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Feasibility assessment of CO_2 capture retrofitted to an existing cement plant: post-combustion vs. oxy-fuel combustion technology

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Abstract

This research presents a preliminary techno-economic evaluation of CO_2 capture integrated with a cement plant. Two capture technologies are evaluated, monoethanolamine (MEA) post-combustion CO_2 capture and oxy-fuel combustion. Both are considered potential technologies that could contribute to reduction of CO_2 emissions in the cement industry. The study compares these two technologies in terms of technical performance, investment costs, and operational costs. The case study is applied to the one of the largest cement plants in Portugal, Alhandra. The results show that the amount of CO_2 avoided using the post-combustion MEA technology is lower due to additional emissions from reboiler steam production. Moreover, the total capital investment of the post-combustion CO_2 capture system is estimated at 260 $M€_{2014}$ and the annual operation and maintenance costs of around 43 $M€_{2014}$; whereas the oxy-fuel combustion CO_2 capture requires a capital investment of about 217 $M€_{2014}$ and 37 $M€_{2014}$ annually for operation and maintenance. This indicates that the oxy-fuel CO_2 capture technology may be a better choice in terms of costs. However, this technology implies higher technical uncertainties concerning integration with the cement plant.

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Keywords: Cement plant; Post-combustion CO_2 capture; oxy-fuel combustion CO_2 capture, Techno-economic analysis.

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1. Introduction

Cement is one of the most important building materials and its production is a highly energy intensive process. Limestone calcines at temperatures between 900 and 1000 ºC and kiln temperatures are kept at 1500 ºC to achieve calcination [1]. To produce the heat, mostly fossil fuels are used in the combustion system, leading to large amount of anthropogenic CO_2 emissions. The amount of CO_2 produced by decomposition of limestone in the raw mix is even larger than the CO_2 from the combustion process. This ranks the cement manufacturing sector as the second most relevant industry in terms of CO_2 emissions in Portugal, following electricity production. It is responsible for approximately 13 % of CO_2 emissions in the Portuguese energy system [2].

Although the cement industry is yet to deploy a large commercial capture project, CO_2 capture could significantly reduce its CO_2 emissions. Among the three types of CO_2 capture technologies (post-, pre-, and oxy- combustion) post-combustion and oxy-fuel combustion are the most suitable methods for capturing CO_2 at cement manufacturing plant. Pre-combustion CO_2 capture is less suitable because it does not capture the significant amount of CO_2 emission from the limestone calcinations process [3].

The objective of this research is to analyze the performance of the two capture methods when integrated in the cement plant. The case study is applied to the Alhandra cement plant, which uses a dry process with a 5 stage preheater and has a production capacity of around 5000 tonne per day. The feasibility assessment quantifies performance and cost impacts of retrofitting the plant with both CO_2 capture technologies. The objective is accomplished as follows:

- Simulation of the pyro-processing unit of the cement process;
- Technical evaluation of the MEA post-combustion CO_2 capture applied to the Alhandra cement plant;
- Technical evaluation of the Alhandra cement plant using oxy-fuel combustion;
- Preliminary cost analysis of both CO_2 capture methods, post-combustion and oxy-fuel combustion, for the designed systems.

Nomenclature

AACE	Association for the Advancement of Cost Engineering
ASU	Air Separation Unit
CCS	Carbon Capture and Storage
CEPCI	Chemical Engineering Plant Cost index
CHP	Combined Heat and Power
DCC	Direct Contact Cooler
DF	Dust Filters
FGD	Flue Gas Desulphurization
IECM	Integrated Environmental Control Model
M	Millions
MEA	Monoethanolamine
O&M	Operation and Maintenance
SCR	Selective Catalytic Reduction
TCR	Total Capital Requirement

2. Methodology

2.1. Reference case study

The Alhandra cement plant is one of the largest cement plants operating in Portugal. It produces 1,8 Mt of clinker per year and started its production in 2005. The composition of the mix of fuels burned in the pyro-processing unit of the Alhandra plant is presented in Table 1, as well as the composition of the raw materials and the final clinker product.

Table 1. Summary of the main input and output streams used for the simulation of the reference case [4,5].

