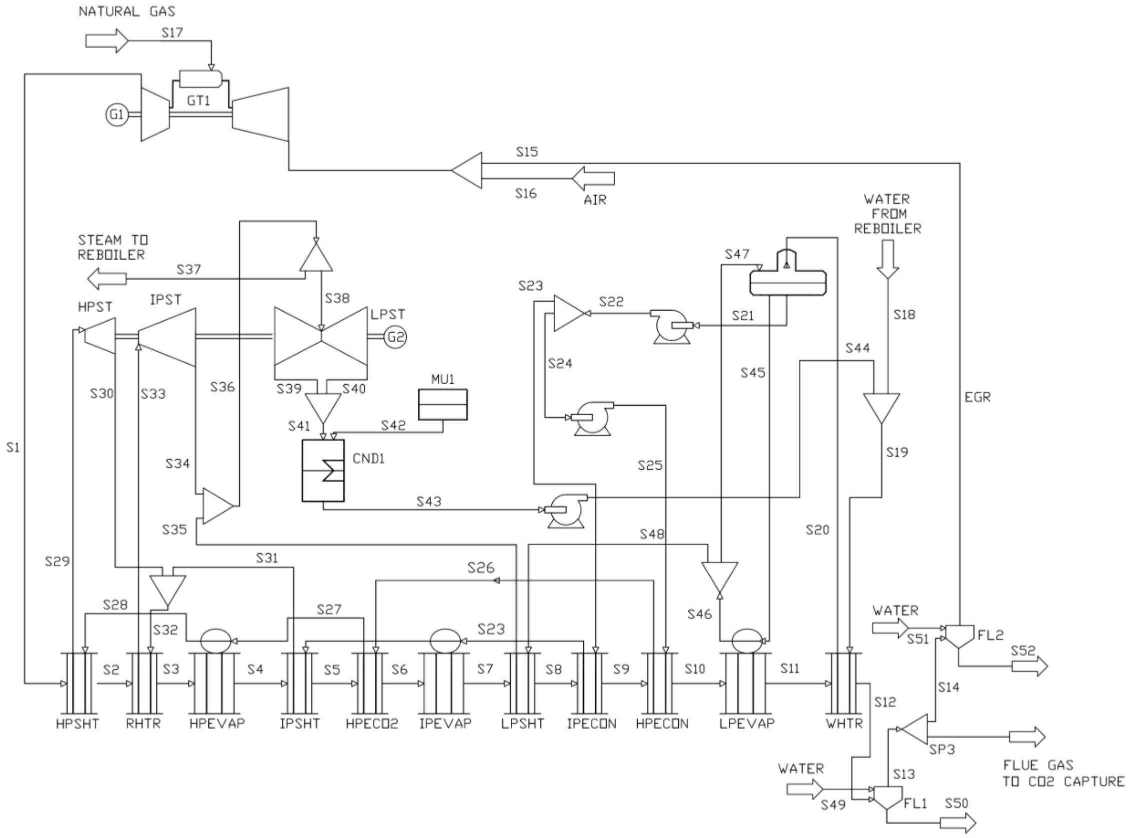

Fig. 4. Layout of NGCC with exhaust gas recirculation and integration with the CO_2 capture system

Table 2. Coefficients for the specific reboiler duty correlation, Eq. (1)

