PERFORMANCE EVALUATION OF NGCC AND COAL-FIRED STEAM POWER PLANTS WITH INTEGRATED CCS AND ORC SYSTEMS

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ABSTRACT

A performance assessment of natural gas-fueled combined cycle (NGCC) power plants and pulverized coal-fired (PC) steam power plants, both equipped with a CO_2 removal system and integrated with an Organic Rankine Cycle (ORC), was performed. For large scale power plants (a fuel chemical power input of 1000 MW was assumed as reference for both NGCC and PC plants), post-combustion CO_2 removal systems based on chemical solvents are expected to reduce the net plant efficiency between 9-12 percentage points at 90% overall CO_2 capture. The recovery of low temperature heat, available from the solvent-based CO_2 removal systems and related process equipment, can be performed in order to increase the plant efficiency. In particular main low temperature heat sources available are: flue gas coolers upstream of the CO_2 capture unit (80-100 °C for NGCC and about 120 °C for PC), amine condenser of the CO_2 desorption column (100-110 °C) and amine reboiler water cooling (130-140°C). This paper evaluates low temperature heat recovery by means of an Organic Rankine Cycle (ORC) that can convert heat into electricity at very low temperatures. By producing additional electrical power by the ORC, the global performance of the above mentioned power plants can be improved. This study shows that the integration of CCS with the steam plant allows to recover a larger amount of waste heat in comparison to NGCC (more than 200 MW versus about 110 MW). As a consequence, integrating ORC technology with a post-combustion capture system leads to an increase of efficiency of about 1-1.5 percentage points for the NGCC plant and of about 2 percentage points for the steam plant, depending on the amount of low temperature heat available. Among several organic fluids available, N-Butane was assumed as organic operating fluid. Optimum cycle operating temperatures and pressures were identified in order to evaluate the most efficient approach for low temperature heat recovery.

1. INTRODUCTION

Carbon capture and storage (CCS) is expected to become an important strategy to reduce greenhouse gases emissions in the power sector. IEA studies estimate that CCS alone will account for 19% of the total CO_2 emissions reduction in 2050. Remaining 81% are due to energy system efficiency increase (38%), fuel switching (20%), renewable (17%) and nuclear (6%). Furthermore, coal-fired steam and natural gas-fired power plants are expected to contribute to about 65% and 30% respectively of the total installed power generation capacity equipped with CCS (IEA, 2010). Many studies, however, have shown that CO_2 capture from power plants, typically performed through post-combustion processes based on amines, is both very capital- and energy-intensive (Rubin *et al.*, 2007, Davison, 2007). In this context, thanks to its ability of convert heat into electricity at very low temperatures, Organic Rankine Cycle (ORC) can assume a fundamental role in recovering low temperature heat rejected from CO_2 capture plants and the auxiliaries required to enable them (Tola and Finkenrath, 2015). In fact ORC can produce additional electrical power improving global performance of the above mentioned power plants.
In post-combustion CO_2 removal process a large steam extraction from the power plant is required to supply the thermal energy necessary to solvent regeneration. This combination with additional

electrical energy for compressing and pumping the CO_2 up to a pressure suitable for transport and storage and for driving exhaust gas fans and solvent circulation pumps, causes substantial efficiency penalties to the power plant. As a result, near-term post-combustion CO_2 removal systems reduce the plant efficiency in the order of 8-12 percentage points at 90 % CO_2 capture (Tola and Pettinau, 2014, Mores *et al.*, 2013). Significant R&D projects are dedicated to the development of more efficient or less expensive capture and compression processes (Rubin *et al.*, 2012). For example, Finkenrath *et al.* (2007) and Jordal *et al.*, (2012) proposed exhaust gas recirculation (EGR) for natural gas combined cycles in order to increase the exhaust concentration of CO_2 and reduce costs associated with the capture unit. Little attention, however, has been given to recovering low temperature heat that is rejected from capture plants and the auxiliaries required to enable them.
This article will examine the performance impact of recovering low temperature heat with an Organic Rankine Cycle (ORC) that is integrated with a post-combustion CO_2 capture system of both pulverized coal-fired (PC) steam plant and natural gas combined cycle (NGCC). The analysis is based on fundamental thermodynamic analyses in order to evaluate the chance of heat recovery options based on ORC technology. The power section performance of both PC and NGCC were evaluated through simulation models based on the commercial software packages GateCycle^{TM}. Models based on HYSYS^{TM} software were used to evaluate performance of both ORC and CO_2 removal section.

2. PLANT CONFIGURATION

A simplified scheme of both PC and NGCC power plants is reported on Figures 1 and 2, respectively.