Input				Output			
Raw materials		Fuels		Final product		Pre-treated flue gas	
Composition		Composition		Composition		Composition	
$CaCO_3$	90.28 %	Petroleum coke	77 %	Al_2O_3	0,7 %	CO_2	16.5 mol%
SiO_2	4.8 %	Alternative fuels	15 %	C_2S	27,1 %	H_2O	13.2 mol%
Al_2O_3	1.9 %	Biomass	6.6 %	C_3S	51,5 %	N_2	62.4 mol%
Fe_2O_3	1.61 %	Fuel oil	0.15 %	C_3A	9,4 %	O_2	7.9 mol%
Others	1.3 %	Gas oil	0.5 %	C_4AF	2,7 %	Total flow	35720 kmol/h
Total flow	392235 kg/h	Natural gas	0.005 %	CaO	8.5 %	Temperature	128 ºC
Temperature	25 ºC	Total flow	25600 kg/h	Total flow	230570 kg/h		
		Temperature	25 ºC	Temperature	50 ºC		

The pyro-processing unit of the cement process was simulated in AspenPlus [6]. The process flow diagram includes a 5-stage preheater, a calciner, a kiln and a clinker cooler. Its simplified layout is shown in Fig. 1. Streams into the system are raw material, fuel inlet into the calciner and kiln and air for combustion and cooling. Streams that go out are the produced clinker and exhaust gases. The simulation was optimized in such manner that out-coming flows were in agreement with actual data from the Alhandra plant.

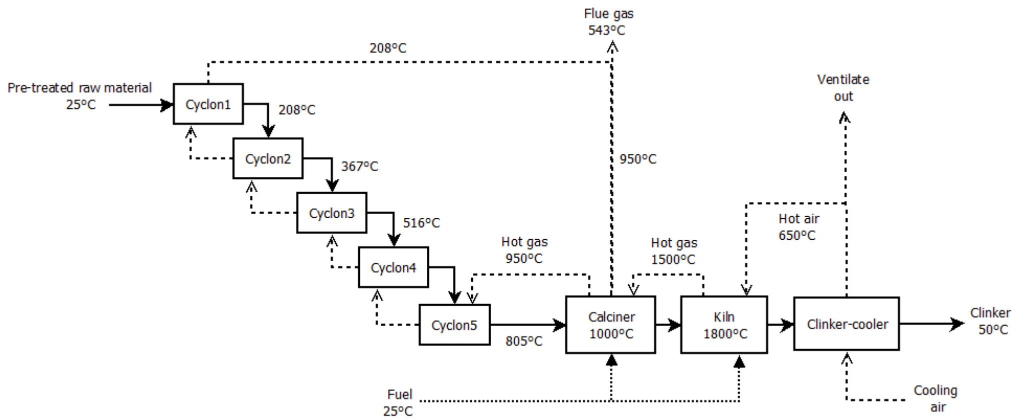

Fig. 1. Simplified diagram of the simulated reference cement plant.

2.2. Post-combustion CO_2 capture

Post-combustion systems separate CO_2 from the exhaust gases of the system by adding an additional unit to the tail-end of the clinker process where the CO_2 is separated from other combustion flue gases. The amine systems are currently the closest to commercial application and therefore are considered as the most mature technology to be applied on existing plants. The flue gases coming from the combustion process and the calcination reaction were considered as inlets into the MEA post-combustion unit. Unlike many coal power plants, cement plants are generally not equipped with SO_2 and NO_x controls. Therefore, dust filter bags, FGD, and SCR facilities need to be additionally installed to avoid unnecessary solvent degradation. It is assumed that the pretreated flue gas entering the CO_2 capture process consists primarily of CO_2, H_2O, N_2 and O_2 (Table 1). Fig. 2 shows the simplified flowsheet of the simulated CO_2 capture unit. It was simulated using ProTreat software [7].

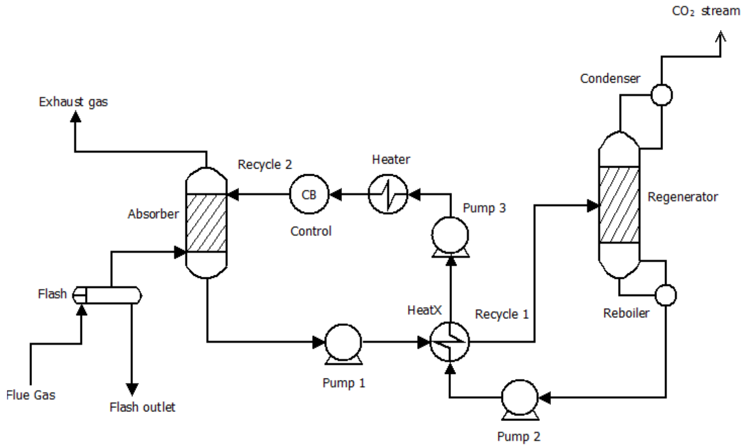

Fig. 2. Diagram of the simulated post-combustion CO_2 capture unit.

