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ECONOMIC IMPLICATIONS OF CARBON CAPTURE OPTIONS FOR POWER GENERATION BASED ON GASIFICATION

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ABSTRACT. The present paper evaluates, from an economical point of view, pre- and post-combustion capture from gasification power plants. The cases of Integrated Gasification Combined Cycle (IGCC) power plant which uses coal mixed with sawdust and generates about 400 MW net electricity with and without CO_2 capture is presented in detail. The comparison is done considering the most important economic indicators e.g. cost of electricity, CO_2 avoided and removed costs etc. Concerning the total investment cost, the calculation results show that the cost of IGCC with Carbon Capture and Storage (CCS) is higher (pre-combustion capture using Selexol® about 23% higher and post-combustion capture using MEA about 36% higher) than the plant without capture. Also, comparing the two main investigated cases for CO_2 capture process, the results show that the electricity production cost for post-combustion capture technology is about 21% higher than the cost for pre-combustion capture technology; CO_2 captured cost for post-combustion capture technology is about 90% higher than for pre-combustion capture technology and CO_2 avoided cost in the post-combustion capture technology case is increased by a factor of 2.15 than in the pre-combustion capture technology case.

Keywords: *Power generation, Carbon Capture and Storage (CCS), Economic assessment.*

INTRODUCTION

The important technological transformations in the field of energy conversion and utilization have led to major changes in the economic and social operation of the world [1]. The increased energy consumption is no

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longer only associated with the conception of progress, but also with a certain number of threats which reflect on our society and environment. For instance energy supplies presently rely mainly on fossil fuels [2]. If consumption continues at the present rates, the proven reserves represent about 52.9 years for oil, 55.7 years for natural gas and almost 109 years for coal [3-4]. Thus the risks of reduction of fossil energy sources and the impact of energy production from fossil fuels on the environment represent a matter of growing concern [2,5]. In addition to the risks for the environment on a local scale, the world is now faced with the danger of global warming caused by CO_2 emissions. A possible way to limit the risks related to climate change caused by CO_2 emissions is to increase the efficiency of power plants and other energy intensive industrial processes or decrease the energy demand in combination with CO_2 capture and long time storage of at least a large proportion of the CO_2 emitted [6]. The only feasible solution for now remains this carbon capture and storage technologies (CCS) [7].

The introduction of carbon capture and storage into large scale industrial processes is expected to have a significant impact on CO_2 emissions. Gasification technology is an energy conversion method having good potential for capturing CO_2 with the low energy and cost penalties [8]. There are various technologic options to fit the carbon capture unit in a IGCC design e.g. gas-liquid absorption or gas-solid (sorbent) pre- and post-combustion capture configurations [9].

The present paper presents an in-depth economic evaluation of a previous work done in our research group [10-12]. An IGCC power plant, based on coal and sawdust co-gasification to generate 360 – 444 MW net electricity with a carbon capture rate higher than 90% (pre-combustion capture is using mixture of dimethyl ethers of polyethylene glycol Selexol® as solvent and post-combustion capture is using monoethanolamine-MEA as solvent) was the basis for the study. The technical description of the investigated technologies (see Figure 1) can be found in the previous published articles [10-11]. The whole power plant concepts were modeled and simulated using ChemCAD software.

The key technical performance indicators presented in previous work [10-12] show that the implementation of CO_2 capture technologies into power plants leads to a substantial reduction of the specific CO_2 emissions for both capture technologies investigated and that the pre-combustion capture technology is more energy efficient than post-combustion capture. In order to have a complete picture and to decide which CO_2 capture technology is the best, an in-depth economical evaluation was conducted. Thus, the present work illustrates a comparison of the current costs of CO_2 capture technologies in order to assess the relative rankings of the different technologies anticipated to meet the most of the future demand for electricity. A detailed economic assessment was done for pre- and post-combustion capture concepts using gas-liquid absorption. The comparison done using the most important economic indicators e.g. cost of electricity (Levelised Cost of Electricity, LCOE), the cost of CO_2 avoided and the cost of CO_2 captured.

