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Techno-economic analysis of Calcium Looping processes for low CO_2 emission cement plants

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Abstract

This work presents the results of the techno-economic analysis of cement plants with Calcium looping (CaL) process for CO_2 capture. Two different CaL integration approaches are compared, namely the tail-end CaL with fluidized bed reactors and the integrated CaL with entrained flow reactors. Specific primary energy consumption for CO_2 avoided (SPECCA) of 3.3 and 3.8 MJ_{LHV}/kg_{CO2} have been calculated for the integrated and the tail end CaL cases respectively. Cost of CO_2 avoided between 50 and 56 €/t_{CO2} have been obtained.

Keywords: CCS; CO_2 capture; Calcium looping; cement; clinker; CEMCAP

1. Introduction

Cement production is responsible for about 8% of global anthropogenic CO_2 emissions [1]. In state-of-the-art dry clinker burning processes, CO_2 produced from $CaCO_3$ calcination represents about 60 % of the total CO_2 emissions, the remaining fraction being emitted from fuel combustion. In the framework of the H2020 CEMCAP project [2], different technologies for CO_2 capture in cement plants have been assessed and benchmarked, namely oxyfuel combustion, chilled ammonia, membrane-assisted CO_2 liquefaction and Calcium Looping (CaL).

In this paper, the results of the techno-economic study performed on the CaL technologies are presented.

2. Calcium looping cement plants

The most straightforward process integration option for CaL in cement plants is the tail-end configuration (Figure 1a), where the CaL process based on fluidized bed reactors is integrated as an end-of-pipe process, treating the cement kiln exhaust gas in the carbonator. In this case, a fraction of the limestone fed to the cement kiln is introduced in the calciner of the CaL process to be used as a CO_2 sorbent. The CaO-rich solid purge from the CaL process is then introduced into the clinker burning line, replacing part of the limestone in the raw meal. The integration level (IL) is

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defined as the ratio between the limestone fed to the CaL process and the total amount of $CaCO_3$ fed to the plant (eq.(1)). The integration level significantly affects the heat input to the CaL calciner (sustained through oxycombustion) and the overall energy balance of the plant. Detailed discussion on the effects of the CaL process parameters on the cement kiln energy balance and on the retrofittability of existing cement kilns can be found in [3].

$$IL = \frac{CaCO_3\ fed\ to\ the\ CaL\ process}{Total\ CaCO_3\ fed\ to\ the\ plant} \tag{1}$$

A second option for CaL process integration is the integrated CaL configuration (Figure 1b). In this case, the carbonator is integrated into the raw meal preheater and a single oxyfuel calciner is used, simultaneously operating as raw meal pre-calciner and as CaL process calciner. Raw meal is preferably used as sorbent in this case and CaL reactors operate in the entrained flow regime because of the small size of the particles (d_{50}=10-20 μm) needed for clinker production. The intrinsic advantage of the integrated CaL configuration is that a single oxyfuel calcination is performed, which implies a significant saving in the fuel consumption of the plant [4].

Both the CaL processes lead to increased fuel consumption for the regeneration of the sorbent at high temperature in the oxyfuel calciner. A steam cycle is therefore needed to recover the thermal power generated in the CaL process by fuel combustion.

