STUDIA UBB CHEMIA, LIX, 4, 2014 (p. 205-215)
(RECOMMENDED CITATION)

TECHNO-ECONOMIC EVALUATION OF CALCIUM LOOPING CYCLE FOR CO_2 CAPTURE FROM SUPER-CRITICAL POWER PLANTS

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ABSTRACT. Calcium looping is an innovative CO_2 capture process using solid CaO as sorbent to remove CO_2 from flue gases. In the work presented in this paper, the calcium looping cycle was applied to a super-critical power plant to capture CO_2 (purity >95%). This capture technology is based on calcium looping process which uses CaO for CO_2 capture. Calcium looping process has very good techno-economic results compared to other CO_2 capture options (e.g. gas-liquid absorption) and has many advantages, one of those being: the raw material used for CO_2 capture (limestone) is abundant and cheap, the high carbon capture rate (>90%) and the relatively small efficiency penalty that it imposes on the power/ industrial process. The energy penalty for carbon capture is about 9 net electricity percentage points. Compared to the design without carbon capture, the specific capital investment is increasing with about 48%, the operational & maintenance (O&M) costs are increasing with 60% and the levelised cost of electricity is increasing with 54%.

Keywords: *Carbon Capture and Storage (CCS), Calcium looping process, Super-critical power plant, Techno-economic assessments.*

INTRODUCTION

In the last years, scientific studies on climate change have progressed considerably offering a new vision over the current problem of warming of the Earth. According to basic physics of heat trapping gases, exponential rise in population and energy consumption, humans have become, trough all the industries developed, the main problem leading to Earth's degradation [1]. Clearly, this is a complex topic with enormous political, socio-economic and emotional dimensions, but the scientific results show quite clear that human activities [2], in particular the wide usage of fossil fuels – e.g. coal is the

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most abundant fossil fuel used for the electric power generation as well as the largest world-wide source of CO_2 emissions [3], then human - driven changes in land use and land cover such as deforestation, urbanization and shifts in vegetation patterns [4], bring serious damages to the climate [5].

Because the primary cause of global climate change is human, the solutions are also within the human domain [6]; the scientists tried in the last years to find the best solution for reducing CO_2 emissions (e.g. improving energy efficiency), but also by developing and deployment of CO_2 capture and storage technologies [7]. One of the solutions found is the Calcium looping, (CaL), process which stands for absorption of CO_2 by means of CaO; in this case the objective is to obtain a pure stream of CO_2 suitable for storage. In this process the solids circulate between two interconnected fluidized bed reactors, the carbonator and the calciner, as shown in Figure 1. Flue gas coming from an existing power plant enters into a carbonator working at 600-650ºC and atmospheric pressure where CO_2 reacts with CaO and converts into $CaCO_3$ [8]. Solids from carbonator are composed mainly of CaO and $CaCO_3$ and are separated at the end of the reaction from the clean flue gas which is released to the atmosphere. The solids are sent to the second reactor (calciner in Fig. 1) where the temperature is kept at around 900°C so that CO_2 is released from $CaCO_3$ and the CaO is recirculated into the carbonator.