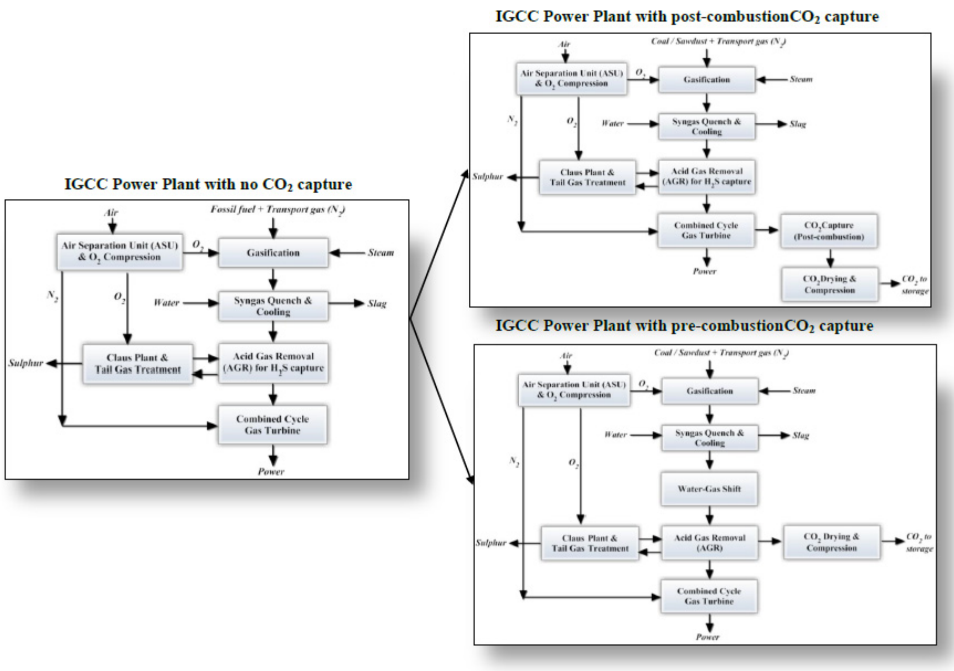

Figure 1. Gasification power plants without and with CO_2 capture (pre- and post-combustion capture)

RESULTS AND DISCUSSION

1. Capital Costs

Investment cost can be divided into four main parts: on – site investment (which covers process equipment and utility investment), off – site investments, engineering fee and working capital [13]. The cost of a specific item of equipment / plant sub-system can be seen as a function of size, material of construction, design temperature and design pressure. Cost data are often presented as cost versus capacity charts, or expressed as a power law of capacity (see equation 1), where C_E represents the equipment cost with capacity Q, C_B represents the know the base cost for equipment with capacity Q_B, M is a constant depending on equipment cost and f_M, f_P and f_T are the correction factors for materials of construction, design pressure and design temperature (available in the open literature) [14]. The correction factor values, used for studies, were chosen for carbon steel, design pressure between 0.50 to 7.00 bar and design temperature of 500ºC [15-16].

$$C_E = C_B \cdot \left(\frac{Q}{Q_B}\right)^M \cdot f_M \cdot f_P \cdot f_T \qquad (1)$$

The technical parameters of various investigated cases (mass and energy balances) were calculated from simulation (for details see [10-11]). Table 1 presents overall plant capital costs estimation of analyzed case studied (Case 1: IGCC without CCS, Case 2: IGCC with Selexol®-based pre-combustion CO_2 capture and Case 3: IGCC with MEA-based post-combustion CO_2 capture.

Table 1. Capital cost estimations for IGCC power plants

Main Plant Data	Unit	Case 1	Case 2	Case 3
Total installed cost	MM €	761.00	932.72	1036.08
Total investment cost	MM €	913.26	1119.26	1243.30
Gross power output	MW_e	519.80	529.79	460.35
Net power output	MW_e	444.72	424.97	359.24
Specific investment cost	$€/kW_{gross}$	1756.95	2112.65	2700.77
Specific investment cost	$€/kW_{net}$	2053.57	2633.74	3460.92

As it can be noticed from Table 1, the total investment cost for power plant with pre-combustion capture process using Selexol® (Case 2) is about 22% higher than the cost for the plant without capture (Case 1). The IGCC investment cost scheme with post-combustion process using MEA (Case 3) is about 36% higher than the total investment cost for the plant without capture. The overall capital cost increase for the cases with CO_2 capture is mainly a result of the increase in the overall plant efficiency, which enlarge the gas processing facilities (gasification island, syngas conditioning train etc.) and the ancillary equipment per kW of generated electricity.

