

# CO<sub>2</sub> Capture from Natural Gas Combined Cycles

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## **ABSTRACT**

This paper presents a comprehensive analysis of three near-term plant configurations for CO<sub>2</sub> capture from natural gas-fired power plants based on combined cycle: (i) amine post-combustion separation, (ii) syngas decarbonization, (iii) oxy-combustion. We address them as ‘near-term’ because they do not involve the development of components requiring unproven technology. All configurations are based on a common set of assumptions, reproducing the performance of a status-of-the-art combined cycle based on ‘FB technology’ gas turbine.

The performance prediction shows that the best efficiency is achieved by post-combustion (with a loss of efficiency of 6.4 points), followed by pre-combustion, both showing about 90% carbon capture. Oxy-combustion shows a lower efficiency with lower emissions (98% capture, virtually no CO, UHC and NO<sub>x</sub> emissions). The post-combustion solution also shows the best economics.

## **INTRODUCTION**

CO<sub>2</sub> capture from fossil fuel power plants is increasingly proposed for greenhouse gases emission mitigation. It can be applied to coal power stations (with boiler and steam cycle or with gasification) or to natural gas combined cycles (NGCC). The first case is probably the most important in a mid-term perspective, due to: (i) the larger amount of avoided carbon per unit of electricity produced, (ii) the larger strategic reserves of coal vs. natural gas. However, capture from NGCCs is more likely to be applied in the short-mid term, for many reasons (lower initial costs, lower technical risks, better operability, etc.) particularly relevant for near-term projects, e.g. large scale demonstration plants. Besides, a considerable fleet of modern and efficient combined cycles is now in service in many countries (e.g. Italy) and, potentially, it can be modified to capture operation.

This paper presents a comprehensive analysis of three near-term plant configurations for CO<sub>2</sub> capture: (i) amine post-combustion separation, (ii) syngas decarbonization, (iii) oxy-combustion. We address them as ‘near-term’ because they do not involve the development of components requiring unproven technology, i.e. novel components can be manufactured and operated by using available knowledge. The three configurations have been often addressed in the literature: however, in this paper we will consider the most efficient and updated technologies, comparing their performance on the basis of a common reference plant and of a consistent set of assumptions.

## **METHOD OF CALCULATION AND REFERENCE CASE**

The thermodynamic performance of the power plants here discussed were calculated by means of GS, which is an in-house computer code developed in the past years at the Department of Energy of Politecnico di Milano. The code is a powerful and flexible tool that can be used to accurately predict the performance of a very wide variety of chemical processes and systems for electricity production. GS was originally designed to assess the

performance of gas-steam cycles for power production and has been progressively developed and improved to calculate complex systems including coal gasification, chemical reactors, fuel cells and essentially all the processes present in advanced plants for power generation from fossil fuels. As a brief reminder, the main features of the code are: (i) capability of reproducing very complex plant schemes by assembling basic modules, such as turbine, compressor, combustor, steam section, chemical reactor, heat exchanger, etc., (ii) built-in correlations to predict turbomachinery efficiency (gas and steam turbine stages and compressors) as a function of their operating conditions, (iii) built-in correlations to predict gas turbine cooling flows, (iv) gas composition at the outlet of each reactor is determined by assuming chemical equilibrium.

The reference case (without capture) is a state-of-the-art combined cycle, based on two GE 9FB gas turbines and a three-pressure reheat steam cycle. Evaporation pressures are 130, 36, 4 bar, maximum steam temperature is 568°C, condensation pressure is 47.6 mbar. Data were provided by Edison SpA, which funded this study. The following Table 1 shows the accuracy of the calculation method after a proper calibration of the input variables.

