

Assessment of Carbon Capture Options for Super-Critical Coal-based Power Plants

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Power generation is one of the industrial sectors with major contribution to greenhouse gas emissions. For climate change mitigation, a special attention is given to the reduction of CO₂ emissions by applying capture and storage techniques in which CO₂ is captured and then stored in suitable safe geologic locations. Carbon capture and storage (CCS) technologies are expected to play a significant role in the coming decades for curbing greenhouse gas emissions and to ensure a sustainable development of power generation and other energy-intensive industrial sectors (e.g. cement, metallurgy, petro-chemical etc.).

This paper evaluates super-critical coal-based power plants with and without carbon capture. The analysis is geared toward quantification of main plant performance indicators such as: fuel consumption, gross and net energy efficiency, ancillary energy consumption, carbon capture rate, specific CO₂ emissions, capital costs, specific capital investments and operational costs etc. For CCS configurations, two post-combustion CO₂ capture options were considered. The first option is based gas-liquid absorption using a chemical solvent (methyl-diethanol-amine – MDEA etc.). The second option is based on calcium looping cycle, in which the carbonation/calcination sequence of CaO/CaCO₃ system is used for carbon capture.

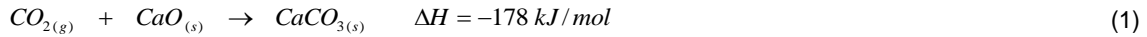
The power plant case studies investigated in the paper produces around 950 – 1,100 MW net power with at least 90 % carbon capture rate. The mathematical modelling and simulation of the whole power generation schemes will produce the input data for quantitative techno-economic and environmental evaluations of power plants with carbon capture (similar power plant concept without CCS was used as reference for comparison). Mass and energy integration tools were used to assess the integration aspects of evaluated carbon capture options in the whole power plant design, to optimise the overall energy efficiency and to evaluate the main sources of energy penalty for CCS designs.

1. Introduction

Energy supply at competitive and affordable prices, environmental protection and climate change prevention by reducing greenhouse gas emissions are one of the main issues that modern society is facing. It is known that fossil fuels used in power generation and other energy-intensive sectors are one of the main responsible for greenhouse gas emissions and this situation is predicted to continue for the years to come. If no action is taken to significantly reduce the greenhouse gas emissions (mainly CO₂), severe climatic consequences are predicted. The key to preventing all these issues is to reduce anthropogenic greenhouse gas emissions. Reducing CO₂ emissions can be done in a variety of methods as presented by International Energy Agency (2012), e.g. large scale applications of CCS technologies (Metz et al., 2005), increasing the renewable energy share in the energy mix, increasing energy efficiency (both in term of energy conversion and utilization processes), fuel switching etc.

This paper evaluates two post-combustion carbon capture options for super-critical power plants. Among various carbon capture options, one mature technology based on gas - liquid absorption using chemical solvent (activated MDEA) and one promising but yet in the development stage based on calcium looping cycle were evaluated. The first carbon capture option based on chemical gas - liquid absorption is a proven technology in chemical industry (Kohl and Nielsen, 1997) but its integration in power plants is still in the pilot stage (scale in the range of 20 - 50 MW). One of the main issue here is the reducing the energy

penalty imposed by solvent thermal regeneration. As shown by an IEA-GHG study (2004), the energy penalty for absorption-based post-combustion capture is in the range of 10 net electricity percentage points. Capital and operational & maintenance (O&M) costs are also a matter of concern for CCS systems. Calcium looping process is a very promising technological option for intrinsically capture CO₂ with lower cost and energy penalties (Fan, 2010). At the moment, the technology is proven at scale lower than 1 MW. Calcium looping process implies the reaction of CO₂ from flue gases with calcium oxide according to the following exothermic reaction:



The carbonation reactor is operated at about 500 – 650 °C in fluidized conditions. The hot gases resulted from the reactor are used for steam generation and the solid phase (calcium carbonate) is recycled continuously to a calcination reactor (operated at about 900 °C also in fluidized conditions) where it is decomposed back to calcium oxide according to reaction:



The calcination process is highly endothermic, accordingly an extra fuel has to be combusted with oxygen (to avoid nitrogen contamination in case of using air) to cover the reactor heat duty. The gas streams of both reactors are cooled down the available heat being used for steam generation.