These results are in accordance with the recent study results of the International Energy Agency [17], Global CCS Institute report [19] and other literature references [19-22]. Comparing these two main cases investigated for CO_2 capture process (pre- and post-combustion capture), the calculation shows that the total investment cost for post-combustion capture is about 11% higher than pre – combustion capture.

2. Operating and maintenance (O&M) costs

Operational and maintenance (O&M) costs cover the cost of fuel (coal and sawdust), auxiliary fuel (natural gas), catalysts, solvents, maintenance costs, manpower costs etc. Usually, the cost of fuel, catalysts and solvents has the largest influence on overall plant economics. These commodities costs are found in trade journals such as Chemical Marketing Reporter and European Chemical News [23].

The operating and maintenance (O&M) costs can be divided in fixed and variable costs (see Table 2). Therefore, for the purpose of this study the fixed O&M costs are estimated to be 0.997 ¢/kWh for the plant without CCS capture, 1.216 ¢/kWh for the plant with pre-combustion CO_2 capture using Selexol® as solvent and 1.419 ¢/kWh for the plant with post-combustion CO_2 capture using MEA as solvent. And the O&M variable costs are assume to be 1.984 ¢/kWh for the plant without CCS capture, 2.369 ¢/kWh for the plant with pre-combustion CO_2 capture using Selexol® as solvent and 2.546 ¢/kWh for the plant with post-combustion CO_2 capture using MEA as solvent.

After the CO_2 has been captured, it must be transported to an appropriate storage site for sequestration (e.g. saline aquifer, depleted oil and gas fields). Pipelines are the primary option for large scale transport, with shipping as a second possibility [24]. According to IPCC 2005 report, generally a range of around \$1 – \$6/tone of CO_2 stored can be expected [25-26].

Table 2. Operating and Maintenance (O&M) power plants costs estimation

Fixed O&M	Case 1		Case 2		Case 3	
	MM€/y	k€ /kWh	MM€/y	k€/kWh	MM€/y	k€/kWh
Maintenance cost	27.07	8.11	31.47	9.87	32.98	12.24
Direct labor cost	4.76	1.42	5.60	1.75	5.60	2.07
Administrative cost	1.43	0.42	1.68	0.52	1.68	0.62
Total	33.26	9.97	38.75	12.16	40.26	14.94

Variable O&M	Case 1		Case 2		Case 3	
	MM€/y	k€/kWh	MM€/y	k€/kWh	MM€/y	k€/kWh
Fuel	58.60	17.56	65.53	20.56	58.60	21.74
Auxiliary fuel	2.13	0.63	2.13	0.66	2.13	0.79
Make up water	0.17	0.04	0.17	0.05	0.17	0.05
Catalysts	0.50	0.15	1.50	0.47	1.50	0.55
Solvents	0.00	0.00	0.96	0.30	0.99	0.36
Chemicals	1.69	0.51	1.70	0.53	1.73	0.64
Waste disposal	3.09	0.92	3.51	1.10	3.48	1.29
Total	66.17	19.84	75.49	23.69	68.59	25.46

As it can be noticed from Table 2, the total O&M cost (MM€/year) for the IGCC scheme with pre-combustion capture using Selexol® (Case 2) is about 14.89% higher than the cost for the plant without capture (Case 1). The IGCC scheme with post-combustion capture using MEA (Case 3) is about 9.47% higher than the total investment cost for the plant without capture. These results are in accordance with the recent study results of the International Energy Agency [17], Global CCS Institute [18] and NETL [22] reports. Comparing these two main cases investigated for CO_2 capture process (pre- and post-combustion capture options), the calculation shows that the total O&M cost for pre-combustion capture technology is about 4.95% higher than post-combustion capture technology.

3. Plant cash flow, CO_2 emitted – avoided, CO_2 captured costs

After extracting the underlying capital and operating costs that reflect the performance characteristics of each technology, levelised costs of electricity (LCOE) is calculated. The cost of energy from the plant can be evaluated using a discounted cash flow methodology (for more details regarding this method see [14]).

The 25-year LCOE is shown for the evaluated cases in Figure 2.