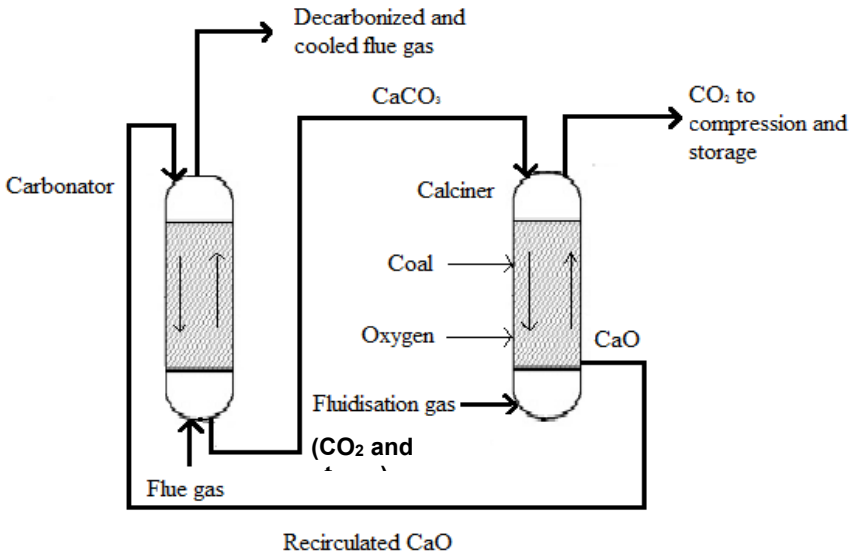

Fig. 1. Calcium looping (CaL) process

Calcium looping process has many advantages, one of those being the fact that CO_2 sorption and sorbent regeneration are carried out at high temperatures, (600 – 650°C and 900 – 1000°C for carbonation and calcination, respectively) therefore, the heat from reactions can be recovered very easily by steam generation. Among other advantages it can be said that with this process it can be obtained a concentrated steam of CO_2, more than 90%, suitable for storage and the materials used are widely available and cheap, (derived mostly from limestone).

Process reactions:

$$CaO + CO_2 \longrightarrow CaCO_3 \quad \text{- carbonator reaction} \quad (1)$$

$$CaCO_3 \longrightarrow CaO + CO_2 \quad \text{- calciner reaction} \quad (2)$$

RESULTS AND DISCUSSION

Process Model

Calcium looping model has been developed using commercial process flow modeling software, CHEMCAD 6.1.3. The process diagram of super-critical power plant with CaL unit including all the important components is shown in Fig. 2.

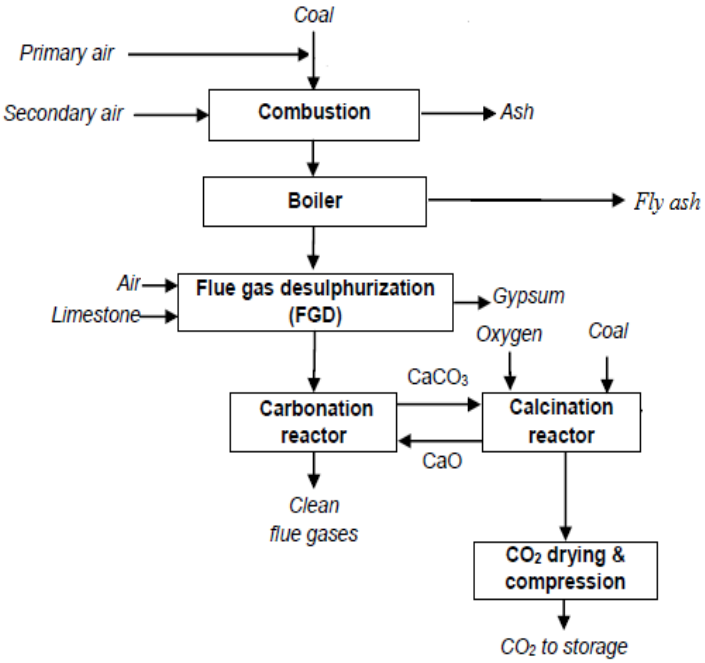

Fig. 2. Process diagram of power plant with CaL

The whole plant is structured in two important parts – the first part of the installation it is represented by coal-based combustion power plant with super-critical steam conditions, and the second part, the calcium looping process, where CO_2 is captured from the flue gases [9]. The main interest of the article is concentrated on the second part of the process – calcium looping unit but also on the techno-economic evaluation of the whole plant. Common aspects such as CO_2 capture rate, energy efficiency, economic aspects were observed in order to establish which is the most convenient approach to have a profitable process [10].

In the first part of the installation, the coal is burned with combustion air in boiler, (modeled as a Gibbs reactor), at atmospheric pressure, then the flue gases are desulphurised by reacting with limestone slurry and oxidation air resulting flue gases and gypsum. The desulphurised flue gas is used in the second part of the process, meaning the capture of CO_2 - the flue gas, (composition from Table 1), and CaO enters into the carbonator where a temperature of 620°C favors the formation of $CaCO_3$.

Table 1. Composition of the desulphurised flue gas from the power plant

Component	Composition (% vol.)
Carbon dioxide	18.12
Carbon monoxide	0.10
Water	4.37
Nitrogen	69.85
Oxygen	6.55
Argon	1.01
Total	100.00

After heat recovery units, who generate steam from available hot streams, the super-critical steam is then expanded in a steam turbine to produce energy. Decarbonized and cooled flue gas is released into the atmosphere, while formed calcium carbonate is converted back into CaO and gaseous CO_2 in a calciner, at 950°C, where thermal power for the endothermic reverse reaction, (calcination), is given by oxy-combustion of coal, oxy-combustion is necessary in order to maintain a high concentration of CO_2 [11]. The regenerated sorbent produced in the calciner is then sent to the carbonator for a new sorption cycle, while the CO_2 is cooled and compressed for permanent storage after final purification [12].