φ	90%	95%
A	3.0777	3.5124
B	0.0022	-0.0034
C	0.6625	2.9001
D	0.6611	1.8943

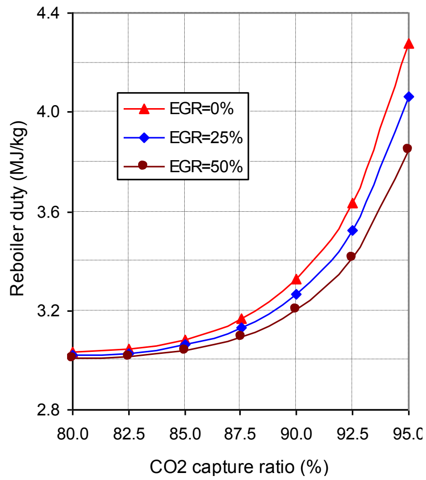

Fig. 5. Reboiler duty vs. the CO_2 capture ratio for various EGR

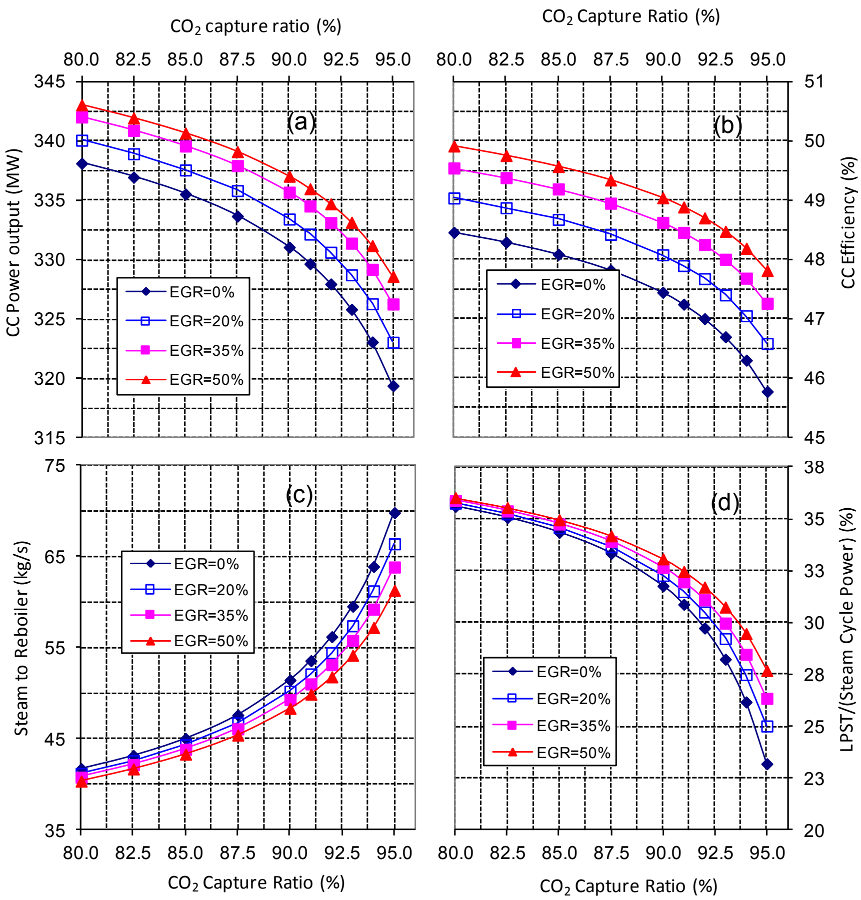

Fig. 6. Effects of CO_2 capture system integration on NGCC performances

As observed above, the integration between the steam section and the carbon capture system affects the performances of NGCC power plant. In this regard, Fig. 6 highlights the impact of the CO_2 capture ratio and the percentage of exhaust gas recirculation on steam extraction rate, net NGCC performances, as well as on the percentage incidence of the low-pressure turbine power with respect to the total rated steam plant capacity.

Fig. 6c shows that the steam extraction for amine regeneration increases markedly for φ higher than 90%. Thus, for EGR=35%, the steam extraction flow rate rises from 41 to 64 kg/s, passing φ from 80 to 95%. For a fixed capture ratio, the steam extraction rate decreases with EGR, due to the lower exhaust gas flow rate to be treated. Alternatively, for a fixed steam flow extraction, the increase of exhaust gas recirculation allows a higher CO_2 removal. Moreover the beneficial effects of EGR are more pronounced for higher values of the capture ratio; in fact, increasing EGR from 20 to 50%, the steam mass flow rate extracted to regenerate the solvent reduces of about 7% for φ=95% (only 2% for φ=80%).

The effects of exhaust gas recirculation and CO_2 capture ratio on net NGCC power and efficiency are depicted in Fig. 6a and 6b, taking also into account for energy requirements of CO_2 capture and compression systems. For EGR=35%, increasing φ from 80 to 95%, the rated power decreases of about 5%, passing from 342 to 326 MW, while the net efficiency decreases of about 2 percentage points, reaching 47.3%. On the other hand, for a fixed CO_2 capture ratio, increasing exhaust gas recirculation reduces energy penalties on NGCC performance; the beneficial effect of EGR is particularly significant on net efficiency, that increases of about 2 percentage points passing EGR from 0 to 35% , regardless of CO_2 capture ratio.

Rising the steam extraction rate with φ, the percentage incidence of the LPST power on the whole steam cycle output reduces (Fig. 6d), still remaining above 20% for φ=95%. The integration of the CO_2 capture system also affects the exhaust gas temperature, that ranges from 107°C (EGR=50%, φ=80%) to 126°C (EGR=0%, φ=95%).

4. Impact of CO_2 capture system on NGCC economics

The effects of CO_2 capture system integration on NGCC economics have been evaluated considering the cost of electricity (COE) and the cost of CO_2 avoided.