As it can be seen from Figure 2, the LCOE is largely dominated by capital costs at least 50% of the total in all cases, followed by fuel costs and operating costs. The CO_2 transport and storage LCOE component comprises less than 3% of the total LCOE in both IGCC CO_2 capture cases. The best methods of assessing the profitability of all the investigated cases are based on projections of the cash flows during the plant life. Figure 3 shows the cash flow curves for these investigated processes.

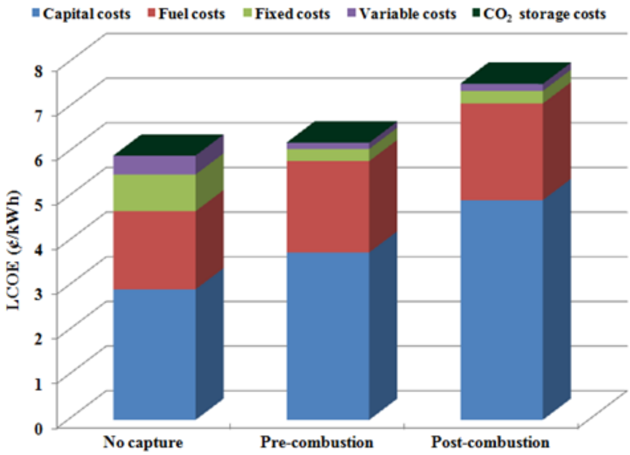

Figure 2. Levelised costs of electricity (LCOE) for investigated power plant cases

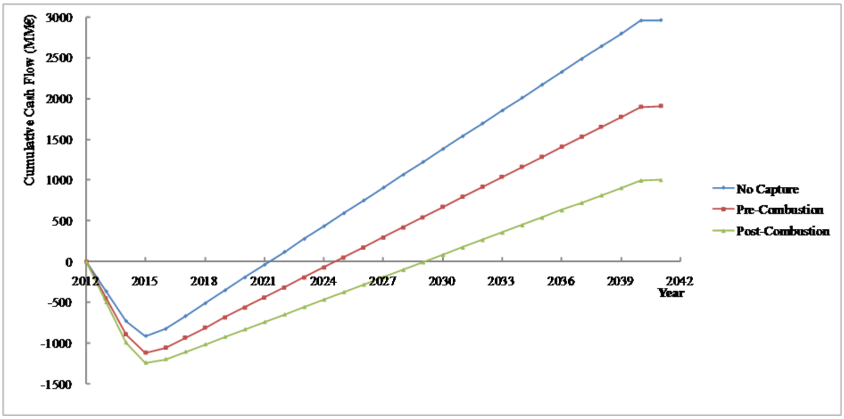

Figure 3. Cash flow curves for power plants without and with CO_2 capture (pre- and post-combustion capture)

The Figure 3 show the evolution of cumulative cash flow as a function of time in the case of the plant without CCS, the case of pre – combustion capture and the case of post – combustion capture. The payback period is extend over a number of years (7 years for the plant without CCS scenario, 10 years for the plant with pre-combustion capture technology scenario and 15 years for the plant with post-combustion capture technology scenario) leading to a significantly negative initial cash flow, and then as the plant comes online and starts to generate electricity, the cash flow rises according to the amount of power produced and the operational costs of the plant.

According to Intergovernmental Panel on Climate Change (IPCC) reports, additional to the levelised cost of electricity, there are other metrics used for comparing CCS technologies such as cost per ton of CO_2 avoided or emitted relative to the plant without CCS and cost of CO_2 captured [25]. As it was already discussed in previous paragraphs, the CO_2 capture and storage purpose is to reduce CO_2 emissions to the atmosphere. According to that view, it is not the amount of CO_2 captured per unit of production (per kWh electricity) that is important, but is the amount of CO_2 emission avoided [26-29]. So, the cost of CO_2 captured was calculated in two different ways, the cost of CO_2 removed and the cost of CO_2 avoided, as illustrated in equations 2 and 3:

$$CO_2\ \text{Removal Cost} = \frac{LCOE_{with\_CCS} - LCOE_{without\_CCS}}{CO_2\ \text{removed}} \left[\frac{Euro}{t_{CO_2}}\right] \quad (2)$$

$$CO_2\ \text{Avoided Cost} = \frac{LCOE_{with\_CCS} - LCOE_{without\_CCS}}{CO_2\,\text{emissions}_{without\_CCS} - CO_2\,\text{emissions}_{with\_CCS}} \left[\frac{Euro}{t_{CO_2}}\right] \quad (3)$$

Table 3 shows the electricity production costs, CO_2 avoided and captured costs, for all investigated IGCC cases without and with CO_2 capture.