Reference combined cycle, no capture	Manufacturer's data	Calculated value	Perc. variation
<b>Gas Turbine:</b>			
Natural gas flow, kg/s (air flow imposed)	16.187	16.198	0.07%
Gross electric power output, MWe	272.6	272.44	-0.06%
Gross electric efficiency, %	38.18	38.11	-0.07 points
Turbine outlet temperature, °C	622.8	622.7	-0.1°C
<b>Steam Cycle:</b>			
HP steam flow, kg/s	167.00	167.27	0.16%
IP steam flow, kg/s	20.83	20.88	0.24%
LP steam flow, kg/s	20.39	20.24	-0.74%
Exhaust gas temperature at stack, °C	89	88.6	-0.4°C
Steam turbine gross electric power, MWe	299.70	299.29	-0.14%
Net electric power, combined cycle, MWe	822.10	821.37	-0.09%
Net electric efficiency, combined cycle, %	57.60	57.45	-0.15 points

*Table 1 – Accuracy of the calculation method applied to the reference combined cycle*

## **POWER PLANTS WITH CO<sub>2</sub> CAPTURE**

### **POST-COMBUSTION**

The post-combustion option makes use of a conventional mono-ethanol-amine (MEA) gas separation process, reported in Fig.1. MEA is up-to-now the most widely used absorbent fluid for low partial pressure acid gases. Exhaust gas recirculation techniques were not considered, to avoid modifications to the gas turbine and to make the configuration viable for retrofitting of existing plants. Therefore, the power plant section differs from the reference case just for the steam extraction, providing heat to the stripper of the separation section.

The operational parameters of the MEA process (solution flow rate, purity of lean solution, stripping pressure) were optimized to achieve the best compromise between carbon removal efficiency and cycle efficiency. An example of this optimization is given in Fig.2, as far as the L/G ratio (liquid/gas mass flow rates) at the absorber inlet is concerned: a fixed CO<sub>2</sub> removal rate (90%) can be achieved by elevated solution flows with a relatively high inlet CO<sub>2</sub> concentration (low purity) of vice-versa. The results of the optimization are also shown in Table 2, showing a minimum in specific steam consumptions of about 3.75 MJ/kg CO<sub>2</sub>.

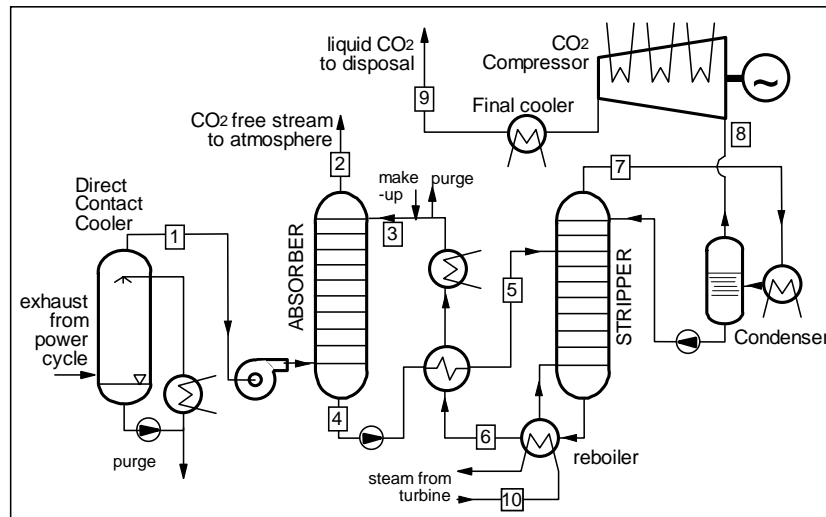


Figure 1 – Configuration of the MEA acid gas separation plant for post-combustion capture.

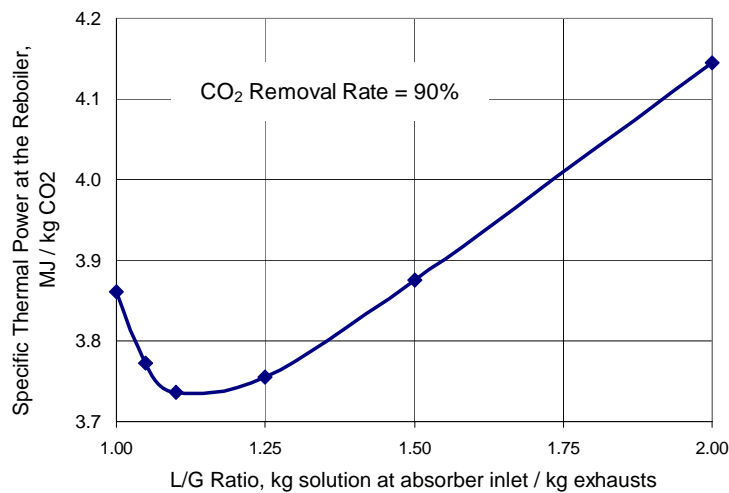


Figure 2 – Specific thermal power for solution regeneration in the MEA plant.

