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Analysis of CO_2 post-combustion capture in coal-fired power plants integrated with renewable energies

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Abstract

In light of the current consumption and proven reserves of fossil-fuels, it is beyond doubt that they will continue to play an important role in the World energy scenario, making crucial the implementation of solutions for carbon emissions reduction. One promising option for decarbonising existing or new-build power plants is post-combustion capture by chemical absorption. Besides its environmental benefits, this process causes a decrease of power plant capacity, due to heat and electricity requirement of CO_2 capture and compression systems. A possible way to overcome this drawback is the use of auxiliary systems based on renewable technologies. In this paper two options for integrating renewable energies into a coal-fired power plant with CO_2 post-combustion capture are investigated. The first one envisages the use of an auxiliary biomass boiler, providing an additional power capacity, besides satisfying the CO_2 capture heat requirement. In the second option, a concentrating solar power (CSP) system is used to meet part of regeneration heat duty, in place of steam extraction from the main power plant or steam production by a biomass boiler. The study will assess the effect of renewable source availability and energy conversion efficiency on the design of the auxiliary power unit, as well as on the energy performances of coal-fired power plant retrofitted with CO_2 capture.

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*Keywords:*Carbon capture; Coal; Auxiliary system; Integration; CSP; Biomass.

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1. Introduction

Coal represents the most widely distributed fossil fuel, with proven reserves estimated at around 900 billion tonnes [1]. Currently, coal-based power plants provide more than 40% of global electricity production and it is expected they will remain a key technology in meeting the future energy needs, especially in developing countries [2]. Nevertheless, these plants also account for over 28% of CO_2 emissions, thus requiring the implementation of carbon reduction measures, in order to mitigate the impact of global climate changes.

Post-combustion capture based on amine-scrubbing represents one of the most suitable technique for capturing CO_2 from exhaust flue gas, as it requires minor changes in power plant layout [3]. However, the CO_2 capture retrofit imposes a not negligible loss in power plant capacity, due to the need to extract part of steam for solvent regeneration, as well as to the parasitic power losses of capture and compression units.

In this respect, several options have been studied to reduce the power plant derating, including the integration of an auxiliary unit co-producing heat and electricity. When the combined heat and power (CHP) system is fed by fossil fuels, an additional flue gas stream to be treated is produced, negatively affecting the size and costs of the CO_2 capture island [4]. Using renewable energies in place of fossil fuels to feed the auxiliary unit allows to overcome this issue, besides further reducing the CO_2 emitted per unit of electricity production.

A limited number of studies have addressed the integration of renewable technologies in fossil fuel power plants retrofitted with CO_2 capture. Kang et al. [5] optimized the operation of a coal-fired power plant, integrating a natural gas fired CHP system and a wind turbine to support the heat and electricity requirement of capture island. Some studies assessed the potential benefits of solar assisted post-combustion capture. In this respect, Cohen [6] and Mokhtar [7] evaluated the techno-economic feasibility of integrating a CSP system fulfilling all or part of the reboiler steam requirement. Solar-assisted solvent regeneration was compared by Zhao et al. [8] to the feed-water repowering operated by replacing the high quality steam bleedings with a CSP system based on a parabolic trough collector.

Other researchers investigated the use of a biomass-fired auxiliary unit producing both heat and electricity for the CO_2 capture island, with the aim to assess its effect on energy and economic performances of retrofitting natural gas [9] and coal-fired power plants [10].

Nomenclature

Symbols		Greek symbols	
$CO_{2,em}$	Specific CO_2 emissions, kg/MWh	η	Efficiency
m	Mass flow rate, kg/s	φ	Capture ratio
P	Power, MW		
P_{th}	Thermal power to the reboiler, MW_{th}	Acronyms	
q_{th}	Reboiler duty, MJ/kg	BB	Biomass Boiler
R_{BIO}	Biomass requirement, ktonne/year	BIO	Biomass
		CHP	Combined Heat and Power
Subscripts		CSP	Concentrated Solar Power
BP	Back Pressure	DNI	Direct Normal Irradiance
CS	CO_2 capture system	IPST	Intermediate Pressure steam turbine
CP	Compression	HPST	High Pressure Steam Turbine
EXH	Exhaust	LPST	Low Pressure Steam Turbine
EXTR	Extraction	LHV	Low Heating Value
S	Steam	PC	Pulverized coal power plant
SH	Superheated	ST	Steam Turbine