Table 3. Cost of electricity, CO_2 avoided and removal costs

Description	Units	Case 1	Case 2	Case 3
Solvent	-	-	Selexol®	MEA
LCOE	¢/kWh	5.92	7.61	9.25
CO_2 avoided cost	€/t_{CO2}	-	21.40	46.11
CO_2 removal cost	€/t_{CO2}	-	19.58	37.24

As it can be noticed from Table 3, the electricity production cost for the IGCC scheme with pre-combustion process using Selexol® is about 28.54% higher than the electricity production cost for the plant without capture and for the IGCC scheme with post-combustion process using MEA is about 56.25% higher than the electricity production cost for the plant without capture. The results show the advantages of pre-combustion capture for IGCC plants.

Comparing the two main investigated cases for CO_2 capture process (pre – and post – combustion capture technology), the results show that the electricity production cost for post-combustion capture technology is about

21% higher than the electricity production cost for pre-combustion capture technology, CO_2 captured cost for post-combustion capture technology is about 90% higher than CO_2 captured cost pre-combustion capture technology and CO_2 avoided cost in the post – combustion capture technology case is increased by a factor of 2.15 than the CO_2 avoided cost in the pre-combustion capture technology case.

4. Sensitivity analysis

A sensitivity analysis was conducted to determine which model parameters most affect the electricity production cost, CO_2 avoided and removal costs for each CCS investigated option. This sensitivity analysis is of particular importance to give weight and predictability to any economic evaluation. Figure 4 and Figure 5 present the resulting change in electricity, CO_2 avoidance and removal costs when varying capital and O&M cost, fuel cost, discount rate and load factor for previous mentioned cases.

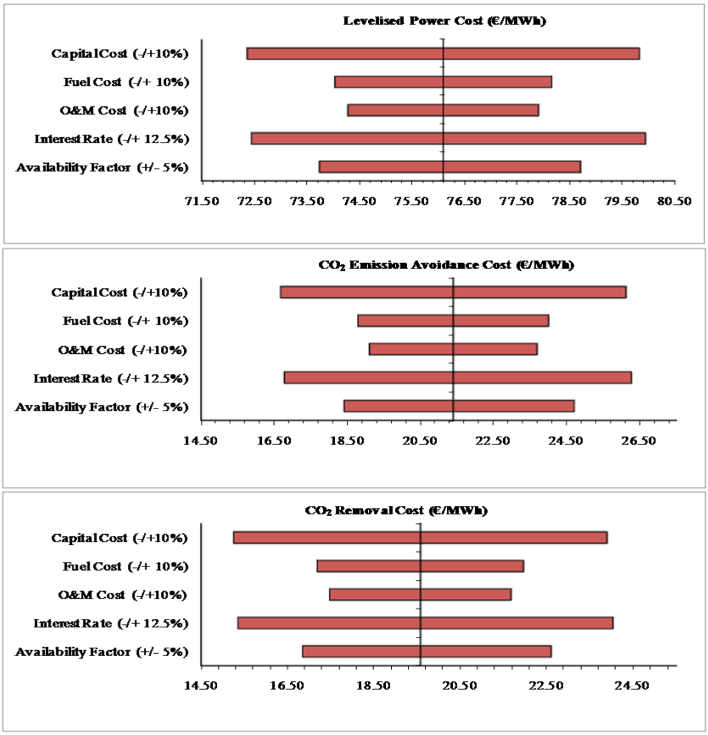

Figure 4. Change in the cost of electricity, CO_2 avoidance and CO_2 removal costs for pre – combustion capture

The vertical axis presents the levelised value of electricity cost, CO_2 avoidance and CO_2 removal costs, and the horizontal bars indicate the percentage modifications of these values caused by a variation in the assumptions for capital and O&M cost (A), fuel cost (B), discount rate (C) and load factor (D).

A) From the sensitivity analysis results illustrated in Figure 4 and Figure 5 it can be observed that the influence of capital cost on electricity production cost, CO_2 avoided and removal costs is more pronounced than the influence on O&M cost in both investigated CCS technologies. This can be easily explained by the significant share of the capital cost in the whole economic assessment.