The cost of electricity of NGCC with CO_2 capture is evaluated using the EPRI methodology [18], and assuming 2011 as base year for capital costing. Regarding the NGCC, the capital cost is evaluated through cost models described in detail by authors in [19]. As regards the system for CO_2 capture and storage, the total installed equipment cost (TEC) is assessed according to the cost functions summarized in Table 3, referring to the CO_2 capture system and the CO_2 drying and compression system. For the capture system, data are reported distinguishing equipment with different scaling parameters. All values (base size and cost, scale factor) were evaluated using the software IECM 8.0.2 [17], varying the CO_2 capture ratio and the exhaust gas flow rate to be treated. A further capital cost of 1.23 M$ has been considered for the steam extractor in the power plant block [17]. The total overnight capital (TOC) of the capture system is evaluated from TEC, considering the additional costs related to the balance of the plant, the engineering process and the contingencies, accounting for 12, 8 and 20% of TEC respectively. If EGR exceeds 40%, to take into account for the major design modifications required to accommodate the low combustor oxygen concentration, the NGCC contingencies include also 45% of the gas turbine capital cost [12].

The main assumptions for estimating COE are summarized in Table 3: data highlight the specific contributions to fixed and variable O&M costs, including the percentage incidence of further variable O&M (due to costs of activated carbon, caustic, reclaimer waste disposal, water), and to CO_2 storage, transport and monitoring costs.

Tab. 3. Cost functions for estimating the total installed equipment cost of CO_2 capture system

Equipment	Scaling parameter	Base size	UOM	Base cost [2011$]	Scale factor
CO_2 capture system					
Direct contact cooler, Flue gas blower, CO_2 absorber vessel	Q_{FG}	369	m^3/s	164010	0.6
Heat exchangers, Circulation pumps, Sorbent regenerator	M_S	38	kg/s	492330	0.6
Sorbent reclaimer, Sorbent processing	M_{CO2}	24	kg/s	196350	0.6
Reboiler	M_S*M_{MEA}	56126	kg/s*tonne/hr	90	0.6
Drying and compression system	M_{CO2}	24	kg/s	682870	0.6

Tab. 4. Main economic assumptions for COE evaluation

Parameter	Value
Operational period, yr	25
Yearly operating hours, h/yr	7446
Capital charge factor, yr^{-1}	0.105
Discount rate, %	10
Annual cost escalation rate, %	3
Construction time, yr	2
Fixed O&M, $/kW-yr	16.2
Sorbent cost, $/tonne	2630
Inibitor cost , %MEA	20
Further variable O&M, %MEA	25
CO_2 transport cost, $/tonne	6
CO_2 storage cost, $/tonne	3
CO_2 monitoring cost, $/tonne	1

The cost of CO_2 avoided is evaluated as

$$Avoided\,cost\ of\ CO_2 = \frac{COE_{with\ rem} - COE_{ref}}{CO_{2,em\ ref} - CO_{2,em\ with\ rem}} \tag{2}$$

where the numerator compares the NGCC with CO_2 capture and the reference plant (NGCC without CO_2 removal) in terms of COE ($/MWh), the denominator the same power plants in terms of specific CO_2 emissions (kg/MWh).

The effects of operating conditions of the capture system (φ=80,90,95%) and the NGCC (EGR=0,35,50%) on COE and cost of CO_2 avoided are summarized in Fig. 7, for a natural gas cost of 6 $/GJ. With respect to the NGCC reference plant, the integration of the CO_2 capture system produces a COE increase