In this study two options for integrating renewable energies into a coal-fired power plant with CO_2 post-combustion capture are investigated. The first one concerns the use of an auxiliary boiler fed by woody biomass, that meets the heat requirement of CO_2 capture system and eventually provides an additional power capacity, by expanding the superheated steam in a back-pressure steam turbine. The second one envisages the integration of a CSP system based on Fresnel technology to produce a fraction of steam for the reboiler operation, while using the conventional steam extraction or steam production from an auxiliary biomass boiler to compensate for the daily variation of solar resource availability.

The heat integration options based on renewable energies are compared to the case of conventional steam extraction operated upstream the low pressure steam turbine of coal-fired power plant. The energy analysis of power system is carried out using the GateCycle software [11], while ChemCad platform [12] is used to simulate the CO_2 capture process based on amine absorption.

2. Pulverized-coal power plant with CO_2 removal system

A 100 MW coal-fired power plant has been selected as study case to investigate the retrofit with a post-combustion CO_2 capture system (Figure 1). At design conditions, the subcritical boiler is fed with a fuel flow rate of 9.4 kg/s, thus producing a superheated steam flow rate of 79.3 kg/s at 540°C and 180 bar. Hence, with a LHV efficiency of 42%, the coal-fired power plant emits 752 kg_{CO2}/MWh. In order to capture 90% of CO_2 from power plant exhausts, a MEA-based absorption system has been added [13]. With a stack flue gas flow rate of 94.2 kg/s and a reboiler duty of 3.5 MJ/kg_{CO2} [14], the thermal power requirement for solvent regeneration states at 65.7 MW_{th}.

In this study, several options for providing heat to the reboiler are compared, including the steam extraction from the power block, operated at crossover pipe between IPST and LPST and the integration of an auxiliary unit based on a biomass boiler or a CSP system.

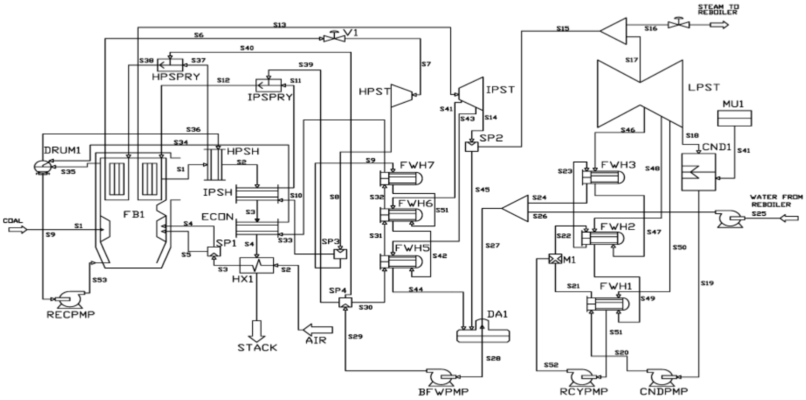

Figure 1 – Layout of coal-fired power plant with steam extraction for the CO_2 capture system

2.1 Auxiliary unit based on biomass boiler

The boiler auxiliary system, based on a fixed bed technology, burns a woody biomass (LHV=19.0 MJ/kg) with 40% excess of air. Passing through the heat exchange section, the exhaust flue gases are cooled down to 130°C and then vented into the atmosphere, without increasing at first approximation the CO_2 emissions. Indeed, the production of CO_2 from biomass combustion exactly offsets that trapped during the photosynthetic fixation; hence, neglecting the emissions from collection, the only source of CO_2 is that related to the transportation of biomass [9], that has been evaluated assuming a short supply chain (within 70 km from the site of the biomass plant) and the use of heavy duty vehicles with a capacity of 27 tonnes.

According to the complexity of the system layout, the auxiliary unit only produces the saturated steam (p_{SH}=3 bar, T_{SH}=134°C) required for the stripping reboiler operation or it also provides an additional power capacity, byexpanding the superheated steam (p_{SH}=80 bar, T_{SH}= 540°C) in a back pressure steam turbine (BP-ST).