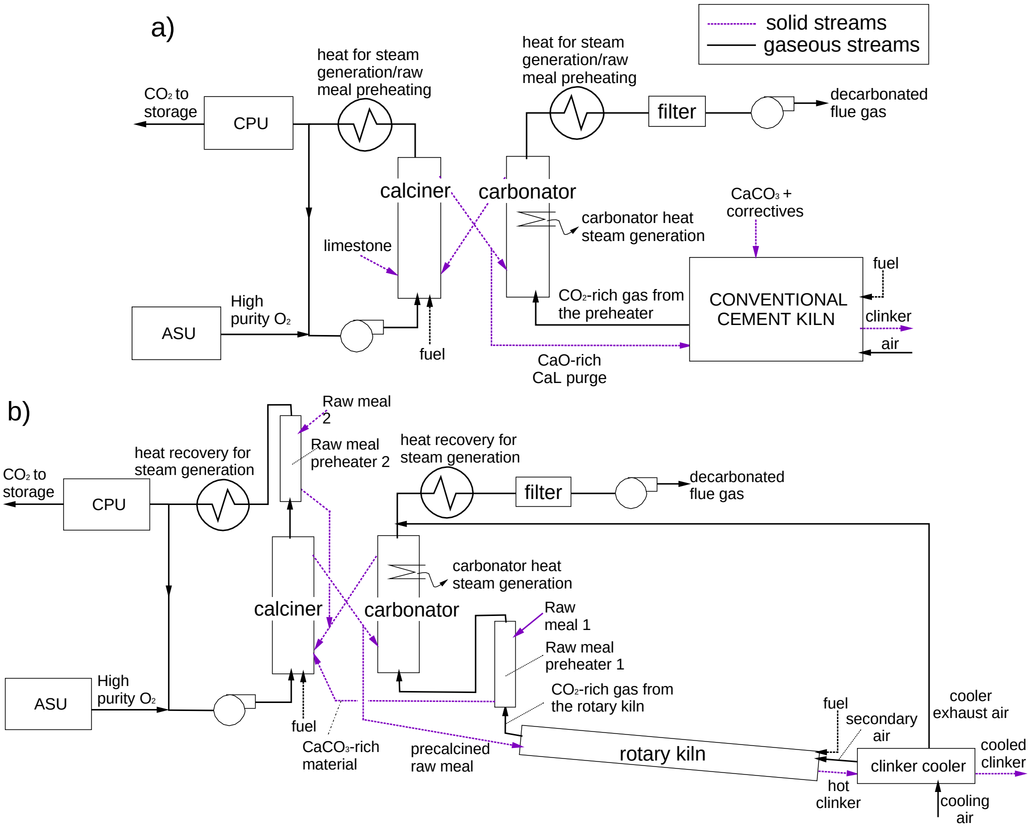

Figure 1. Conceptual scheme for the integration of a CaL process into a cement plant: (a) tail-end configuration; (b) highly integrated configuration using raw meal as CO_2 sorbent precursor.

3. Heat and mass balance

Heat and mass balances are calculated with the in-house process simulation code GS [5], which was formerly validated for the calculation of the heat and mass balances of the benchmark cement kiln without CO_2 capture [6].

Fluidized bed carbonator for the tail-end CaL and entrained-flow carbonator for the integrated CaL process have been modelled with the Matlab models described in [7,8].

For a detailed discussion of the calculation methodology and assumptions of the cement plant with the tail-end CaL system, the reader is addressed to [3]. In this work, cases with integration level of 20% and 50% presented in [3] have been selected as representative cases of the technology.

The integrated CaL cement kiln has been calculated with assumptions consistent with the CEMCAP project framework [9].

In Table 1, the overall results of the heat and mass balance are reported. Overall direct CO_2 emissions are reduced by 86.3-93.6%. The CO_2 mass balance is influenced by three parameters: the CO_2 capture efficiency of the carbonator, the amount of fuel burned in the oxyfuel calciner and the CO_2 lost from the CO_2 purification unit.

For all the CaL processes, a significant increase of the direct fuel consumption is obtained, due to the additional fuel consumed for sorbent regeneration. The higher the fuel consumption, the higher the heat generated in the CaL island and the power produced by the steam cycle. In the plant with the highest fuel consumption (tail-end CaL with IL=20%) the steam turbine generates electricity in excess compared to the consumptions of the cement plant and of the CO_2 capture island (the latter mainly for CO_2 compression and oxygen production) and the plant becomes a net exporter of electricity. In the other CaL cases, the steam cycle largely compensates the power absorbed by plant auxiliaries, but the cement kiln remains a power consumer.