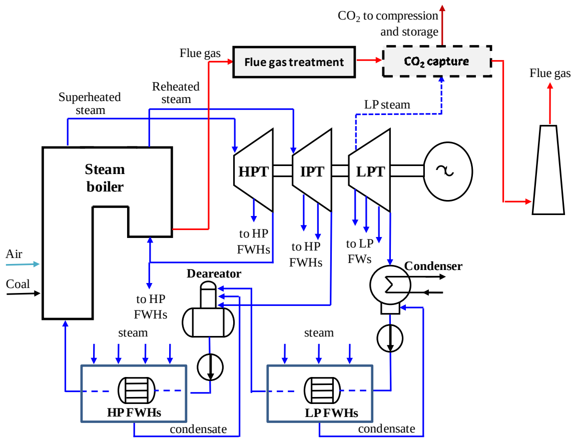

Figure 1: Simplified schemes of PC power plant

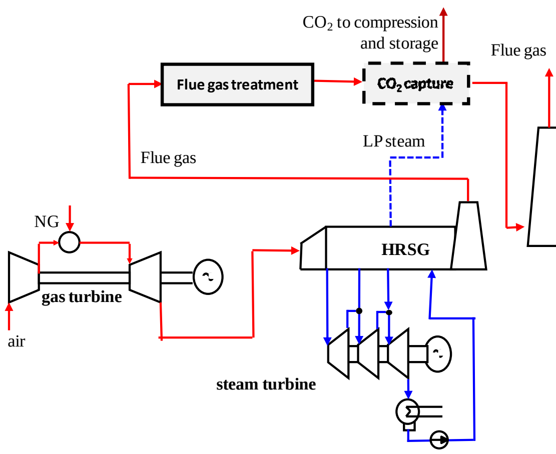

Figure 2: Simplified schemes of NGCC power plant

The steam power plant considered in this study is a generic medium-size (in the order of 400 MW of power output) pulverized coal-fired plant. The fuel chemical power input has been assumed equal to 1000 MW, corresponding to a mass flow of 39.4 kg/s of a coal with a lower heating value (LHV) of about 25.4 MJ/kg. The PC plant is based on a Rankine cycle with superheated and reheated steam and with eight regenerative steam extractions. A condenser pressure of 3.5 kPa has been assumed. The steam power plant has been considered equipped with a conventional tail-end flue gas treatment, which includes baghouse filters for particulate removal, a low temperature flue gas desulphurization system and a selective catalytic reduction denitrification system. Main cycle operating parameters are reported on table 1.
The natural gas combined cycle (NGCC) considered in this study is a generic medium-size (in the order of 600 MW) plant based on a typical gas turbine integrated with a heat recovery steam generator (HRSG) and a triple pressure steam cycle. For comparative purposes, a fuel chemical input equal to 1000.0 MW has been assumed also for the NGCC, corresponding to a natural gas mass flow of 20.0 kg/s (considering a natural gas LHV of 50 MJ/kg, as for methane).. Table 2 shows main operating parameters of the NGCC.

Table 1. Main operating parameters of the steam cycle

Fuel chemical power input	MW	1000.0
Coal mass flow	kg/s	39.4
Coal lower heating value (LHV)	MJ/kg	25.39
Air mass flow	kg/s	359.8
HP/IP/LP steam mass flow	kg/s	334.75/300.95/268.57
HP/IP/LP steam temperature	°C	537.9/540.0/322.6
HP/IP/LP steam pressure	MPa	25.0/3.4/0.7
Number of extraction		8
Extraction pressures	MPa	4.4/3.5/2.2/1.2/0.7/0.4/0.2/0.06
Deareator pressure	MPa	0.6
Condenser steam temperature and pressure	°C/kPa	26. 7/3.5
High/low pressure heat exchangers minimum ΔT	°C	-1.5/1.5

Table 2. Main operating parameters of the NGCC power plant

Gas turbine		
Fuel chemical power input	MW	1000.0
Natural gas mass flow	kg/s	20.0
Natural gas lower heating value	MJ/kg	50.0
Exhaust mass flow	kg/s	877.4
Exhaust temperature	°C	642.0
Steam cycle		
HP steam temperature/pressure	°C/MPa	565.0/16.3
IP steam temperature/pressure	°C/MPa	565.0/2.4
LP steam temperature/pressure	°C/MPa	311.0/0.45
Condenser pressure	kPa	3.5
Cooling water temperature	°C	17.0
Cooling water temperature rise	°C	6.7
Temperature difference in the condenser	°C	3.0

Both the steam and the NGCC power plants have been also studied in the more complex configuration considering a CO_2 capture and compression system, in the so-called PC-CCS and NGCC-CCS power plants. As mentioned, chemical absorption with amine-based solvents is currently considered the most suitable option for CO_2 removal from flue gases. In the present study, monoethanolamine (MEA) was chosen among the amines, despite its high energy requirements for the regeneration process, since it is one of the most proven and widespread technologies (Abu-Zhara *et al.*, 2007). Figure 3 shows a simplified scheme of the CO_2 removal section.