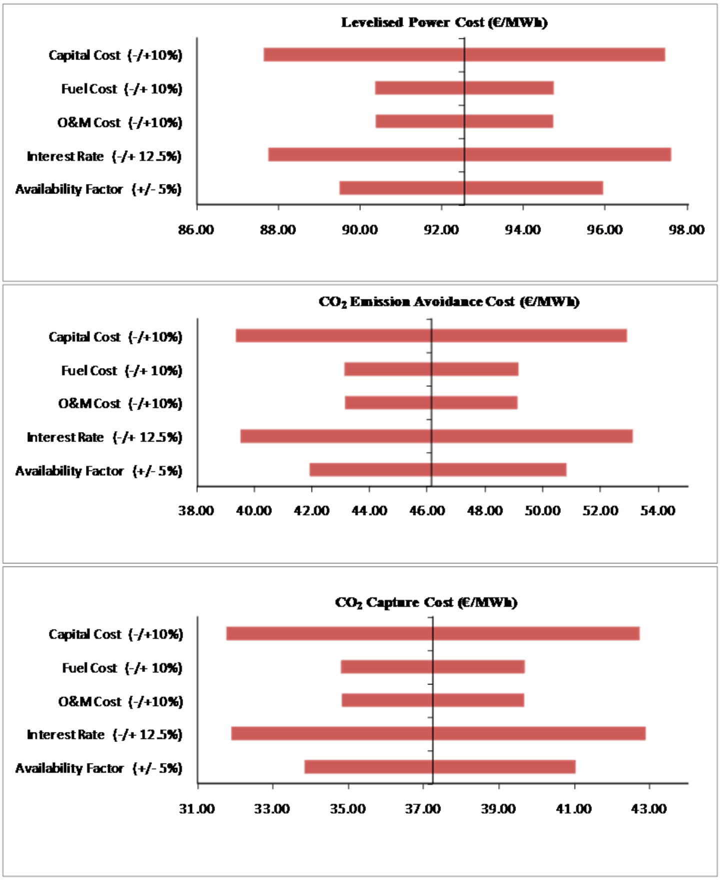

Figure 5. Change in the cost of electricity, CO_2 avoidance and CO_2 removal costs for post – combustion capture

B) Regarding the fuel price influence it can seen that for the 10% increase of the fuel price, the electricity cost, for Selexol® pre – combustion capture plant, increases with 0.21 ¢/kWh, the cost of CO_2 emission avoidance increases with 2.61 €/tCO_2 and the cost of CO_2 removed increases with 2.39 €/tCO_2 For the MEA post – combustion capture plant the electricity cost increases with 0.21 ¢/kWh, the cost of CO_2 emission avoidance increases with 3.01 €/tCO_2 and the cost of CO_2 removed increases with 2.43 €/tCO_2. For the 10% reduction in fuel price the costs decrease with the same factors: for pre-combustion capture case 0.21 ¢/kWh for electricity cost, 2.61 €/tCO_2 for CO_2 avoidance cost and 2.39 €/tCO_2 for CO_2 removal cost and for post-combustion capture case 0.21 ¢/kWh for electricity cost, 3.01€/tCO_2 for CO_2 avoidance cost and 2.43 €/tCO_2 for CO_2 removal cost.

C) A 8% discount rate, in constant money values was used for the base case. If the discount rate is reduced from 8% to 7%, the cost of electricity from the plant with Selexol® pre – combustion capture increases with 0.38 ¢/kWh, the cost of CO_2 emission avoidance increases with 4.88 €/tCO2 and the cost of CO_2 removed increases with 4.46 €/tCO_2. For the MEA post – combustion plant the costs increases with 0.53 ¢/kWh, the cost of CO_2 emission avoidance increases with 6.98 €/tCO_2 and the cost of CO_2 removed increases with 5.64 €/tCO_2.

D) To illustrate the effects of operation at lower and higher load factors, Figure 4 and Figure 5 show the costs for the plants at 89.25% and 80.75% load factors. As it can be noticed, operation at low load factors increases the costs of electricity, CO_2 avoidance and removal costs in both carbon capture cases. The increase is greater for post-combustion capture plant than for pre-combustion case. This is because the fixed costs of pre-combustion capture plant are lower than those of post-combustion. This aspect is important from operational point of view these power plants being suitable to be operated in base load scenario.