Indirect fuel consumption and CO_2 emissions associated to the electric power balance are computed assuming that power is exchanged with a state-of-the-art pulverized coal USC power plant with electric efficiency of 44.2% and specific emission of 770 kg_{CO2}/MWh_e. From the equivalent fuel consumption and CO_2 emissions (i.e. accounting for both direct and indirect consumption and emissions) [9], the specific primary energy consumption for CO_2 avoided (SPECCA) can be calculated. From this global performance indicator, the integrated CaL plant, which is the case with the lowest fuel consumption, results the best case with a SPECCA of 3.27 MJ_{LHV}/kg_{CO2}, to be compared with 3.76-3.86 MJ_{LHV}/kg_{CO2} of the tail-end cases. It must be highlighted that this result is strongly dependent on the assumed efficiency and emission factor of the reference power generation technology [3].

Table 1. Main results of the heat and mass balance (clk = clinker).

	Cement kiln w/o CCS	**Tail end CaL (IL=20%)**	**Tail end CaL (IL=50%)**	**Integrated CaL**
CO_2 capture efficiency in the carbonator, %	-	88.8%	90.0%	82.0%
Total direct CO_2 emission, kg_{CO2}/t_{clk}	865.2	118.5	79.1	55.1
Direct emission reduction, %	-	86.3%	90.9%	93.6%
Direct fuel consumption, MJ_{LHV}/kg_{clk}	3.24	8.72	7.10	5.44
Net electricity consumption, kWh_e/t_{clk}	131.6	-110.3	57.7	158.3
Indirect fuel consumption, MJ_{LHV}/kg_{clk}	1.07	-0.90	0.47	1.42
Indirect CO_2 emission, kg_{CO2}/t_{clk}	101.3	-84.9	44.4	134.0
SPECCA, MJ_{LHV}/kg_{CO2}	-	3.76	3.86	3.27

4. Economic analysis

Economic analysis has been performed with the methodology described in [9]. Breakdown of the calculated cost of CO_2 avoided is reported in Figure 2. The largest contribution in all cases is associated to the capital costs, followed by fuel costs and fixed Opex. Contribution of electricity (assumed value of 58.1 €/MWh_e) may be positive or negative depending on whether the CaL cement plant consumes more or less power than the reference plant without CO_2 capture. On the whole, cost of CO_2 avoided (CCA) between 50 and 56 €/t_{CO2} have been calculated for the different cases, to be compared with CCA higher than 80 €/t_{CO2} estimated for the benchmark amine-based CO_2 capture technology [10].

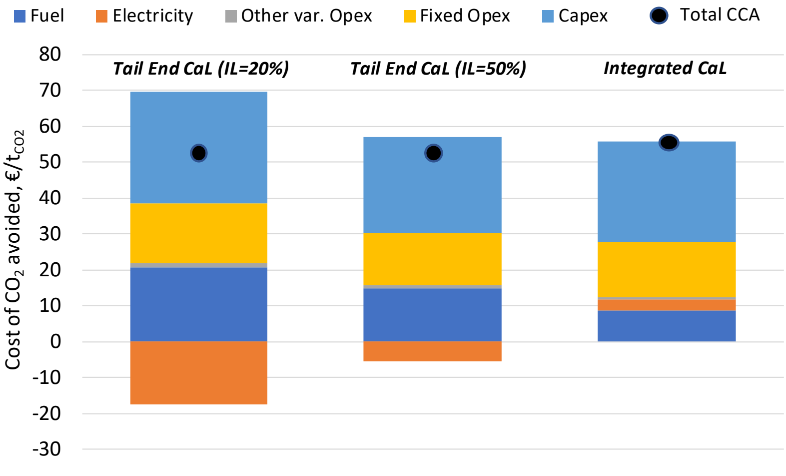

Figure 2. Breakdown of the cost of CO_2 avoided.

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