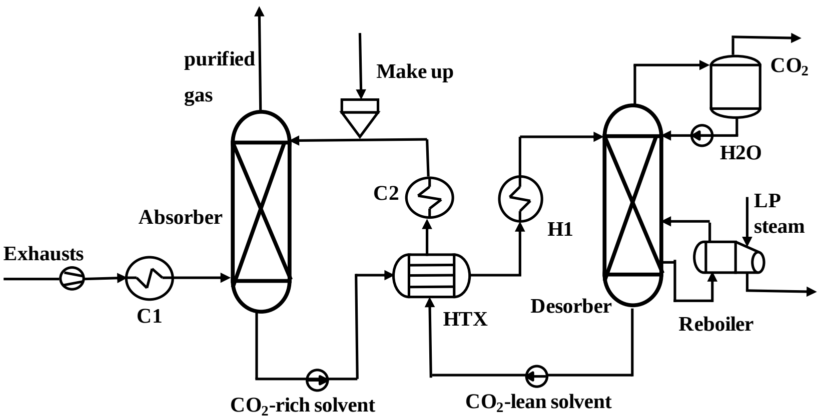

Figure 3 Simplified scheme of the CO_2 removal section.

Exhaust gas is cooled to 30-50 °C and enters into the absorber, where the CO_2 is captured by the aqueous MEA solution. The CO_2-free gas is discharged from the top, while the CO_2-rich solvent is heated up to about 100 °C and sent to the regeneration column (Desorber). Inside the stripper a CO_2-water vapour mixture is released from the CO_2-rich solvent through the reboiler heat. In the upper section of the regeneration column a large fraction of steam condensates, whereas the CO_2-rich flow is sent to the compression section. The CO_2-lean solvent extracted from the bottom is cooled and recirculated back to the absorption column. Downstream the CO_2 removal section requirements for CO_2 transport and storage are matched through a conditioning and compression section. At first, the CO_2 compression process is carried out above the critical pressure (about 74 bar) in gaseous phase through intercooled compressors and then in liquid phase through a pump. In particular a pressure of 11 MPa and CO_2 purity above 99.5% are requested.

3. PLANT PERFORMANCE

3.1 PC and NGCC reference power plants

The reference PC power plant shows a net power output equal to 420.2 MW. The fuel chemical power input is 1000 MW plus a further thermal power of 13.3 MW, due to the flue gas treatment section. Globally the net efficiency of the plant is 41.47%. The flue gas treatment requires also an electrical power of 8.2 MW (about 2% of the overall PC power). The flue gas is characterized by a mass flow of 395.5 kg/s with a CO_2 molar fraction of 15.0%. The CO_2 emitted by the plant is equal to 87.6 kg/s corresponding to 735.9 g/kWh.
Better performance and lower CO_2 emissions are achieved with the NGCC power plant. At 15 °C ambient temperature, NGCC shows a net power output equal to 592.0 MW and a net efficiency of 59.2%. The flue gas is characterized by a mass flow of 877.4 kg/s with a CO_2 molar fraction of 4.1%. The CO_2 emitted by the plant is equal to 55.2 kg/s corresponding to 336 g/kWh.

3.2 Plants plus CO_2 removal systems

Lower performance is expected for both power plants when equipped with a CO_2 removal system. As a basis for the study, a post-combustion capture system based on a mixture of MEA (30 % by weight) and water and an absorber column temperature of 45°C have been assumed.
Figure 4 shows both the electrical power requirements of the CO_2 capture system (flue gas fan power and solvent compression power) and the specific thermal energy for the regeneration as a function of the CO_2 removal rate. Figure 5 shows CO_2 capture and emitted as a function of the CO_2 removal rate for both PC and NGCC power plants.

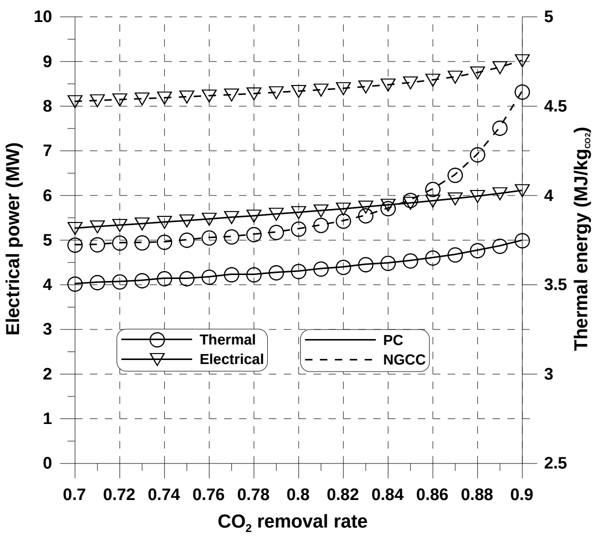

Figure 4 Electrical power requirements and specific thermal energy as a function of CO_2 removal rate