5. Variation of relevant boundary conditions

An overall techno – economical process evaluation reveals that under the base case boundary conditions of this work, Selexol® solvent (for pre-combustion capture) and MEA solvent (for post-combustion capture) are best suited for a retrofit integration in the considered IGCC power plant (see previous paragraphs). The present section reports an investigation of how does the plant performance parameters changes if the CO_2 capture performance changes (more specifically the variation of the carbon capture rate). The bellow cases were investigated and compared (using ChemCAD simulations):

- Case A: IGCC with no carbon capture (this case is identical with Case 1 presented in previous sections);
- Case B: IGCC with 70% CO_2 pre-combustion capture using Selexol®;
- Case C: IGCC with 80% CO_2 pre-combustion capture using Selexol®;
- Case D: IGCC with 90% CO_2 pre-combustion capture using Selexol®;
- Case E: IGCC with 70% CO_2 post-combustion capture using MEA;
- Case F: IGCC with 80% CO_2 post-combustion capture using MEA;
- Case G: IGCC with 90% CO_2 post-combustion capture using MEA.

Table 5. Overall gasification power plants performance indicators

Main Plant Data	Units	B	C	D	E	F	G
Gross power	MW_e	529.91	529.85	529.79	472.29	462.82	460.35
Net power	MW_e	425.56	425.27	424.97	378.84	365.94	359.24
Gross efficiency	%	45.00	44.99	44.98	44.85	43.96	43.72
Net efficiency	%	36.13	36.11	36.08	35.97	34.75	34.11
CO_2 capture rate	%	71.25	80.37	91.43	69.5	79.42	90.88
CO_2 emissions	kg/MWh	240.31	164.08	79.63	181.01	139.20	95.44

Comparing these three post-combustion IGCC capture cases (Case E, Case F and Case G) with the pre-combustion IGCC capture cases (Case B, Case C and Case D) can be concluded that net electrical efficiencies are lower in the case of using post-combustion capture technique (with 0.16% lower for 70% capture, with 1.36% lower for 80% capture and with 1.97% lower for 90% capture). Table 6 presents the capital costs estimations as well as specific investment costs (per kW gross and net) for the evaluated cases.

Table 6. Overall gasification power plants capital cost estimation

Main Plant Data	Units	B	C	D	E	F	G
Total installed cost	MM €	909.85	920.21	932.72	984.27	1006.5	1036.0
Total investment cost	MM €	1091.8	1104.2	1119.2	1181.1	1207.8	1243.3
Specific investment cost	€/$kW_{e\ gross}$	2060.3	2084.0	2112.6	2500.8	2609.7	2700.7
Specific investment cost	€/$kW_{e\ net}$	2565.6	2596.5	2633.7	3117.7	3300.6	3460.9

As it can be noticed from the Table 6, comparing gasification power plant without carbon capture (Case A, see [10-11]) with the same energy conversion technology but with post-combustion capture (Cases E, F and G), the total investment cost per net kWe for the CCS cases are about 51.81% (Case E), 60.72% (Case F) and 68.53% (case G) higher than the total investment cost for the case without capture (Case A).

Comparing the post-combustion capture cases (Cases E, F and G) to the pre-combustion capture cases (Cases B, C and D) it can be observed that capital investment costs are much higher in the case of using post-combustion capture technique (with 21.51% higher for 70% capture, with 27.11% higher for 80% capture and with 31.40% higher for 90% capture). The reason for this fact is related with the fact that a much more gas flow has to be treated in case of post-combustion capture than in case of pre-combustion and the capture unit is bigger. The incremental cost due to CO_2 capture for the CCS IGCC investigated cases can be observed as well in Figure 6.