2.2 Auxiliary unit based on CSP system

The solar field is based on a direct steam generation operated by linear Fresnel collectors of Novatec Solar technology [15]. The base module includes 16 rows of primary mirrors, with a length of 44.8 m and a width of 72 cm, for a total reflective area of around 514 m^2. The required temperature increment and steam flow rate production is then achieved by properly connecting in series and parallel the base modules.

Table 1. Monthly values of DNI and *Tair* in Brindisi (Italy)

Month	DNI [kWh/m^2]	*Tair*[°C]
January	60.65	9.5
February	72.29	9.9
March	121.11	11.5
April	163.28	14.1
May	202.96	17.9
June	226.32	21.8
July	236.98	24.5
August	223.10	24.8
September	153.09	22.1
October	111.75	18.2
November	66.18	14.1
December	51.19	11.0
Year	*1688.91*	*16.6*

Thermal power production of solar collectors has been evaluated as a function of direct normal irradiation (DNI), temperature increase and optical efficiency factor, according to the methodology described in a previous study of the same authors [16].

In order to evaluate the solar resource availability, a software developed at the Department of Mechanical, Energy and Management Engineering (University of L'Aquila) has been used [17]. Considering a potential power plant installation in the city of Brindisi (Italy), direct normal irradiation and air temperature data on an hourly and monthly basis have been estimated (Table 1). Hence, by properly averaging hourly data, five diurnal profiles of DNI and T_{air} have been evaluated, describing a typical day of each season and the mean annual daily behavior.

The solar field has been designed assuming the highest value of DNI (870 W/m^2) and solar height (77.8°), detected on June 21 at noon, an azimuth angle of zero and an ambient air temperature of 30°C. Assuming a series of 10 base modules, an optical efficiency of 67% and a water to steam temperature increase from 110 to 140°C, the thermal power production per line states at 2.7 MW [18]. Hence, in order to provide the whole thermal power required by the reboiler at design conditions, a number of 24 lines in parallel is required [16].

3. Comparing the energy performances of retrofit options based on renewable energy integration

Assuming that the stripper reboiler heat duty is satisfied by extracting a fraction of steam (mEXTR=24.9 kg/s) at the exit of intermediate pressure steam turbine (Case 0), as shown in Figure 1, the coal-fired power plant capacity drastically reduces to 79.1 MW (-21%), also due to the electricity consumption of CO2 capture and compression units (PCS+PCP =7.4 MW). Hence, the net efficiency reduces of around 9% pts compared to design conditions, stating at 33.1%.

Table 2 – Comparison of heat supply options based on steam extraction and biomass boiler integration

	Design case	Off-design cases with CO_2 capture (*φ=90%*)			
		Case 0	*Case 1*	*Case 2*	*Case 3*
POWER UNIT					
P_{ST} [MW]	100	86.5	100	100	94.3
m_{COAL} [kg/s]	9.4	9.4	9.4	9.4	9.4
m_{SH} [kg/s]	79.3	79.3	79.3	79.3	79.3
m_{EXTR} [kg/s]	-	24.9	-	-	9.5
m_{EXH} [kg/s]	94.2	94.2	94.2	94.2	94.2
CAPTURE UNIT					
P_{th} [MW]	-	65.7	65.7	65.7	65.7
q_{th} [MJ/kg]	-	3.5	3.5	3.5	3.5
P_{CP} [MW]	-	5.5	5.5	5.5	5.5
P_{CS} [MW]	-	1.9	1.9	1.9	1.9
AUXILIARY UNIT					
m_{BIO} [kg/s]	-	-	4.9	3.8	3.1
$P_{BB,\,th}$ [MW]	-	-	94.9	71.4	58.9
$P_{BP\text{-}ST}$ [MW]	-	-	21.2	-	13.2
m_S [kg/s]	-	-	29.8	30.3	18.5
p_S [bar]	-	-	3	3	3
T_S [°C]	-	-	148.4	133.5	148.4
R_{BIO} [ktonne/year]	-	-	134	100	83
P_{NET} [MW]	100	79.1	114	92.8	100
η_{NET} [%]	42.0	33.1	34.1	29.9	33.6
$CO_{2,\,em}$ [kg/s]	752.0	95.3	66.6	81.7	75.7

In order to overcome these issues, several alternatives for CO_2 capture retrofit have been analyzed:

- ***Case 1***: steam from a CHP unit with BB and BP-ST;
- ***Case 2***: steam from BB;
- ***Case 3***: steam extraction and steam from CHP unit;
- ***Case 4***: steam extraction and steam from a CSP system;
- ***Case 5***: steam from CHP unit and CSP system.