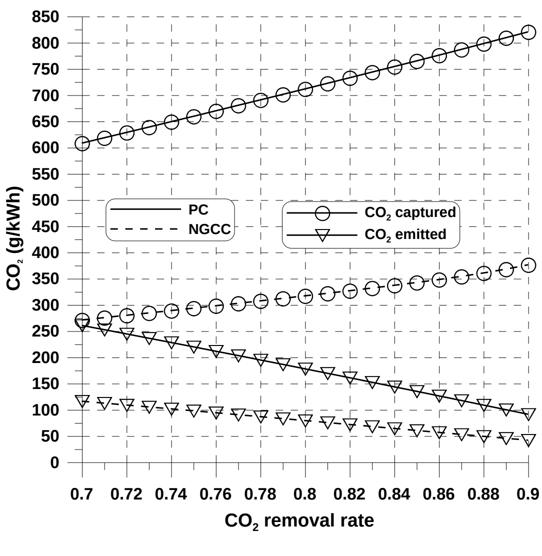

Figure 5 CO_2 captured and emitted as a function of CO_2 removal rate

NGCC is characterized by a larger flue gas mass flow to be treated in comparison to PC, with sensibly higher electrical power requirements. Besides, in PC plant, the higher CO_2 concentration in exhaust requires less solvent for CO_2 capture and consequently the specific thermal energy for solvent regeneration is lower. Figure 4 shows that electrical power requirements slightly increase with CO_2 removal rate, due to the larger power required by the solvent pump, in PC they range between 5.3 and 6.1 MW. Electrical consumptions of the NGCC are higher (about 3 more MW). For the PC power plant specific thermal energy required by the reboiler is about 3.5 MJ/kg assuming a CO_2 removal rate equal to 0.7 and increases up to 3.75 MJ/kg for a CO_2 removal rate equal to 0.9. Due to the lower CO_2 concentration in the flue gas, a higher specific thermal energy is required by the NGCC, up to 4.6 MJ/kg, assuming a CO_2 removal rate equal to 0.9. For the PC steam plant the amounts of CO_2 to be removed is larger, leading to higher values of both CO_2 captured and emitted in comparison to NGCC. As expected, Figure 5 shows that amounts of CO_2 captured and CO_2 emitted are increased and decreased respectively, increasing the CO_2 removal rate. At a CO_2 removal rate of 0.90, the amount of CO_2 captured is equal to 820.4 g/kWh (PC) and 376.3 g/kWh (NGCC). Both the plant show CO_2 emissions lower than 100 g/kWh, at a CO_2 removal rate of 0.90, in particular NGCC (41.8 g/kWh).
Figures 6 shows the plant net power and the net plant efficiency reduction as a function of the CO_2 removal rate for both PC and NGCC. As expected, the introduction of the CO_2 removal system remarkably reduces net power of both plants. The power reduction is mainly due to steam extraction for amine regeneration, but also the CO_2 compression train and the electrical consumptions of the capture system, reported on figure 4, contribute. With reference to the NGCC plant, amine regeneration causes 77.2% of the total power reduction, whereas CO_2 compression and system requirements account for 15.1% and 7.7%, respectively. NGCC performance is more affected by CO_2 removal rate, due to the greater increase of the specific thermal energy required for solvent regeneration. Overall, NGCC net power decreases to 513.2 MW assuming a CO_2 removal of 70%, whereas it drops down to 475.4 MW for a CO_2 removal of 90%. PC net power reduction is more restrained, leading to a PC net power equal to 337.7 MW for a CO_2 removal rate of 0.9. As a consequence of power reduction, also net plant efficiency is largely reduced by the introduction of the CO_2 removal section. Figure 6 shows that in comparison to reference PC efficiency (41.5%) the net plant efficiency decreases of 15.6% and 19.6%, at 0.7 and 0.9 of CO_2 removal rate, respectively. Greater increases of the efficiency penalties with CO_2 removal rate are calculated for NGCC. In comparison to reference efficiency (59.2%), net plant efficiency decreases of 13.3% and 19.7%, at 0.7 and 0.9 of CO_2 removal rate, respectively. Globally, for a reference value of CO_2 removal rate equal to 0.9, net plant efficiency of PC and NGCC are equal to 33.3% and 47.5%, respectively.

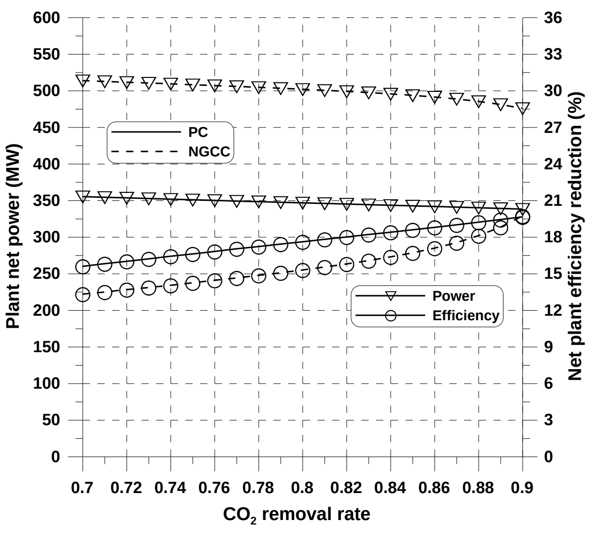

Figure 6 Plant net power and net plant efficiency reduction as a function of CO_2 removal rate