L/G ratio, kg/kg	1.00	1.05	1.10	1.25	1.50	2.00
Solution flow rate at absorber inlet, kg/s	653.34	686.01	718.68	816.68	980.01	1306.6
Lean solution loading, molCO <sub>2</sub> / molMEA	0.23	0.24	0.25	0.28	0.31	0.35
Rich solution loading, molCO <sub>2</sub> / molMEA	0.50	0.50	0.50	0.49	0.49	0.49
Cooling duty, MW	163.29	161.09	160.85	165.47	177.96	207.13
Recuperator duty, MW	166.26	173.81	181.18	202.33	234.78	292.54
Reboiler thermal power, MW	143.00	139.80	138.40	139.10	143.60	153.60

Table 2 – Performance of the MEA plant at various L/G ratios.

### PRE-COMBUSTION

The pre-combustion option here shown (fig.3) makes use of the best technologies to improve the efficiency of the natural gas conversion to hydrogen. It is based on an air-blown auto-thermal reformer, operating at 1050°C with an optimized S/C of 1.25 (larger use of steam improves the chemical conversions and the CO<sub>2</sub> capture, but penalizes the power cycle). The plant configuration has been intensively optimized, by the introduction of: (i) a pre-reforming section, heated by the high temperature reformed syngas, (ii) a double shift reactor, to optimized the heat recovery and CO conversion, (iii) a separation process, combining the physical and chemical absorption properties of MDEA (methyl-diethanol-amine) to minimize the energy requirements for the solvent regeneration (fig.5). An example of optimization is given in figure 6, where we investigated the effects on the capture efficiency of: (i) the

‘solution loading’ in the absorber (related to the L/G ratio), (ii) the relative amount of solution sent to the stripper, for a better thermal regeneration, following the pressure-swing regeneration (physical effect).