The majority of the heat used to regenerate the CaO-based adsorbent from $CaCO_3$ and the heat from carbonation reaction is used to generate super-critical steam, which provides additional energy and contribute to the overall energy efficiency of the plant.

The main equipment used for the simulation of Ca – looping process and the main equipment used by super-critical power plant without CO_2 capture is described in Table 2. The calcium looping cycle was designed to have a CO_2 capture rate of at least 90%.

Table 2. Design characteristics for the main plant units

Plant units	Design characteristics
Boiler	Temperature: 1200 – 1400°C Super-critical steam conditions
Steam (Rankine) cycle	290 bar/582^{o}C with two steam reheats at 75 bar/580^{o}C and 20 bar/580^{o}C
Carbon capture (calcium looping) unit	Carbonation reactor: 550 – 650°C Calcination reactor: 850 – 950°C Gibbs free energy model for both reactors Pressure drop: 0.1 bar
Air Separation Unit (ASU)	Power consumption: 225 kWh/t O_2
CO_2 conditioning unit - for compression and drying	CO_2 final pressure: 120 bar CO_2 final temperature: 50°C 4 compression stages
Steam expander	Final expansion pressure: 46 mbar Compressor efficiency: 85%
Heat recovery unit	Minimum temperature difference: 10^{o}C Pressure drop: 2 - 4% of inlet pressure

Economic Evaluation

The simulation performed in ChemCAD offered the necessary data, (mass and energy balances), to assess the overall techno-economic plant performance indicators. The simulation results were used to assess the key techno-economic and environmental plant. The study included capital cost estimations, specific investment costs per kW generated power, operation and maintenance costs, CO_2 capture costs, cumulative cash flow etc.

The cases evaluated in this paper:

Case 1 - Super-critical power plant without carbon capture;

Case 2 - Super-critical power plant with post- combustion CO_2 capture based on calcium looping cycle [13].

Table 3 presents the main technical and environmental indicators for Case 1 and 2.

Table 3. Plant technical and environmental performances

Main plant data	Units	Case 1	Case 2
Coal flowrate	t/h	156.74	241.74
Coal LHV	MJ/kg	25.17	
Thermal energy of the feedstock - LHV	MWh	1095.87	1690.16
Steam turbine output	MW_e	502.32	686.14
Gross electric power output	MW_e	502.32	686.14
Coal processing power consumption	MW_e	5.47	8.45
Power island power consumption	MW_e	21.98	24.24
CO_2 compressor power consumption	MW_e	0.00	71.81
Total ancillary power consumption	MW_e	27.55	104.51
Net electric power output	MW_e	474.87	581.62
Gross electriclal efficiency	%	45.83	40.59
Net electrical efficiency	%	43.33	34.41
Carbon capture rate	%	0.00	90.00
Specific CO_2 emissions	kg/MWh	800.58	65.27

As it can be seen from Table 3, the power plant with calcium looping generates a net electric power output of nearly 600 MW_e and a carbon capture rate of 90% in the conditions of a process which requires a significant heat duty. The high running temperature of the whole cycle makes possible heat recovery in form of generated steam.

The next step is to make an estimation of the capital costs. The methods used for estimation of the cost of the equipment are quotations from dealers, (used in the final version of the project) and correlations of cost, (used for the analysis of different technological variants of the process). In this case the equations were obtained using cost relations based on the relationship between cost of equipment and the main geometrical characteristics: volume, area, mass or technological: area, flow, etc. [14].The cost of the equipment was estimated using Equation 3.

$$C_E = C_B * (Q/ Q_B)^M \quad (3)$$

Where:

C_E – equipment cost with capacity Q;

C_B – known base cost for equipment with capacity Q_B;

M – constant depending on equipment type.