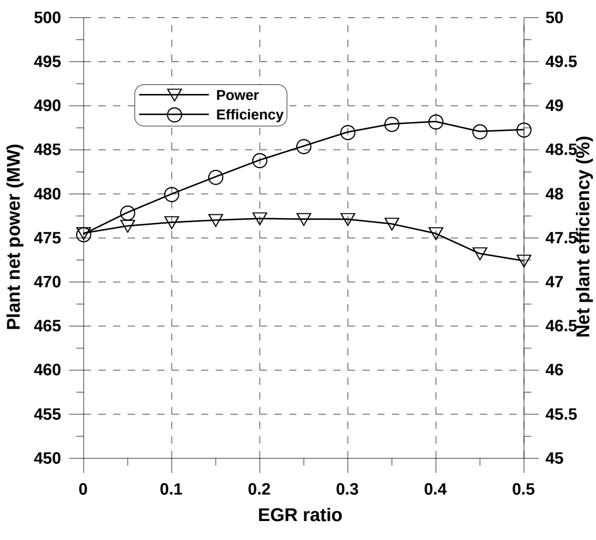

Figure 7 NGCC net power and net efficiency as a function of EGR ratio

3.3 Exhaust gas recirculation

Exhaust gas recirculation (EGR) has been developed mainly for oxy-fuel plants fed by coal, where exhaust gas is partially recycled back to the boiler with the aim of controlling flame temperature. EGR has also been proposed for post-combustion capture when using gaseous hydrocarbon fuels. In fact, key challenges of post-combustion capture are related to the high exhaust volumes and comparably low CO_2 concentration in the flue gas. For an NGCC with post-combustion capture, EGR increases the exhaust concentration of CO_2, improving the capture efficiency (lower energy requirements for the amine system) and substantially reducing capture equipment size and costs. Sipocz and Tobiesen (2012) reported that efficiency losses are reduced by approximately 1 percentage points and Rokke (2006) reported that capital expenditure for the capture unit is reduced by 20-30%.

Figure 7 shows both the net power plant and net plant efficiency of the NGCC as a function of the EGR ratio, defined as the ratio between the exhaust gas recirculated back to the compressor and the total exhaust gas mass flow. Results are reported for an exhaust gas cooling temperature equal to 30 °C. Figure 7 shows that an overall optimum in terms of net plant efficiency of about 48.8% could be expected at EGR ratios equal to 0.4. On the contrary, NGCC-CCS net power is just barely affected by EGR ratio. At an EGR ratio equal to 0.4, a net power of 475.5 MW has been calculated.

4. LOW TEMPERATURE HEAT SOURCES

Low temperature heat rejected from the solvent-based CO_2 removal system could be a potential energy source for enhancing plant performance of both PC and NGCC power plants. In fact so far little attention has been given to recovering the low temperature heat rejected from capture plants and the auxiliaries required to enable them. In particular this paper examines the effect of recovering this low temperature heat by a bottoming Organic Rankine Cycle (ORC) (Lecompte *et al.*, 2015).

Different sources of available low temperature heat from amine-based post-combustion CO_2 removal systems can be theoretically used for heat recovery in an ORC. In general the following major low-grade heat sources can be identified: (i) exhaust gas cooler, (ii) amine reboiler condensate cooling, (iii) stripper condenser, (iv) CO_2 compressor intercoolers and (v) lean solvent coolers.

In particular, cooling down exhaust gas leads to a discharge of a large amount of low temperature (80-120 °C, depending on technology) thermal energy. Furthermore, in the CO_2 capture section a large amount of waste heat is available from the stripper condenser (at 100-120 °C) and the amine reboiler condensate cooling (at 130-140 °C). In the stripper condenser a mixture of CO_2 and water vapor condensates making available both sensible and latent heat for heat recovery at a variable temperature. The saturated hot water (in the order of 4 bar) exiting from the reboiler unit is also available for feeding the ORC. Additional sensible heat could be recovered from CO_2 compressor intercoolers, at a temperature level dependent on the CO_2 compressor chain configuration. Since CO_2 compressors are generally characterized by low pressure ratios in order to reduce CO_2 compression work, temperature of the waste heat from compressor intercoolers would be insufficient for heat recovery in an ORC. Therefore heat recovery from the compressor intercoolers is not analyzed in this study. Furthermore, low temperature heat could be provided from cooling the lean-CO_2 solvent. Since this thermal energy is almost fully used to preheat the rich solvent, this potential heat source is not included in this study.