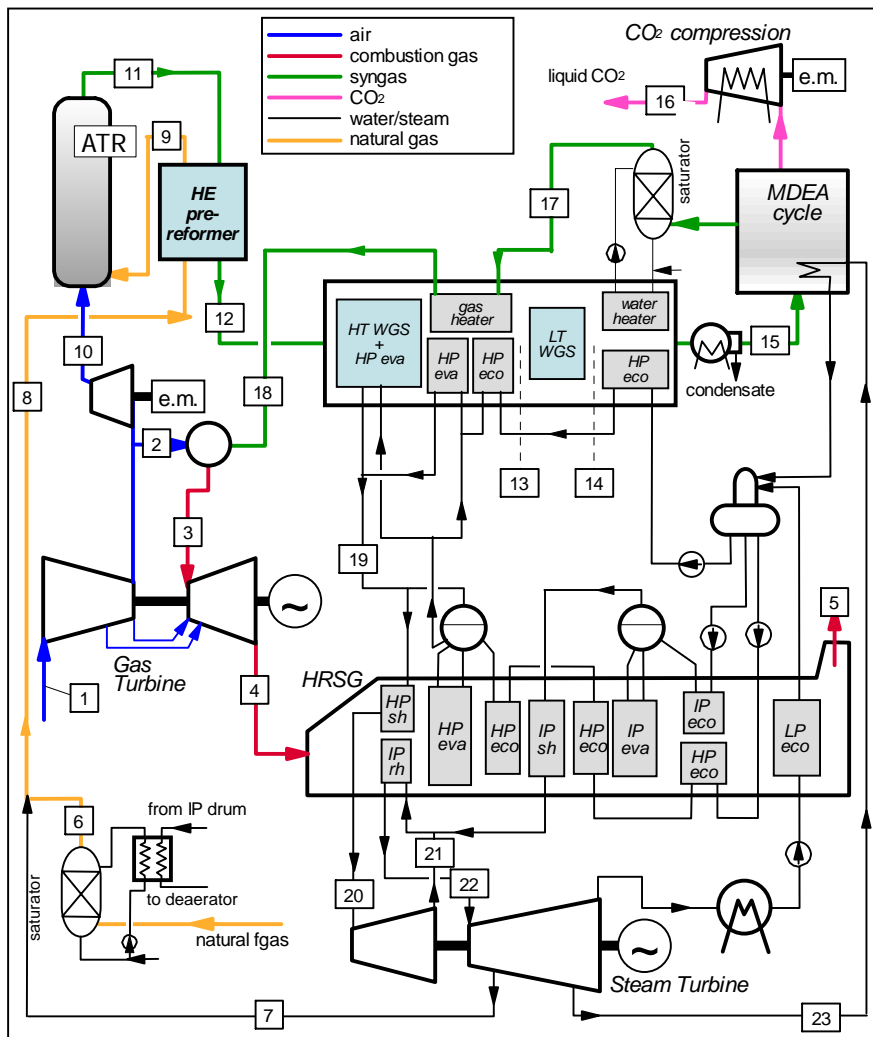


Figure 4 – Plant configuration for pre-combustion capture.

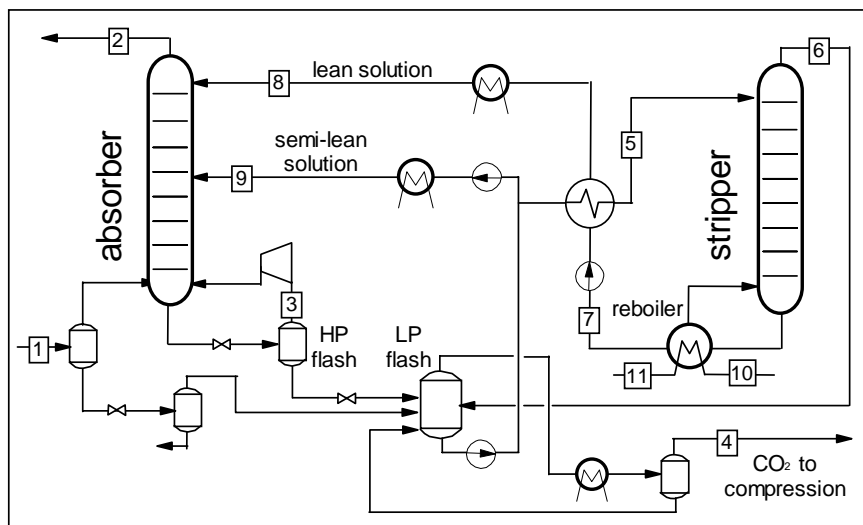


Figure 5 – Plant lay-out of the MDEA separation plant for pre-combustion capture..

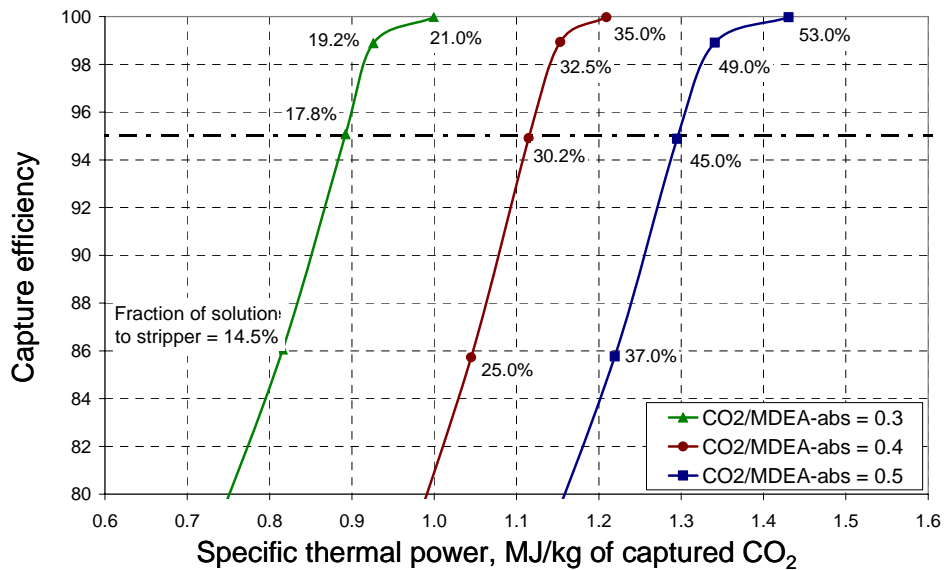


Figure 6 – Removal efficiency of the MDEA plant.