3.1. Integration of an auxiliary biomass boiler

Table 2 summarizes the simulation results of retrofit options based on a biomass boiler integration. In *Case 1*, the auxiliary system provides both heat and electricity to the CO_2 capture island. If the steam extraction is entirely replaced by the biomass steam production (m_S=29.8 kg/s), the power plant capacity increases to 114 MW, due to the additional power produced by the BP-ST (P_{BP-ST}=21.2 MW). Compared to *Case 0*, the efficiency penalty is slightly lower (-8% pts), while the specific CO_2 emissions referred to the net power output (P_{NET})drastically reduces to 66.6 kg/MWh (-30%). With a biomass flow rate of 4.9 kg/s and assuming a power plant capacity factor (CF) of 85%, the corresponding annual requirement states at 134 ktonne/year. Considering the limited availability of woody biomass for the site of interest [19] and with the aim to limit the radius of biomass collection area (lower than 70 km), two potential alternatives have been investigated.

Considering an auxiliary unit layout based on steam production only (*Case 2*), the annual biomass requirement reduces to around 100 ktonne/year (m_{BIO}=3.7 kg/s). From the energy point of view, the power plant capacity reduces to 92.8 MW, while the efficiency penalty exceeds 12% pts, due to the production of low grade heat.

Combining the steam production from a CHP auxiliary unit with steam extraction (*Case 3*) allows to further reduce the biomass needs, as well as to mitigate the negative impacts on power plant performances. If the steam production accounts for around 60% (m_S=18.5 kg/s) of the overall reboiler thermal power duty, the annual biomass requirement states at 83 ktonne/year (m_{BIO}=3.1 kg/s). Due to the power capacity provided by BP-ST (P_{BP-ST}=13.2 MW), the power plant derating is eliminated (P_{NET}=100 MW), thus leading to an efficiency penalty of around 8% pts (η_{NET}=33.6%) and specific CO_2 emissions of 75.7 kg/MWh.

3.2. Integration of a CSP system

According to the solar resource availability, the solar collectors are able to provide part of the steam for solvent regeneration, thus requiring a back-up system to meet the remainder fraction.

In this study two alternatives for assisting the solar steam production have been compared. In the first one (*Case 4*), the CSP system is combined with steam extraction from the coal-fired power plant, assuming a high-pressure steam turbine (HPST) overload of 10%, in order to mitigate the corresponding derating of power capacity; in the second one (*Case 5*), a biomass boiler operating at the pressure required by the stripper reboiler is used to compensate for the variability of solar steam production.

It is noted that the net power plant efficiency has been evaluated accounting for the solar energy transferred to the CSP system, while the heat rate has been referred to the thermal power provided by coal and biomass combustion [20].

In both cases the solar steam production achieves the highest values in the middle of the day (11:00 a.m.), varying between 14.5 kg/s and 24 kg/s for a typical winter and summer day. In these conditions, the CSP system is able to provide more than 50% (winter) and 80% (summer) of the reboiler thermal power requirement.

In *Case 4*, the mean annual capacity derating states at -14%, leading to a yearly electricity production gain of 2.9% compared to the case of conventional steam extraction (*Case 0*). Figure 2a shows that the net efficiency at night is the same as *Case 0*, while it reduces with the increase of solar heat contribution, due to the higher low grade steam production. This effect is even more pronounced during summer, when the net efficiency reaches a minimum value of 30.8% (11:00 a.m.). However, due to the increase of power plant generating capacity, the CSP system allows for a decrease of heat rate, whose maximum extent ranges from -7% (10140 kJ/kWh; winter) to -12% (9618 kJ/kWh; summer). On the other hand, the specific CO_2 emissions on a mean annual basis slightly reduces to around 93 kg/MWh.