The paper assesses techno-economic and environmental aspects of coal-based super-critical power plants which generate 900 - 1,100 MW net power with CCS. As benchmark option, the same power plant without CCS was evaluated. The carbon capture rate was higher than 90 %, the captured CO₂ stream is compressed to 120 bar and has to comply with designed quality specification (>95 % vol. CO₂ purity).

2. Power plant configurations

Super-critical power plants are state-of-the-art in combustion-based power generation, most of newly built power plants being of this type (IEA, 2012). The super-critical power plant concept evaluated in this paper has the steam cycle parameters 290 bar / 582 °C with two reheats at 75 bar / 580 °C and 20 bar / 580 °C. In combustion-based power plants with post-combustion capture, the flue gases are used for steam generation and after desulphurisation they are treated for carbon capture (Gaspar and Cormos, 2012). Two options were assessed, one based on chemical gas - liquid absorption and one based on chemical gas - solid adsorption. Figures 1 and 2 present the conceptual designs of super-critical power plant with post-combustion capture based on gas - liquid absorption (Figure 1) and calcium looping cycle (Figure 2).

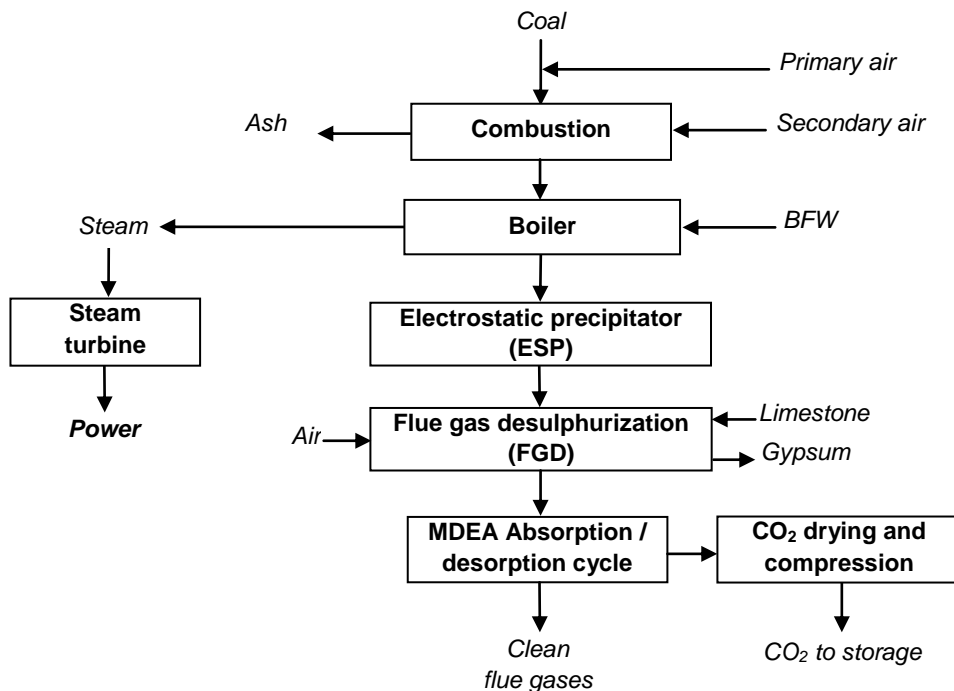


Figure 1: Super-critical power plant with post-combustion capture based on gas - liquid absorption