The exhaust gas from the cement plant is cooled down to 50 ºC before it enters into the absorber, to improve the absorption of CO_2. Also, the flue gas is pressurized in order to overcome a pressure drop when passing through the absorption column. The presented MEA scrubbing system consists of two main elements: an absorber where CO_2 is removed and a regenerator, where CO_2 is released and the original solvent is recovered. In this research, the main focus is minimizing the thermal energy requirement for the solvent regeneration and the solvent flow since these two parameters significantly lower the energy requirement and consequently reduce the total costs of the CO_2 capture process [8,9]. The representative solvent is 30% aqueous MEA, under lean sorbent loading 0.2 and the optimized sorbent flow was determined to be 50000 kmol/h, while capturing 90 % of CO_2. Reboiler steam demand is assumed to be met with a dedicated auxiliary natural gas boiler. However, the additional boiler emits CO_2 itself which is released into the atmosphere. This offsets part of the CO_2 captured.

2.3. Oxy-fuel combustion CO_2 capture

Oxy-fuel combustion is gaining increasing interest from the cement industry. Wrampe and Rolseth showed several benefits, including increased clinker production, heat recovery, and combustion conditions [10]. With this technology, oxygen is used for combustion instead of air. It produces a flue gas mainly consisting of H_2O and CO_2 and therefore allowing simple CO_2 purification. However, oxygen combustion increases the temperature profile in the kiln which can cause structural damage to the equipment [11,12]. It is therefore essential that a portion of the CO_2 rich flue gasses are recycled back to the combustion zone to moderate the flame temperature. This has a direct impact on the energy balance and the plant operation and yet the quality of the final product needs to be maintained. Another operational concern of an oxyfuel layout is corrosion from the flue gases in the recycle loop.

Fig. 3 presents a simplified simulated process diagram of the oxy-fuel combustion CO_2 capture system implemented into the reference cement plant. An ASU, recirculation duct and CPU were added to the simulation of pyro processing unit. The preheater, calciner and rotary kiln were kept unchanged. The effect of the flue gas recirculation rate was studied to obtain the desired oxy-fuel combustion capture process and was defined to be 0.595 in order to keep the temperature of the kiln at 1800 ºC. The flue gas leaving the calciner consist of 88 % of CO_2. Part of the flue gas enters the preheater and the remaining is cooled down and enters the CO_2 purification and compression. Additional modifications in the reference plant were considered, such as the adjustments in the burner and a proper sealing to avoid air leakage. Another important modification is the cooler improvement for the two-stage clinker-cooler. This layout is important to separately operate the two different gas atmospheres, the flue gas/oxygen mixture and the cooling air. The cooling air leaves the cooler at temperature of 485 ºC and its heat is used for raw material drying. The overall quality of the final product is unchanged under oxy-fuel conditions.

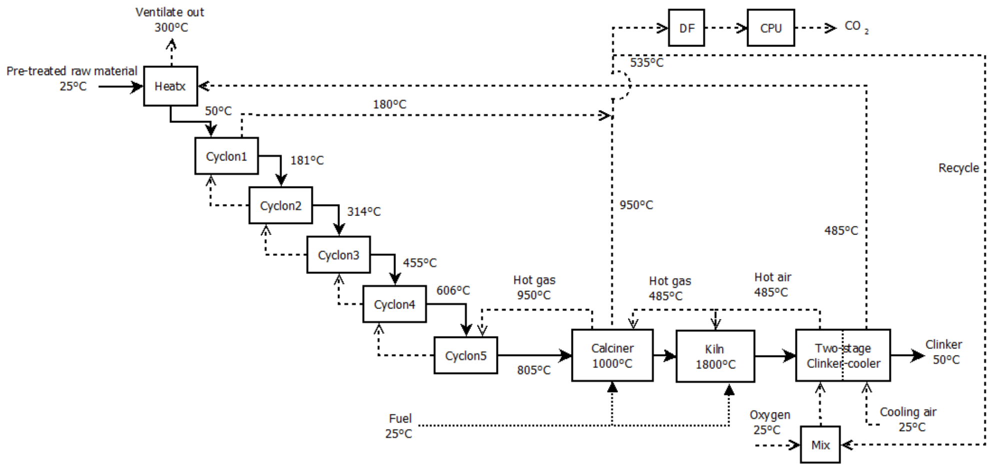

Fig.3. Simplified diagram of the oxy-fuel combustion CO_2 capture at the cement plant.