In *Case 5*, the power plant capacity derating drastically reduces to around 7%, being fully ascribed to the power losses for CO_2 capture and compression operations. Increasing the solar energy availability, the net efficiency slightly increases compared to *Case 2* (29.9%), as the solar contribution allows to reduce the biomass fed to the boiler for the steam production; moreover the specific CO_2 emissions weakly reduce up to a minimum value of 81.3 kg/MWh (summer), as the decrease of biomass requirement mitigates the corresponding CO_2 emissions for transport. More noticeable is the benefit on the heat rate,

showing a maximum reduction of around 10% (10653 kJ/kWh) and 20% (9738 kJ/kWh) during a typical winter and summer day. This is related to the decrease of m_{BIO}, that leads to a significant reduction of annual biomass requirement (80.9 ktonne/year) compared to *Case 2*.

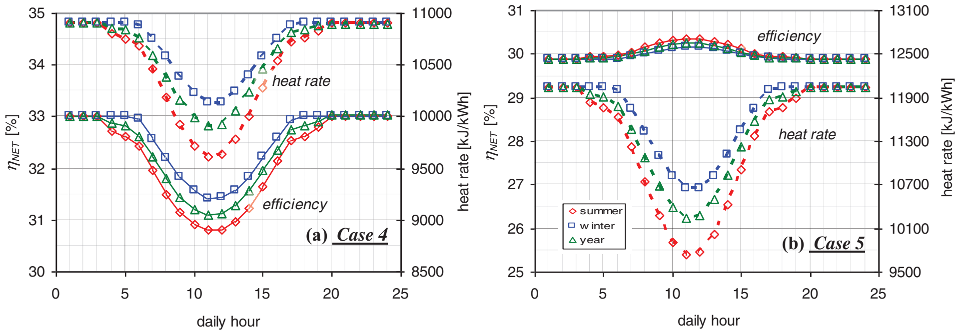

Fig.2 .Energy performances of heat supply options based on CSP system combined with steam extraction (a) and biomass boiler (b)

4. Conclusions

This paper has investigated the potential benefits of integrating renewable energies into a 100 MW coal-fired power plant, retrofitted with a CO_2 capture process based on amine scrubbing. Two main options have been analyzed from the energy point of view, basically involving the use of a biomass boiler and a CSP system, producing a fraction of the heat requirement for the solvent regeneration.

Assuming that the thermal power for the stripper reboiler operation is provided by a biomass CHP unit (*Case 1*), the power plant capacity increases of around 14%. The efficiency penalty (-8% pts) compared to design conditions ($\eta_{NET,D}$= 42%) weakly reduces compared to the case of conventional steam extraction (*Case 0*), while the specific CO_2 emissions passes from 95.3 kg/MWh to 66. 6 kg/MWh. If the auxiliary CHP unit is combined with a steam bleeding providing around 40% of the heat duty, the annual requirement of woody biomass drastically reduces to 83 ktonne/year (-38%). With almost the same net efficiency of *Case 1* (33.6%), the power plant derating is eliminated, against an increase of specific CO_2 emissions (75.7 kg/MWh).

Due to the discontinuity of solar energy resource, the integration of a CSP system allows to cover only a fraction of steam required for the solvent regeneration, reaching a maximum value of 80% during summer. If the solar steam production is assisted by a conventional steam bleeding from the power block, the mean annual power plant derating states at -14%; compared to *Case 0,* the net efficiency decreases during the day up to around 31%. However, the steam production from solar collectors also allows for a non negligible reduction of heat rate, reaching a peak value of 12% (9618 kJ/kWh). Combining the CSP system with steam production from a biomass boiler, the mean annual power plant derating further reduces (-7%), against a decrease of net efficiency, being it always lower than 31%. Compared to *Case 2*, this option also allows to drastically reduce the mean annual heat rate, as a result of the decreased biomass requirement (80.9 ktonne/year). .

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Biography

Roberto Carapellucci is an associate professor of Management of Energy Conversion Systems at the University of L'Aquila. He has about 30 years of teaching and research experience. He has been author of about 100 scientific papers on various topics, including advanced power generation, system modeling, renewable technologies, carbon capture. He is referee for several international peer-reviewed journals.