### OXY-COMBUSTION

The oxy-fuel option (fig.7) includes: (i) a double column air separation unit, producing high purity (98.5%) oxygen, (ii) a semi-closed gas turbine cycle with a CO<sub>2</sub>-H<sub>2</sub>O expander fed by oxy-combustion products diluted by recirculated CO<sub>2</sub>, (iii) a CO<sub>2</sub> liquefaction process, including the separation of inert gases (N<sub>2</sub>, O<sub>2</sub>, Ar) via a cryogenic process.

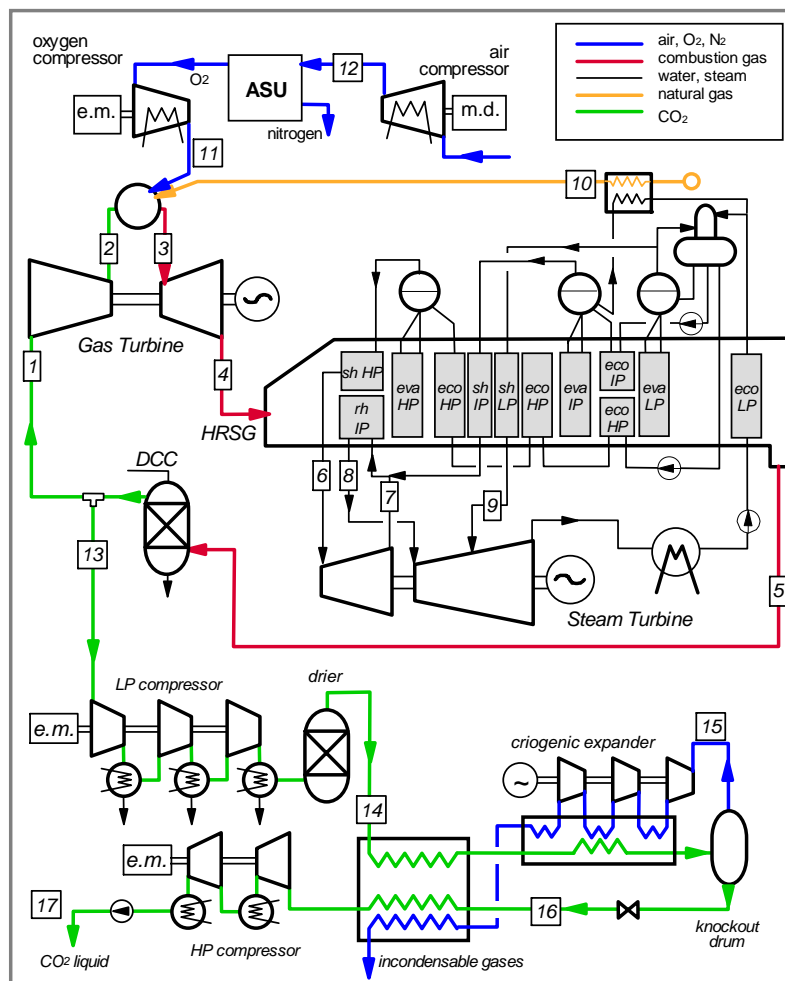


Figure 7 – Plant configuration for oxy-combustion capture.

The relevant issue in this plant is the Joule cycle machine, which operates with a mixture of CO<sub>2</sub> and water, having thermodynamic properties very different from air/combustion gases. To keep a cycle efficiency close to the one of conventional machines, the same temperature history must be reproduced by means of a much higher pressure ratio: our optimized value is about 44, vs. 18 of the original machine. A full re-design of the machine is therefore required, also keeping into account the better transport properties of CO<sub>2</sub>, enhancing the blade cooling requirements. This re-design does not entail new technologies or new methodologies, but it requires a lot of efforts and development costs: this is the major drawback of any oxy-fuel system, posing an hard obstacle to their applications.