5. ORGANIC RANKINE CYCLE

5.1 ORC layout

Since waste heat sources at similar temperature are available in a post-combustion capture section, in this paper a parallel configuration of heat recovery has been selected. In fact, in series or cascaded layouts are potentially simpler in design, but their application typically would require a notable temperature difference between the waste heat sources used. In comparison, a parallel heat recovery layout comes with operational challenges related to controlling different and potentially fluctuating mass flow through each of the parallel heat exchangers in a single ORC loop. Nonetheless, a parallel heat recovery layout in principle allows for simultaneous heat recovery from different waste heat sources at very similar temperature.

5.2 ORC fluid

Depending on waste heat source temperature, different suitable organic working fluids can be selected. For this specific application, taking into account operating conditions, carbon dioxide and N-Butane are considered as potential ORC working fluids. In fact, both of them could be well matched with the available waste heat temperature levels by adjusting the cycle operating pressures. Table 3 shows CO_2 and N-Butane saturation pressure as a function of temperature.

Table 3. Saturation T and p for CO_2 and N-Butane

Temperature (°C)	Pressure (bar)	Pressure (bar)
	CO_2	N-Butane
10	44.9	1.5
20	57.3	2.1
30	72.1	2.8
40	- *	3.8
50	-	4.9
60	-	6.4
70	-	8.1
80	-	10.1
90	-	12.5
100	-	15.3

* CO_2 critical point at 73.8 bar and 31 °C

CO_2 could be an interesting choice as organic working fluid, due to synergies in the fluid handling or safety infrastructure with the CO_2 capture system, lower costs and a better match with the exhaust gas cooling curve, due to the lack of vaporization in the operating range under consideration. However, CO_2 shows some disadvantages, in particular a higher pump work, due to the supercritical conditions, and higher equipment costs, due to the very high operating pressure required. For example, at 20 °C CO_2 condensates at 57.3 bar, whereas, N-Butane at a significantly lower pressure of 2.1 bar. Due to the lower operating pressure, N-Butane was selected as organic fluid for more detailed analysis.

5.3 Results

As previously mentioned, in this study the ORC system recovers waste heat simultaneously at slightly different temperature by using parallel waste heat exchanger arrangements. Due to the parallel flow configuration, all heat exchangers must operate at the same upper operating pressure of N-Butane. In addition, heat exchangers here considered do not include fluid superheating section and however N-Butane exits the evaporator at saturation conditions, with the highest operating temperature. As a consequence, the maximum operating pressure in the cycle is specified by saturation properties of N-Butane. Table 4 shows the main characteristics of the Organic Rankine Cycle.

Table 4. Main operating parameters of the Organic Rankine Cycle

Maximum cycle pressure (turbine inlet)	bar	6-12
Maximum cycle temperature (turbine inlet)	°C	58-88
Vapor fraction at the turbine inlet		1
Minimum cycle pressure (condenser)	bar	2.5
Minimum cycle temperature (condenser)	°C	25
Minimum ΔT at the heat exchanger	°C	5

A condenser pressure equal to 2.5 bar was fixed, corresponding to a condensation temperature of 25 °C. Since waste heat sources are available at different temperatures for both power plants, a sensitivity analysis has been carried out as a function of the maximum pressure of N-Butane in the Organic Rankine Cycle. A maximum ORC pressure in the range 6 and 12 bar was assumed, corresponding to a saturation temperature between 58 and 88 °C. A minimum temperature difference of 5 °C was assumed in the heat exchangers between the heat source and the organic working fluid. A higher pressure of organic fluid leads to a higher evaporation temperature, reducing the amount of heat that

can be recovered. On the other hand, a higher pressure inside the evaporator maximizes the turbine work, while additional required pump work to achieve the higher pressure is comparably low. For these reasons heat recovery can be optimized through a trade-off between key operating parameters.
Figures 8 and 9 show the waste heat recovered as a function of the ORC maximum pressure for both PC (Figure 8) and NGCC (Figure 9) power plants. The figures report the total heat recovered and the heat recovered from each of the three different heat sources analyzed in this study. In particular, results of the NGCC are reported considering a reference scenario based on an EGR ratio equal to 0.4.

