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Post-combustion carbon capture for heavy industry application: a comparison between calcium looping and ammine scrubbing

Daniele Ferrario[a,*], Umberto Pasqual Laverdura[b], Maria Luisa Grilli[b], Andrea Lanzini[a]

[a]*Energy Department, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy*
[b]*Energy Technologies and Renewable Sources Department, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA, 00123, Via Anguillarese 301, Rome, Italy*

Abstract

The decarbonization of heavy industries remains one of the most complex challenges in reducing anthropogenic GHG emissions. Specifically, cement and steel, which are considered hard-to-abate sectors, account for around 14% of global emissions [1], [2]. Reducing CO_2 emissions from their production process is particularly challenging, as large amounts of CO_2 are generated not only from the combustion of fossil fuels, especially coal, but also from process-specific chemical reactions, such as the calcination of limestone and the reduction of iron oxides [3], [4]. For this reason, Carbon Capture and Storage, and in particular Post-combustion carbon capture, is among the few technological solutions able to achieve near-zero emissions in cement and steel production [1], [2]. In detail, Calcium Looping (CaL) and amine scrubbing using aqueous solutions of monoethanolamine (MEA) are two promising technologies for the CO_2 capture from these industries. MEA has already reached commercial scale for cement and can also be integrated into steel plants. The incorporation of MEA in the production process enables substantial reductions in CO_2 emissions, albeit at the cost of a significant steam consumption [4]. CaL, instead, belongs to a second generation of CO_2 capture technologies and is currently at the demonstration stage. This system relies on the reversible reactions between CaO (solid CO_2 sorbent) and CO_2, namely carbonation (exothermic reaction) and calcination (endothermic reaction), which typically takes place in two fluidized bed reactors (carbonator and calciner). Compared to other capture processes, CaL can be highly energy efficient. Indeed, the thermal energy required to drive the calcination, which is usually supplied through oxy-combustion of fuel, can be largely recovered to produce steam and then converted to electricity. Furthermore, it is considered particularly promising for large-scale application and presents several synergies with cement and steel production, making it an interesting option for these industries [3], [5].

This study aims to evaluate the potential of post-combustion carbon capture for CO_2 emissions abatement across the cement and steel sectors by estimating the environmental, energy, and economic performances of CaL and MEA-integrated cement and steel production plants.

The reference plants, based on the best available techniques for cement and steel production [6], [7], were defined and characterized. State-of-the-art cement plants are based on dry clinker kilns, while the most widely adopted steel production method is carried out in large industrial complexes. These “integrated steel mills” include blast furnaces,

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[*] Corresponding author. Tel.: +39-011-090-102
E-mail address: daniele.ferrario@polito.it

basic oxygen furnaces, and several auxiliary plants such as lime kilns, sinter plants, steel casters, hot rolling mills, and also captive power plants, where the off-gases produced in the furnaces are recovered and combusted for on-site electricity generation. The mass and energy balances of the reference plants, both with and without CO_2 capture, were estimated through detailed process modeling. Four main integrated configurations were analyzed (Figure 1): (i) cement plant with MEA; (ii) cement plant with CaL; (iii) steel plant with MEA; and (iv) steel plant with CaL.