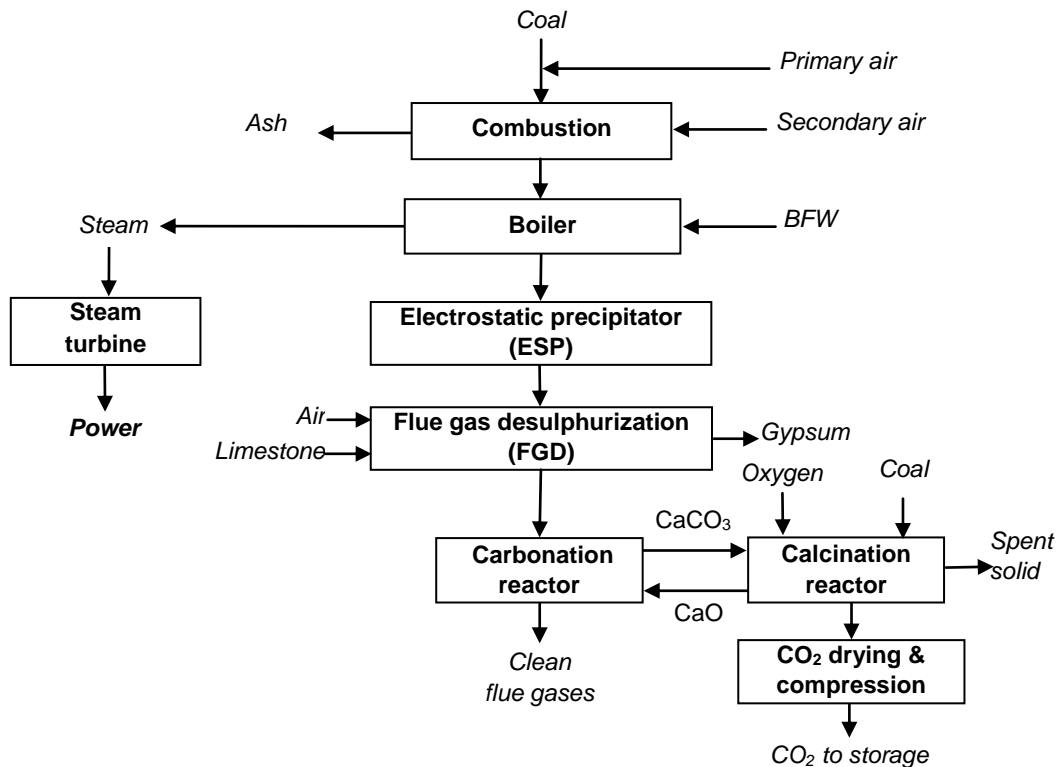


Figure 2: Super-critical power plant with post-combustion capture based on calcium looping cycle

3. Main design assumptions, modelling, simulation and thermal integration analysis

The following cases were evaluated in this paper:

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

Case 2 – Super-critical power plant with post-combustion CO₂ capture based on gas-liquid absorption;

Case 3 – Super-critical power plant with post-combustion CO₂ capture based on calcium looping cycle.

The cases have the same power block configuration, the differences being in the flue gas treatment for carbon capture. The main design assumption of all evaluated plant concepts are presented in Table 1.

Table 1: Main design assumptions

Parameter	Case 1	Case 2	Case 3
Coal characteristics	Analysis: 66.52 % C, 3.78 % H, 1.56 % N, 5.46 % O, 0.52 % S, 14.15 % ash, 8 % moisture; calorific value: 25.17 MJ/kg (a.r.)		
Boiler	Super-critical conditions		
Air separation unit (ASU) purity and power consumption	-	-	95 % O ₂ 225 kWh/t O ₂
Flue gas treatment	Limestone FGD, 98-99 % efficiency		
Carbon capture unit	-	MDEA-based absorption-desorption cycle	Calcium looping cycle
CO ₂ drying and compression	-	120 bar, TEG dehydration	
Captured CO ₂ quality specification- (vol.)	-	>95 % CO ₂ , <250 ppm water, <100 ppm sulphur, <100 ppm oxygen, <4 % other gases	
Steam cycle	Steam parameters: 290 bar / 582 °C Two reheats: 75 bar / 580 °C & 20 bar / 580 °C		
Condenser pressure	46 mbar		
Cooling water temperature	15 °C		
Heat exchanger ΔT _{min} .	10 °C		
Heat exchanger pressure drop (ΔP)	1 %		

Power plant concepts with and without CCS were modelled and simulated using ChemCAD (for combustion and flue gas treatment aspects) and Thermoflex (for power block unit). Developed mathematical models were validated against available industrial and experimental data (IEA-GHG, 2004; Kohl and Nielsen, 1997). No significant differences were reported. After simulation, the energy balances were subject of process integration analysis using pinch technique for quantification of energy efficiency as presented by Anantharaman and Berstad (2012). As illustrative example, Figure 3 presents hot and cold composite curves for calcium looping cycle (the available heat in carbonation and calcination reactors was used for steam generation which was then integrated in the power block).