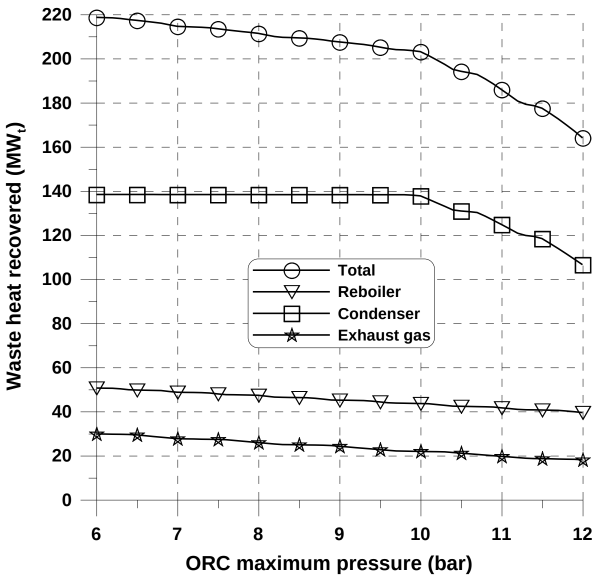

Figure 8 Waste heat recovered as a function of ORC maximum pressure

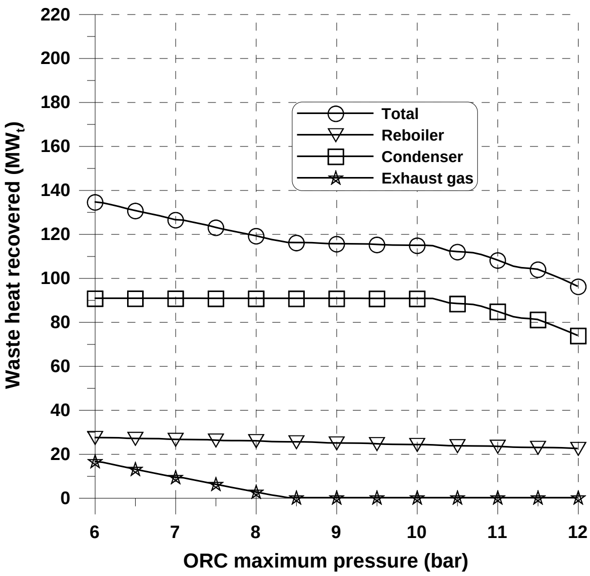

Figure 9 Waste heat recovered as a function of ORC maximum pressure.

Figures show that a larger amount of heat is recovered from the PC in comparison to NGCC. As mentioned above, an increase in the ORC maximum operating pressure reduces the overall waste heat recovery, and the single heat recovered, although not all the sources are impacted by a similar intensity. In both plants the largest amount of waste heat is recovered from the stripper condenser. An increase of the operating pressure results in a constant (about 138 MW and 91 MW for PC and NGCC, respectively) waste heat recovered from the stripper condenser until a maximum pressure of about 10 bar is reached. An even higher pressure reduces the possible waste heat recovery from the condenser, which has a water exit temperature slightly higher than 100 °C, since the pinch point minimum temperature difference is reached. Minimum amounts of waste heat equal to 106.5 MW (PC) and 73.8 MW (NGCC) are recovered for an operating pressure of 12 bar. On the contrary, the waste heat recovered from the amine reboiler condensate cooling is not affected significantly by the maximum cycle pressure, due to the comparably high temperature (up to 140 °C) of the saturated water that exits the amine reboiler. In particular, increasing the maximum operating pressure from 6 bar to 12 bar, waste heat recovery decreases from 50.6 to 39.5 MW (PC) and from 27.3 to 22.4 MW (NGCC). Lower amount of waste heat can be recovered from exhaust gas cooling. In the PC plant the heat recovered decreases from 29.7 to 18.0 MW, respectively at 6 and 12 bar. On the contrary, for NGCC, waste heat recovery from exhaust gas cooling is possible only at very low evaporation pressures of N-Butane. In particular the heat recovery would be 16.5 MW at 6 bar, while no waste heat recovery from exhaust gas cooling would be possible at maximum evaporation pressure higher than 8.3 bar. Figures 8 and 9 show also the total amount of waste heat that potentially could be recovered. Figure 8 shows that for the PC plant, the heat recovered would be 218.6 MW at 6 bar operating pressure. A relatively moderate reduction is obtained by increasing pressure up to 10 bar (203.0 MW), while at higher pressure a notable reduction of heat recovered can be noticed, mainly due to reduction in heat recovery from the stripper condenser. A minimum of 164.0 MW is recovered at a operating pressure of 12 bar. A similar trend is shown on Figure 9 for waste heat recovery from

NGCC. A maximum value of 134.5 MW can be recovered at 6 bar, whereas minimum heat recovery is equal to 96.1 at 12 bar. At 10 bar of operating pressure, waste heat recovered is equal to 114.8 MW. Figure 10 and 11 show the ORC net efficiency and the ORC net power as a function of ORC maximum pressure, for PC and NGCC plants respectively. In particular, figures show the total net power and the corresponding net power produced by ORC from each of the three heat sources.