The management of incondensable gases (Ar and N<sub>2</sub> from oxygen impurities, O<sub>2</sub> from excess oxidizer) was investigated in detail: (i) compressed O<sub>2</sub> is mixed in the combustion chamber rather than in GT compressor inlet (cooling flows would have enriched in O<sub>2</sub> the exhausts); (ii) a cryogenic separation process was included during CO<sub>2</sub> compression, before the final liquefaction. The stream released from this process to the ambient includes some CO<sub>2</sub>: this is the only carbon emission of this plant, which can be limited to negligible amounts with further separation processes, such as PSA, not considered here.

## RESULTS

The performance prediction (table 3) shows that the best efficiency is achieved by post-combustion (51%, starting from a NGCC with 57.4%), followed by pre-combustion (49.7), both showing about 90% carbon capture. Oxy-combustion shows a lower efficiency (46%) with lower emissions (98% capture, virtually no CO, UHC and NO<sub>x</sub> emissions).

		<i>No capture</i>	<i>Post-comb.</i>	<i>Pre-comb.</i>	<i>Oxy-fuel</i>
Total net electric power, MW		821.4	728.6	808.2	660.1
Gas Turbine	x2	272.4	272.4	286.3	279.7
Steam Turbine		299.3	241.1	311.8	315.5
Auxiliaries, power cycle		22.8	16.3	25.6	16.5
Auxiliaries, heat rejection		-	8.8	8.1	12.9
Auxiliaries, MEA/MDEA cycle		-	3.7	2.5	-
Air and O <sub>2</sub> Compressors, ASU	x2	-	-	-	75.1
CO <sub>2</sub> Compressor	x2	-	12.4	15.1	17.6
Thermal power rejected, MW		459.9	588.8	537.0	861.9
Condenser		459.9	189.5	358.5	690.3
MEA/MDEA/ASU	x2	-	178.1	65.0	59.8
CO <sub>2</sub> Compressor	x2	-	21.5	25.6	26.0
Fuel thermal power LHV, MW		1429.7	1429.7	1625.0	1429.7
Net efficiency		0.5745	0.5096	0.4974	0.4617
CO <sub>2</sub> generated from fuel, kg/s		81.47	81.47	92.61	81.47
CO <sub>2</sub> captured, kg/s		-	73.91	84.77	78.96
Removal efficiency		-	0.9072	0.9154	0.9691
Specific emission, g CO <sub>2</sub> /kWh		357.09	37.36	34.88	13.72

*Table 3 – Performance of the various plant configurations.*

An indicative cost analysis was also performed (Table 4). The investment costs were estimated on the basis of a large number of literature indications (see some references at the end of paper), introduced in our data base of specific costs of the major components, eventually adapted to the actual plant size. The fuel cost is based on a natural gas cost of 7 €/MJ (about 0.19 €/Nm<sup>3</sup>).

Externalities were also considered in Table 4, to keep into account the different environmental performance of the power plants. In fact, not only the carbon capture rate is

different (see Table 3), but dissimilar NO<sub>x</sub> emission can be anticipated:

- For post-combustion, the same absolute emissions of the reference case apply to a reduced electricity production, due to the loss of efficiency
- For pre-combustion, the elevated hydrogen content in the fuel brings about: (i) a high flame temperature, (ii) the utilization of a diffusion burner, producing more NO. However, syngas is largely diluted by nitrogen (due to air-blown reforming) and water saturation is used (fig.4) to limit the flame temperature, but a moderate improvement of NO emission can be anticipated [13].
- For oxy-fuel, the NO exits the power cycle together with the gaseous CO<sub>2</sub>. During compression and liquefaction, NO is also liquefied and stays in solution within CO<sub>2</sub> (as suggested by theoretical calculations of two-phase equilibrium). No emissions to the atmosphere can be probably achieved.

The ‘damage factor’ of the various pollutants of Table 4 are derived from Extern-E literature [14] (NO<sub>2</sub> 3 €/kg, SO<sub>2</sub> 3.4 €/kg, NMVOC 1.1 €/kg, CO<sub>2</sub> 19 €/ton).