2.4. Cost estimation

Preliminary cost estimates were produces based on the mass and energy flows from the simulations. The estimates include both investment and operational costs. The economic evaluation is based on the methodology presented by Towler and Sinnott [13]. The main investment items for the MEA-based post-combustion system are the columns, lean/rich cross flow heat exchanger, cooler and circulation pumps, as well as the pre-treatment facilities (DF, SCR and FGD) and the additional CHP. The main investment requirements when the oxy-fuel combustion is applied are an ASU, a flue gas recycle fan and the flue gas recycle duct, DCC, CPU, kiln and burner modifications, DF, two-stage clinker cooler, sealing and circulation pumps. The investment costs of each individual item of the CO_2 capture system were estimated through equipment factoring using base values from the IECM economic model [14,15], thereby representing an AACE class 4/5 estimate with an accuracy range of -30 to +50 %.

2.4.1. Assumptions

The following cost assumptions were made:

- The cost estimation includes only CO_2 capture and compression to 13.79 MPa (evaluation of CO_2 transport and storage are excluded in this study);
- There is no heat integration between the cement manufacturing plant and the CO_2 capture units;
- Space availability for the additional units is not analyzed;
- The cement plant is in operation 8000 h/year [4];
- The CO_2 capture will be in operation for the next 20 years;
- The scaling factor for capital costs is assumed to be 0.6 [13];
- All costs are presented in $€_{2014}$. CEPCI and currency conversion of 1 € = 1.3285 US$ is applied;
- A location factor of 1.04 transform the costs from the US basis to the Western Europe [16];
- The base capital costs of the CO_2 capture unit are increased by an additional retrofit cost premium of 25 %, owing to expected site-specific retrofitting challenges [14];
- A real discount rate of 7 % is assumed [14].

Variable O&M cost includes the cost of chemicals, filter bags, waste disposal, water need, fuel and electricity. Fixed O&M costs represents the costs of maintenance, administration and labor. Table 2 shows the prices used for the estimation of O&M costs of the defined process.

Table 2. Prices used for the cost estimates.

Parameter	Unit	Value*	Source
Activated carbon	€/tonne	1282	[17]
Caustic soda	€/tonne	331.6	[17]
Limestone	€/tonne	50.86	[17]
Lime	€/tonne	260.5	[17]
Sorbent	€/tonne	1951	[18]
Reclaimer waste disposal CO_2 capture	€/tonne	192.8	[18]
Water	€/m^3	1.547	[19]
Natural gas	€/GJ	13.04	[20]
Electricity	€/kWh	0.1802	[21]
Labour	€/h	11	[22]
FGD stacking	€/tonne	6.358	[18]
FGD waste disposal	€/tonne	10.9	[18]
NO_x catalyst	€/m^3	4515	[18]
Amonnia	€/tonne	113	[18]
Fabric dust filter bag	€/ks	97.16	[18]
Waste disposal dust filter	€/tonne	14.16	[18]
Misceallenous chemicals for CPU	€/tonneCO_2	0.76	[18]

*when necessary, currency conversion is applied.

3. Results and discussion

Table 3 presents the required modifications, CO_2 emissions balance, and the energy consumption when post-combustion CO_2 capture or oxy-fuel combustion is applied to the cement plant.

Table 3. Technical performance of the post-combustion and oxy-fuel combustion CO_2 capture process.

Parameter	Unit	MEA post-combustion CO_2 capture		Oxy-fuel combustion CO_2 capture	
Modification to the reference plant		No		Kiln burner, two-stage clinker-cooler, sealing	
Additional units installed to the reference plant		DF, SCR, FGD, DCC, CO_2 capture unit, compressor, CHP		ASU, DCC, CPU, CO_2 recycle, DCC, DF, fan, compressor	
CO_2 capture rate	%		67.2		87.1
CO_2 in the flue gas	tonne/h		186.9	Total	459.2
	tonne/h		-	To recycle	273.2
	tonne/h		-	To CPU	186
CO_2 captured	tonne/h		161.9		161.9
CO_2 stack out	tonne/h	Total	61.26		24.06
	tonne/h	Primary stack	18.7		-
	tonne/h	CHP stack	42.56		-
Additional heat requirment	GJ/h		681.8		0
Electricity consumption	MW		9.56		30.93

The table shows that the amount of CO_2 captured is similar for the MEA and the oxy-fuel combustion case. However, under the MEA post-combustion option, a large amount of CO_2 emissions is caused by the additional CHP

(23 % of the total CO_2 emissions in the flue gas), which is vented to the atmosphere. Thus, oxy-fuel CO_2 capture has a larger direct CO_2 emission reduction potential, while producing the same amount of clinker as the reference plant. However, this figure only includes direct emissions, also including potential CO_2 emissions of electricity production might shift the balance away from oxy-fuel.