Table 4. Capital cost and specific investment cost estimations

Units	Scaling Basis	Case 1	Case 2
Solids handling facilities	tonnes of coal/h	41.47	56.16
PF coal boiler	MW_{th} fuel feed	159.65	175.62
Calcium looping unit	MW_{th} calciner	0.00	104.13
CO_2 conditioning	tonnes of CO_2/h	0.00	31.75
Desulphurisation unit (FGD)	kmole/s feed	69.13	84.65
Air separation unit	tonnes of O_2/h	0	124.26
Steam turbine	MW_e gross	146.66	185.3
Utilities and offsite units	25%	104.23	190.46
Total installed cost	**MM Euro**	**521.14**	**952.32**
Owner's cost and contingency	15%	78.17	142.85
Land purchase, permitting etc.	5%	26.06	47.62
Total investment cost	**MM Euro**	**625.37**	**1142.79**
Gross power production	MW_e	502.32	686.14
Net power production	MW_e	474.87	581.62
Investment cost / kW_e (gross)	Euro / kW_e	1244.96	1665.53
Investment cost / kW_e (net)	Euro / kW_e	1316.92	1960.99

Comparing the two evaluated super-critical power plant cases, it can be seen that CO_2 capture by calcium looping cycle implies a significant increase of investment cost, in the range of about 82% increase. All the units have higher capital costs in the second case compared to the case without carbon capture, (due to larger mass and energy flows), in addition there are some new units, e.g. post-combustion CO_2 capture unit by calcium looping, CO_2 processing and drying – which infuence the total investment cost. In the case of CO_2 capture it can be observed an increased value of gross power production, the increase is about 36% comparing with the case without capture. The specific capital investment is increasing with 48% compared to the case without carbon capture.

The next step is the estimation of operation and maintenance (O&M) costs. O&M costs are generally structured in variable and fixed costs relating to their proportionality to the generated power. Variable operating costs are directly proportional to amount of generated power, (e.g. fuel, chemicals, process and boiler feed water, raw materials, calcium sorbent consumed in the process etc.) [15]. Fixed operating costs are mostly independent of the amount of generated power, (e.g. maintenance, direct labor cost, support and overhead cost etc.). Table 5 presents the distributed O&M costs for Cases 1 and 2.

Table 5. Operating and maintenance cost estimations

Fixed O&M Cost	**Case 1**	**Case 2**
Annual maintenance cost	18.05	31.77
Direct labor cost	5.6	5.6
Administrative, support & overhead cost	1.68	1.68
Total (MM Euros / yr)	**25.33**	**39.05**
Variable O&M Cost	**Case 1**	**Case 2**
Fuel	65.11	100.41
Auxilliary feedstock	0.00	0.00
Make-up water	0.04	0.05
Catalysts	0.50	0.50
Solvents	0.38	7.50
Chemicals	1.37	1.48
Total (MM Euros / yr)	**67.40**	**109.94**

Conclusion that can be drawn from Table 5 is that the power plant with CO_2 capture is more expensive in terms of O&M costs. Fixed and variable costs have increased values than in the case of the power plant without CO_2 capture and the major differences come from the fuel and annual maintenance costs. The additional fuel consumption comes from lower energy efficiency and the fuel required for the calciner. Superior annual maintenance cost for the power plant with carbon capture comes from the need to repair a more complex design with additional units, (e.g. calcium looping unit, CO_2 conditioning etc.).

Comparing those two evaluated power plant cases, a significant importance must be given to two parameters that can influence the option of choosing one process over the other, meaning the cost of electricity and the costs of CO_2 capture. The net present value, (NPV), method was used to calculate the levelised cost of electricity, (LCOE) and to compare cash inflows with the cash outflows of the processes with or without CO_2 capture. This net present value determines whether or not the process is an acceptable investment.

The CO_2 capture costs – CO_2 removal and avoidance costs – are important to establish if the carbon capture technology used is more profitable than other. CO_2 capture costs are calculated using the levelised cost of electricity, (LCOE) [16], in the case of the plant with CO_2 capture compared with the cost of electricity without CO_2 capture and the specific CO_2 emissions in both cases. The values were obtained with the Equations (4, 5) and the results are summarized in Table 6.

$$CO_2 \text{ removal cost} = \frac{LCOE_{\text{with CO2 capture}} - LCOE_{\text{without CO2 capture}}}{CO_2 \text{ removed}} \quad (4)$$

$$CO_2 \text{ avoided cost} = \frac{LCOE_{\text{with CO2 capture}} - LCOE_{\text{without CO2 capture}}}{CO_2 \text{ emissions}_{\text{without CO2 capture}} - CO_2 \text{ emissions}_{\text{with CO2 capture}}} \quad (5)$$

Table 6. Cost of electricity and CO_2 capture costs

LCOE with CO_2 capture	**LCOE without CO_2 capture**
7.02 ¢ /kWh	4.55 ¢/kWh
CO_2 emissions with CO_2 capture	**CO_2 emissions without CO_2 capture**
65.27 kg/MWh	800.58 kg/MWh
CO_2 removal cost	**CO_2 avoided cost**
27.81 Euro/t	33.89 Euro/t

It can be observed from the results that the difference between specific CO_2 emissions is very large in advantage being the case with CO_2 capture. The differences between the costs of energy advantages the case without CO_2 capture, the difference being about 35%. This is the economic penalty of the carbon capture design. It must be realized from the above economic evaluations that there are significant capital and operational cost penalties for the carbon capture case, (in addition to the energy penalty as presented in Table 3).