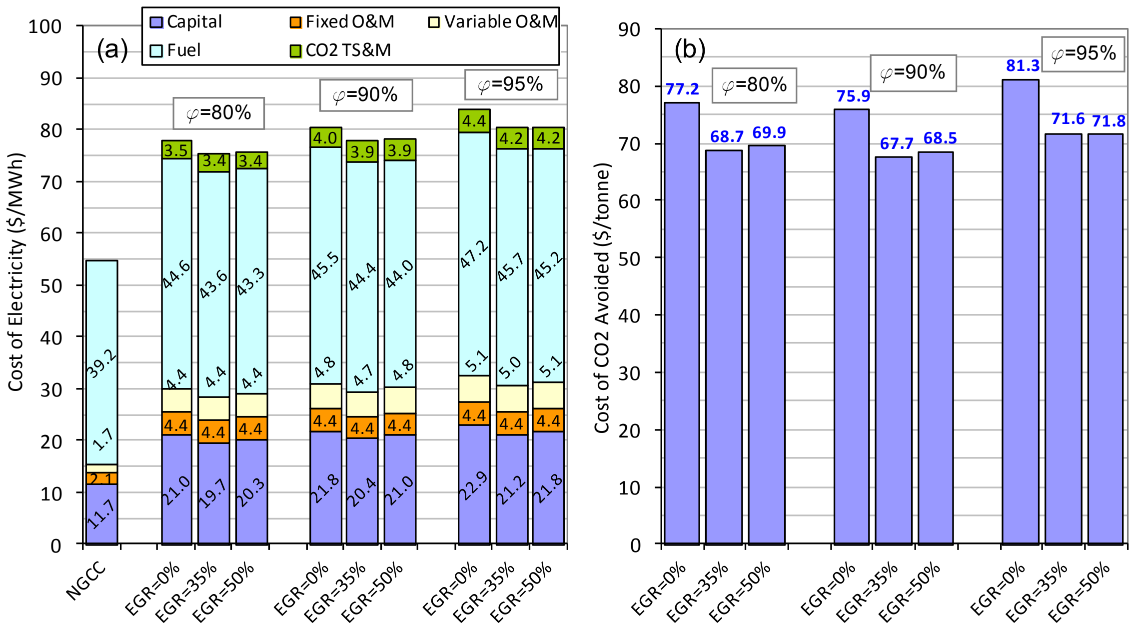

Fig. 7. Effects of carbon capture system operating conditions on COE and cost of CO_2 avoided

up to 40-60%, depending on operating parameters of NGCC (EGR) and CO_2 capture plant (φ). The highest COE value (84.0 $/MWh) occurs in the case with φ=95% and EGR=0%.

As shown in Fig. 7a, for a fixed φ ratio, the percentage of exhaust gas recirculation should not exceed 35% to avoid that the reduction of fuel costs resulting from the greater NGCC efficiency is more than compensated by the capital cost increase for the adaptation of the gas turbine combustor. Thus, assuming EGR=35%, COE increases with the capture ratio φ, passing from 54.6 $/MWh (without CO_2 removal) to 80.6 $/MWh for φ=95%. This COE increase is attributable for about 39% to capital cost, 23% to fuel cost, 22% to fixed and variable O&M and for the remaining 16% to the additional costs for CO_2 transport, storage and monitoring.

As shown in Fig. 7b, regardless of the CO_2 capture ratio, the exhaust gas recirculation reduces the cost of CO_2 avoided of about 10%. This cost takes the minimum value for EGR=35%, ranging from 67.7 $/tonne (φ=90%) to 71.6 $/tonne (φ=95%).

Conclusions

The aim of this paper has been the analysis of energy and economic performances of a gas-steam combined cycle with a CO_2 post-combustion capture system, using an amine scrubbing process. The integration between the two subsystems is accomplished by means of a steam extraction at crossover pipe between intermediate and low pressure steam turbines, supplying thermal energy to the stripper reboiler. In order to reduce the energy requirement for amine regeneration, the CO_2 concentration of the flue gas is properly increased by exhaust gas recirculation, that in turn allows to reduce the size of the removal system.

Simulation results have shown that the specific reboiler duty is around 3 MJ/kg for CO_2 capture ratio not exceeding 85%, while it increases significantly for higher values: at φ=95%, it ranges from 3.8 MJ/kg (EGR=50%) to 4.2 MJ/kg (EGR=0%).

The steam extraction rate and accordingly the energy and economic performances of the integrated system are strictly related to the percentage of exhaust gas recirculation and the CO_2 capture ratio. With EGR=35%, the steam to reboiler increases from 41 to 64 kg/s, varying φ from 80 to 95%; on the other hand, increasing EGR to 50%, the decrease of steam extraction rate is more pronounced at increasing of φ, varying in the range 2-4%. As regard to energy performances, the same increase of the CO_2 capture ratio, at EGR=35%, reduces the rated power from 342 MW to 326 MW (-5%) and the net efficiency from 49.5% to 47.3%. Increasing EGR to 50%, the NGCC capacity slightly increases, whereas the efficiency gain is less than 1 percentage point.

The results of economic analysis highlights that the cost of electricity increases of about 40-60% compared to NGCC without CO_2 removal system (54.6 $/MWh), depending on the extent of exhaust gas recirculation and CO_2 capture ratio. This is mainly due to the raise of capital and fuel costs, accounting for about 37-39% and 22-25% of the overall increase respectively. Integrated system configurations having EGR=35% show the lowest values of COE, that ranges from 75.4 $/MWh (φ=80%) to 80.6 $/MWh (φ=95%). The same behaviour is consequently obtained for the cost of CO_2 avoided, that varies from 67.7 $/tonne (φ = 90%) to 71.6 $/tonne (φ = 95%).

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