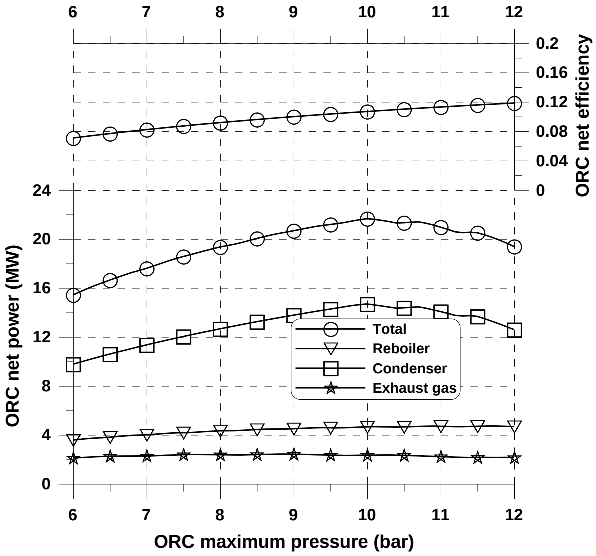

Figure 10 ORC net power and efficiency as a function of ORC maximum pressure

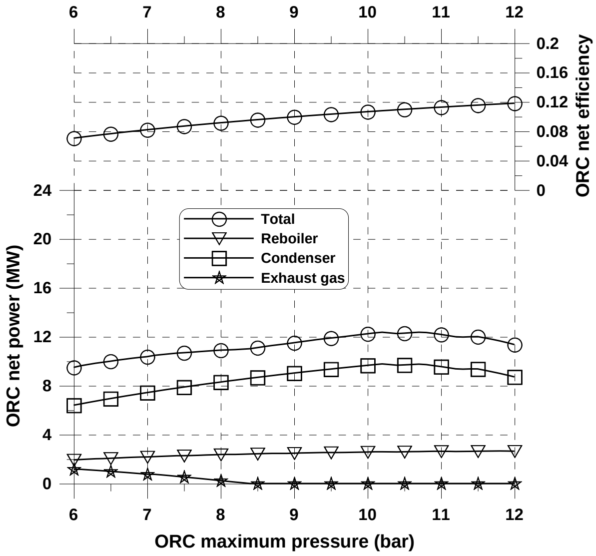

Figure 11 ORC net power and efficiency as a function of ORC maximum pressure.

Unlike waste heat recovered, ORC net efficiency increases with ORC maximum pressure. In particular, for the reference scenario based on a condenser pressure equal to 2.5 bar, cycle net efficiency increases from 7.1% (6 bar) to 11.8% (12 bar). As a consequence of opposite trend for waste heat recovered and net efficiency, the net power generated by the ORC system peaks at around 10.5 bar for PC and at 10 bar for NGCC. Since the largest amount of waste heat is recovered from the stripper condenser, not surprisingly the main contribution to the net Organic Rankine Cycle power stems from this heat source. The maximum net power that can be generated by the studied ORC system integrated with the PC-CCS is 21.6 MW (about 6.4% of the reference plant) at a total low-temperature heat input of 203.1 MW (ORC net efficiency of 10.7%). Due to the lower amount of heat recovered, ORC integrated with NGCC assures a lower additional power. In particular, a maximum additional power of 12.3 MW can be generated (about 2.6% of the NGCC-CCS plant with 40% EGR) at a total low-temperature heat input of 112.0 MW (ORC net efficiency of 11.0%).
The overall impact of ORC integration on net power and efficiency is shown in Table 5, where plant performance is represented with or without CCS and ORC integration.

Table 5. Main plant performance

		PC	NGCC
Gross power of reference plant	MW	454.6	625.2
Net power of reference plant	MW	420.2	592.0
Net power of plant + CCS	MW	337.8	475.5
Net power of plant + CCS + ORC	MW	359.4	487.8
Net efficiency of reference plant	%	41.5	59.2
Net efficiency of plant + CCS	%	33.3	48.8
Net efficiency of plant + CCS + ORC	%	35.5	50.1

Table 5 shows that integrating CCS-power plants with an Organic Rankine Cycle assures a notably reduction of the influence of CO_2 capture penalization on plant power output. In general, considering that this study only evaluates the thermodynamic potential of heat recovery, the introduction of an

Organic Rankine Cycle would allow to increase the overall plant efficiency of 2.2 percentage points for the PC-CCS plant and of 1.3 percentage points for the NGCC-CCS plant. Globally the maximum net efficiency of the NGCC-CCS under investigation could thereby rise to 50.1%, whereas the maximum net efficiency of the PC-CCS increases up to 35.5%.

6. CONCLUSIONS

This paper analyses the option to recover low-grade heat from CO_2-capture processes for both pulverized coal steam plant and natural gas combined cycles by using Organic Rankine Cycle (ORC) technology. Potential waste-heat sources are identified and most appropriate ORC system layouts and working fluids are discussed. Under the assumption that N-Butane is used as an ORC working fluid, and low-grade heat sources are utilized in parallel in a single ORC loop, an overall power plant net efficiency improvement potential of 1.5-2.5 percentage points is estimated, depending on the power plant considered.

NOMENCLATURE

CCS	Carbon Capture and Storage
EGR	Exhaust Gas Recirculationto
LHV	Lower Heating Value
MEA	Monoethanolamine
NGCC	Natural Gas Combined Cycle
ORC	Organic Rankine Cycle
PC	Pulverized Coal

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