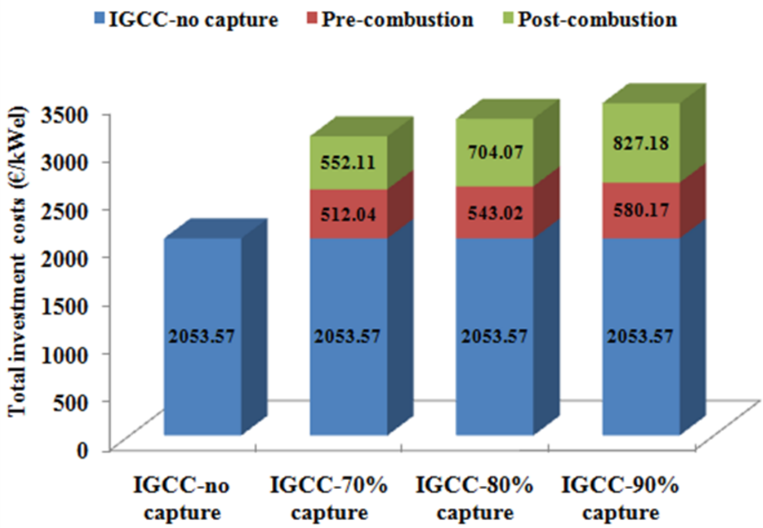

Figure 6. The incremental cost due to pre- and post-combustion CO_2 capture

For the electricity cost evaluation, as in the previously mentioned cases (Cases B C and D), a plant lifetime of 25 years, a load factor of 85%, the coal price of 2.2 €/GJ and sawdust price of 1.12 €/GJ has been assumed.

Table 7. Cost of electricity, CO_2 avoided and removal costs

Description	Units	B	C	D	E	F	G
LCOE	¢/kWh	7.41	7.51	7.61	8.44	8.89	9.25
CO_2 avoided cost	€/t_{CO2}	20.91	20.99	21.40	39.25	43.39	46.11
CO_2 removal cost	€/t_{CO2}	22.31	20.93	19.58	37.55	37.37	37.24

As it can be seen from Table 7 cost of electricity for the IGCC with CCS implemented rises with about 42.56% for Case E, 50.16% for Case F and 56.25% for Case G compared to the Case A. Comparing these three post-combustion capture cases (Cases E, F and G) with the pre – combustion capture cases (Cases B, C and D) it can be observed that the cost of electricity is much higher in the case of using post-combustion capture technique (with 13.90% higher for 70% capture, with 18.37% higher for 80% capture and with 21.55% higher for 90% capture).

CO_2 avoided and removal costs are important and useful metrics for comparing economics of a specific CO_2 capture process against alternative capture technologies. Comparing investigated technologies: post-combustion IGCC capture cases (Cases E, F and G) with the pre-combustion IGCC capture cases (Cases B, C and D) can be observed that both CO_2 captured and CO_2 avoided costs are much higher in the case of using post – combustion capture technique (by a factor of 1.87 higher for 70% capture, by a factor of 2.06 higher for 80% capture and by a factor of 2.15 higher for 90% capture for avoided costs and by a factor of 1.68 higher for 70% capture, by a factor of 1.83 for 80% capture and by a factor of 1.90 for 90% capture for captured costs).

The reported results in this paper could be of significant importance for the case that a demo project on carbon capture and storage technology will be implemented in Romania [30].

CONCLUSIONS

CCS technologies are aiming to mitigate the CO_2 emissions from power generation as well as from other energy-intensive industrial sectors (e.g. oil refineries, chemicals, metallurgy, construction materials etc.). This paper is evaluating from economic side two carbon capture technologies suitable for IGCC power plants. The assessment targeted pre-combustion and post-combustion CO_2 capture technologies because these two are the most common and commercially mature technologies today.

Concerning the total investment cost, the calculation results show that the total investment cost for the gasification power plants with CO_2 capture process is higher (pre-combustion process using Selexol® about 22% higher and post-combustion process using MEA about 36% higher) than the total investment cost for the plant without capture. Also, comparing the two main investigated cases for CO_2 capture process, the results show that the electricity production cost for post-combustion capture technology is about 21% higher than the electricity production cost for pre-combustion capture technology, CO_2 captured cost for post-combustion capture technology is about 90% higher than CO_2 captured cost pre-combustion capture technology and CO_2 avoided cost in the post-combustion capture technology case is increased by a factor of 2.15 than the CO_2 avoided cost in the pre-combustion capture technology case. As an overall conclusion of the present economic evaluation is that the pre-combustion capture using physical solvents is more suitable for capturing CO_2 from the gasification-based power plants than the post-combustion capture using chemical solvents.

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