	No capture	Post-comb.	Pre-comb.	Oxy-fuel
1st year carrying charge	0.1450	0.1549	0.1549	0.1549
Overnight plant cost, €/kW	414	780	948	1004
Operating hours, h/year	7800	7800	7800	7800
Yearly average efficiency	0.5601	0.4969	0.4850	0.4502
COE investment, €/MWh	7.69	15.50	18.83	19.93
COE O&M, €/MWh	2.99	5.25	5.26	5.60
COE fuel, €/MWh	44.99	50.72	51.96	55.98
<b>COE total, €/MWh</b>	<b>55.67</b>	<b>71.46</b>	<b>76.05</b>	<b>81.51</b>
Cost of CO <sub>2</sub> captured, €/ton		42.16	52.64	58.51
Cost of CO <sub>2</sub> avoided (plant), €/ton		48.16	61.68	73.37
Cost of CO <sub>2</sub> avoided, including transport and final storage (7 €/ton)		<b>57.30</b>	<b>71.05</b>	<b>83.40</b>
Externalities NO <sub>2</sub> , €/MWh	0.46	0.52	0.90	0.00
Externalities SO <sub>2</sub> , €/MWh	0.02	0.02	0.00	0.00
Externalities NMVOC, €/MWh	0.00	0.01	0.00	0.00
Externalities CO <sub>2</sub> , €/MWh	8.74	0.91	0.85	0.34
<b>Total cost with externalities, €/MWh</b>	<b>64.89</b>	<b>72.92</b>	<b>77.81</b>	<b>81.85</b>

*Table 4 – Economic performance of the various plant configurations.*

Again, the best solution is post-combustion with a cost of the avoided CO<sub>2</sub> of about 50 €/ton at the plant battery limit. On another point of view, the cost of electricity, inclusive of quoted ‘externalities’, rises from 65 €/MWh for the no-capture solution to 73-82 €/MWh of the various considered plants, a ‘sustainable’ increase for low carbon emission electricity.

The cost of the CO<sub>2</sub> avoided depends on the fuel cost, due to the loss of efficiency related to capture, as shown by fig.8 for the most interesting case of post-combustion capture.

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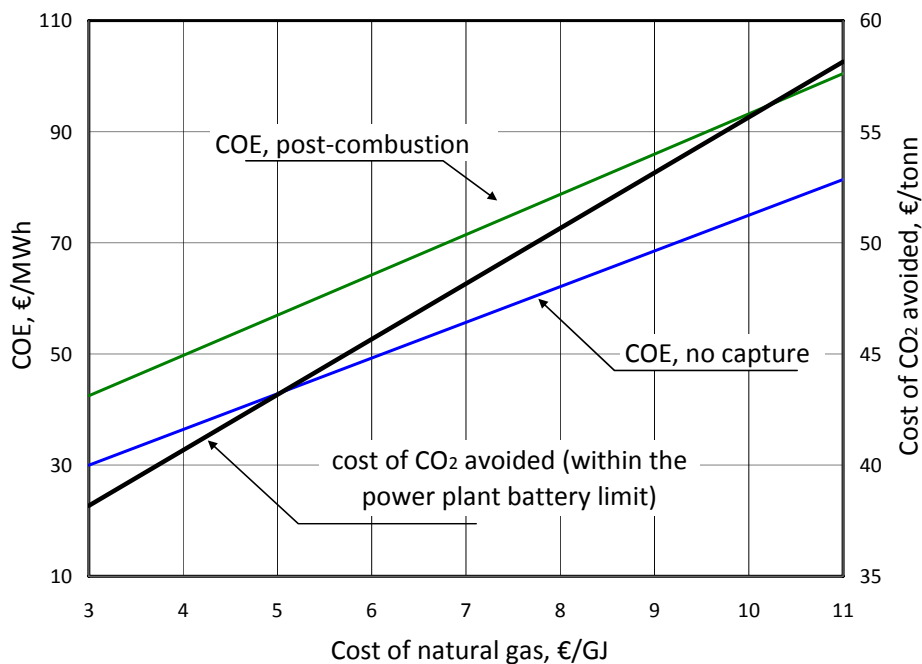


Figure 8 – Cost of electricity and of avoided CO<sub>2</sub> as a function of the fuel cost.

**Keywords:** NGCC, CO<sub>2</sub>, Capture, Oxyfuel, Amine, Shift.