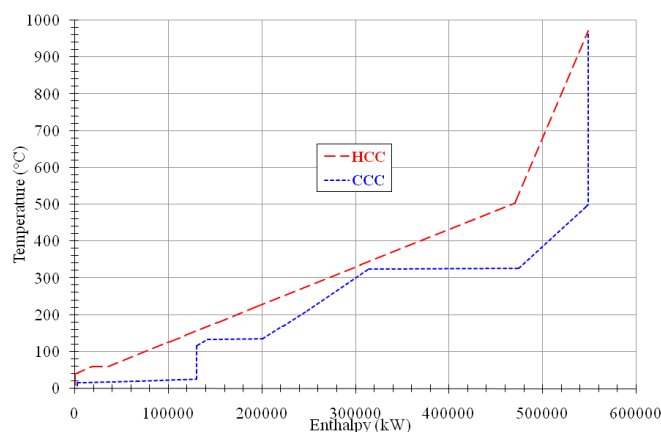


Figure 3: Composite Curves for calcium looping cycle (Case 3)

4. Results and discussions

The next step after mathematical modelling, simulation and thermal integration analysis of evaluated concepts was to use the results to assess the key techno-economic and environmental plant performances. Table 2 presents the main technical and environmental indicators for evaluated cases.

Table 2: Key plant performance indicators

Main plant parameter	Units	Case 1	Case 2	Case 3
Coal flowrate (as received)	t/h	313.48	396.70	433.48
Coal LHV (as received)	MJ/kg		25.17	
Coal thermal energy (A)	MW _{th}	2,191.74	2,773.60	3,030.74
Steam turbine output	MW _e	1,004.64	1,082.66	1,299.20
Gross power output (B)	MW _e	1,004.64	1,082.66	1,299.20
ASU power consumption	MW _e	-	-	48.40
Boiler power consumption	MW _e	10.94	13.82	15.14
Carbon capture unit power consumption	MW _e	-	57.40	102.42
Power island power consumption	MW _e	43.96	60.02	44.80
Total ancillary power consumption (C)	MW _e	54.90	131.44	210.76
Net power output (D = B - C)	MW _e	949.74	951.22	1,088.44
Gross power efficiency (B/A * 100)	%	45.83	39.03	42.86
Net power efficiency (D/A * 100)	%	43.33	34.30	35.91
Carbon capture rate	%	0.00	90.51	92.66
CO ₂ specific emissions	Kg/MWh	800.58	86.82	69.94

As can be noticed from Table 2, the CCS cases generate 950 - 1,100 MW net power with net electrical efficiencies in the range of 34.4 - 35.9 %. The carbon capture rate was in the range of 90 - 93 % with specific CO₂ emissions significantly reduced to 70 - 86 kg/MWh compared with 800 kg/MWh for the case without CCS. Carbon capture energy penalty varies from 7.4 % for Case 3 (calcium looping cycle) to 9 %

for Case 2 (MDEA gas-liquid absorption). The main source of energy penalty for gas-liquid absorption is solvent regeneration step which requires a heat duty of about 3.2 MJ/kg CO₂. This results is in line with literature sources (Davison, 2007). For calcium looping cycle, the calcination step (reaction 2) also requires a significant heat duty but the high running temperature of the whole cycle make possible heat recovery in form of generated steam. As overall conclusion, calcium looping looks promising for super-critical power plants for reducing carbon capture energy penalty compared with alkanolamines.

The next evaluated aspects were the economic indicators. The first two cases were evaluated also in term of capital and operational costs. The Case 3 was not evaluated in term of economic indicators due to present technology development (laboratory and pilot stage below 1 MW). Firstly, capital cost was estimated using cost correlations, the whole methodology was presented in details in another paper (Cormos, 2012). For estimation of capital costs, the plant concept was divided into basic sub-systems (e.g. boiler island, flue gas desulphurisation, carbon capture unit, CO₂ compression and drying, power island and utilities & offsite units). For each of these sub-systems, equipment capital costs were estimated as a power law of capacity (see Eq(3)) which were expressed based on the material / energy flows that the equipment has to handle within the process.

$$C_E = C_B * \left(\frac{Q}{Q_B}\right)^M \quad (3)$$

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.