Other important economic aspect of the process is the profitability of the plant and the period of time that will be necessary to payback the made capital investment [17-18]. To evaluate this matter, cumulative cash flow is used. Cumulative cash flow represents a financial statement that reflects the inflow of revenue vs. the outflow of expenses resulting from operating, investing and financing activities during a specific time period [19-21].

In our power plant cases with and without carbon capture, the life time of the power plant was 28 years, (3 years for construction and 25 years for operation). Results of the cumulative cash flow analysis are displayed in Figure 3 and state the fact that the payback period is about 11 years. At the end of the plant life, the power plant with CO_2 capture is more productive in terms of cash flow, knowing a rapid growth and a significant difference towards the case without CO_2 capture [22].

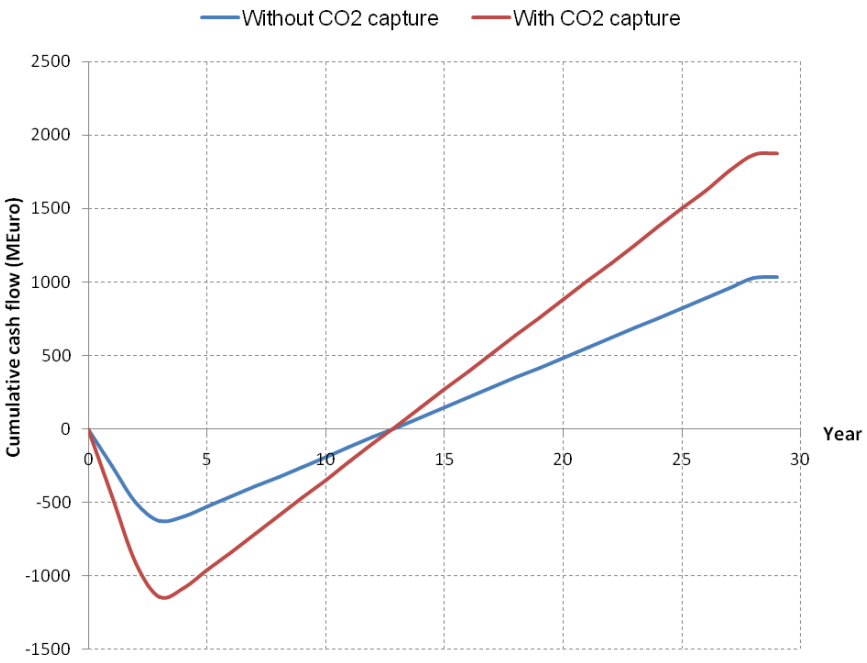

Fig. 3. Cumulative cash flow analysis

CONCLUSIONS

This paper analyzes the techno-economic performances of two power plants in two situations: with and without CO_2 capture. The performance of the CO_2 capture process mainly depends on the flow of CaO coming from the calciner, the make-up flow, and the solid inventory. Carbonate looping process implies an extra capital investment, maintenance costs, and energy penalties comparing with the plant without CO_2 capture. These extra costs mean an increase of 82% of total investment cost, 10% of fixed operating costs (e.g. direct labour), 63% of variable costs (e.g. fuel, chemicals), but bring also a higher profitability after the payback period of the investment and a capture rate of 90%. Those are very promising results which highlights the potential of calcium looping process to significantly reduce CO_2 emissions from atmosphere.

It is certain that carbonate looping process is a new promising carbon capture technology for future power plants over the world, but also, it is certain that are aspects than can be improved and studied.

ACKNOWLEDGEMENTS

This work was supported by a grant of Romanian National Authority for Scientific Research, CNCS – UEFISCDI: project ID PN-II-ID-PCE-2011-3-0028: "*Innovative methods for chemical looping carbon dioxide capture applied to* energy conversion processes for decarbonised energy vectors poly-generation".

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