For the MEA case, the CO_2 emission reduction comes at the expense of 682 GJ/h of additional heat for solvent regeneration. In terms of electricity, the largest consumer is the CO_2 compressor. The oxy-fuel combustion process has higher consumption of electricity than the MEA case due to requirements from ASU and CPU.

Table 4 summarizes the direct capital and O&M costs of the designed CO_2 capture processes. The largest capital requirement for the post-combustion CO_2 capture process comes from the columns and the compression unit. Under the oxy-fuel combustion, the highest investments include the ASU and CPU (which includes the CO_2 compression), accounting for 68 % of the total investment costs. The cost estimates of the oxy-fuel configuration include an estimation of required modifications to the reference plant, such as adjustments to the burner and proper sealing to avoid air leakage.

In both configurations, the main operating costs are connected to the consumption of electricity. For the post-combustion CO_2 capture, the additional natural gas to the CHP also presents an important share of the O&M costs. Like the investment costs, the O&M costs of the oxy-fuel option are lower than those of the MEA option. This study hence suggests that also from an economic perspective oxy-fuel combustion may be preferable over MEA capture.

Table 4. Cost estimates of the post-combustion and oxy-fuel combustion CO_2 capture systems.

MEA post-combustion CO_2 capture		Oxy-fuel combustion CO_2 capture	
Capital investment	M€$_{2014}$		M€$_{2014}$
Pretreatment of flue gases		*Pretreatment of flue gases*	
Dust filters	10.12	Dust filters	10.54
Selective catalytic reduction	6.58	*Additional units*	
Flue gas desulphurization	45.4	Air separation unit	54.39
CO_2 capture process area		Flue gas recycle fan	1.08
Flash	10.52	Recycle flue gas pipeline	5.73
CO_2 absorber vessel	32.02	Flue gas cooler	14.61
Heat exchanger	1.95	Cryogenic purification unit	45.14
Sorbent circulation pumps	5.85	*Modification to the reference cement plant*	
Sorbet regenerator	21.48	Kiln burner	10.72
Reboiler	10.5	Two stage clinker cooler	3
Cooler of recycle	7.06	Sealing	0.07
Sorbent reclaimer	0.41	*CO_2 system process facilities capital*	
Sorbent processing	0.7	Engineering cost	10.71
Additional heat supply		General facilities capital	14.53
Auxiliary gas boiler	11.22	Project contingency cost	21.79
Post-treatment of CO_2		Process contingency cost	7.26
Drying and compression unit	21.67	Interest charges	10.31
CO_2 system process facilities capital		Royalty fees	7.26
General facilities capital	22.62	*Total capital requirement*	216.6
Project contingency cost	15.83		
Process contingency cost	33.93		
Interest charges	11.31		
Royalty fees	1.31		
Total capital requirement	260.25		

O&M costs	M€$_{2014}$/year		M€$_{2014}$/year
Variable	35.3	Variable	30.28
Fixed	8.03	Fixed	6.9
Total	43.33	Total	37.18

4. Conclusions

This work presented a preliminary techno-economic assessment of CO_2 capture from a cement plant using A) MEA post-combustion technology with additional steam production in a NG boiler and B) oxy-fuel combustion technology. The results indicate that the oxy-fuel option is capable of achieving higher removal rates of the cement plants' direct CO_2 emissions (87 % versus 67 % for MEA). This is mainly due to the additional emissions of steam production which is required for the MEA post-combustion CO_2 capture unit, and the exclusion of secondary emissions from electricity use, which benefits the oxy-fuel case. Also from an economic perspective, the studied oxy-fuel configuration presents the lowest investment and operational costs. The TCR of the MEA and oxy-fuel case are 260 and 216 M€, respectively. The operational costs are 43 and 37 M€/a. The techno-economic results thus point towards oxy-fuel combustion as the preferable option for the studied cement plant. A drawback of the oxy-fuel case is that it requires more adaptations to the core clinker production process, increasing uncertainties in process performance and product quality. Post-combustion CO_2 capture could be readily implemented and may therefore be an easier option for retrofitting in the short term.

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