Once the total capital (investment) cost is estimated for each power plant concept, the specific capital investment (SCI) per gross or net power generation (€/kW) was calculated using Eq(4). Table 3 presents the plant unit capital costs as well as specific capital investments for Cases 1 and 2.

$$SCI \text{ per kW(gross/net)} = \frac{\text{Total investment cost}}{\text{Gross/ Net power output}} \quad (4)$$

Table 3: Capital cost and specific capital investments

Main plant parameter	Units	Case 1	Case 2
Solids handling facilities	MM €	82.94	97.80
Super-critical coal boiler	MM €	319.30	385.48
Post-combustion capture (MDEA)	MM €	0.00	552.02
CO ₂ Processing and Drying	MM €	0.00	52.56
Flue gas desulphurisation (FGD)	MM €	138.26	166.92
Steam turbine	MM €	293.32	310.22
Utilities and Offsite Units	MM €	208.46	391.26
Total installed cost (excl. contingency)	MM €	1,042.28	1,956.26
Owner's Cost and Contingency	MM €	156.34	293.44
Land Purchase, permitting, surveying	MM €	52.12	97.82
Total investment cost (TIC)	MM €	1,250.74	2,347.52
SCI per kW gross power output	€/ kW	1,244.96	2,168.39
SCI per kW net power output	€/ kW	1,316.92	2,467.83

Introduction of CCS implies a significant increase of capital cost (~88 %) compared with designs without CCS. This is due to the influence of post-combustion capture (CO₂ capture and conditioning units are about 32 % of total plant costs). The specific investment costs is increasing with 74 % (gross power) and 87 % (net power). The following step is the estimation of operation and maintenance (O&M) costs. O&M costs are generally allocated as variable and fixed costs. Variable operating costs are directly proportional to amount of generated power (raw materials consumed in the process, chemicals, solvents, waste disposal etc.). Fixed operating costs are essentially independent of the amount of generated power (maintenance, direct labour cost, administrative etc.). Figure 4 presents the distributed O&M costs for Cases 1 and 2.

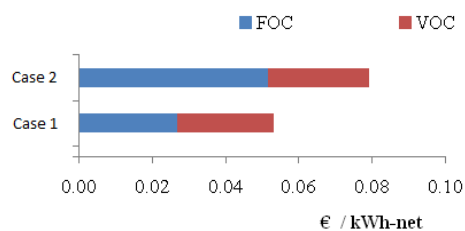


Figure 4: Operation and maintenance (O&M) cost

The O&M costs for CCS case increases with about 50 % compared with the case without CCS. Cost of electricity (COE) is about 40 €/MWh for the case without CCS and 62 €/MWh for the case with CCS (55 % increase). For calcium looping option, literature sources (Connell et al., 2013) suggest that economic performances are better than post-combustion alkanolamine-based carbon capture. For instance, specific investment costs of super-critical power plant fitted with calcium looping unit are in the range of 1,900 - 2,100 €/ kW and cost of electricity is in the range of 48 - 60 €/MWh (Yongping et al., 2010).

5. Conclusions

This paper analyzes super-critical power plants in two situations: with and without CCS. As carbon capture options, MDEA-based gas-liquid absorption and calcium looping cycle were examined. The introduction of CCS step implies 7.4 – 9 % energy penalty, the lowest value being for calcium looping case. This result underlines the potential of calcium looping to significantly reduce CO₂ capture energy penalty due to high temperature heat recovery. As future works, scale-up issues, dynamic behaviour, detailed economics as well as applications of calcium looping in other non-power industrial processes (e.g. cement, steel etc.) will be examined. For CCS case based on gas-liquid absorption the economic evaluations showed 88 % capital costs, 50 % O&M costs and 55 % COE increase compared with similar design without CCS.

6. Acknowledgements

This work was supported by a grant of the Romanian National Authority for Scientific Research, CNCS – UEFISCDI, project ID PNII-CT-ERC-2012-1 / 2ERC: “Innovative systems for carbon dioxide capture applied to energy conversion processes”.

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