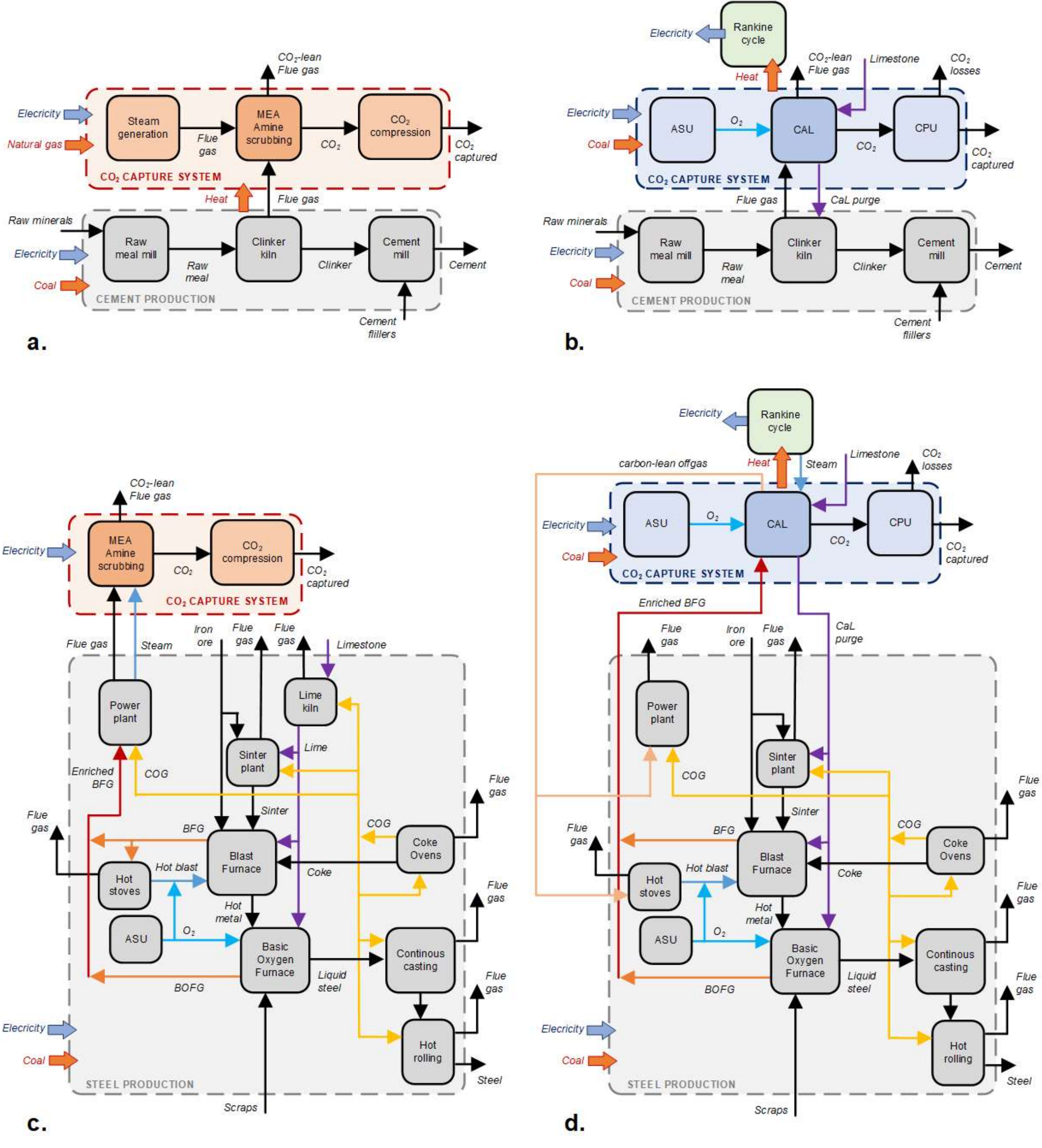

Figure 1 – Equivalent CO_2 emissions (Cradle-to-Gate) boundary for the different configurations studied.

MEA can be integrated into both the production plants as an end-of-pipe system, treating flue gas from the clinker kiln in the cement plant and flue gas from the captive power plant in integrated steel mills. In cement plants, its steam demand can be met partially by heat recovery and the remainder supplied by a dedicated steam generator fueled by natural gas [4]. In steel plants, the required steam can be extracted from the steam turbine of the captive power plant, resulting in an increased grid electricity consumption. CaL can also be implemented as an end-of-pipe solution in cement plants, with the electricity produced by the heat recovery system potentially covering the entire electricity demand of the integrated plant. In steel mills, CaL can be used to decarbonize the off-gasses before their combustion in the captive power plants and other plant auxiliaries, as a sorption-enhanced water gas shift system, leading to promising results in CO_2 emissions reduction [3].

The results obtained from the process modeling were then used in a subsequent life cycle analysis, performed with a Cradle-to-Gate boundary, and a detailed economic analysis, which includes the costs for CO_2 capture and CO_2 transportation and storage. All the main upstream processes, such as raw material extraction and transportation, fuel extraction and transportation, electricity generation, and CO_2 transportation and storage, were considered to estimate the fossil resource use (fossil fuel consumption) and carbon footprint (equivalent CO_2 emissions) for cement and steel production with and without carbon capture and storage.

The performances of the MEA and CaL-integrated configurations were evaluated in terms of equivalent CO_2 emissions reduction, increase in fossil fuel demand, and costs per equivalent CO_2 avoided (Figure 2). The findings indicate that integrating CaL in the cement and steel production could achieve larger CO_2 emissions reductions at competing costs compared to MEA. The costs per tonne of avoided CO_2 are largely driven by operational expenditures in the MEA-integrated systems, whereas capital expenditures are more significant in CaL systems. Furthermore, in CaL configurations, the electricity generated through heat recovery could lead to important savings in upstream emissions (depending on the carbon intensity of the grid) and operative costs, playing a crucial role in the final environmental and economic performances.

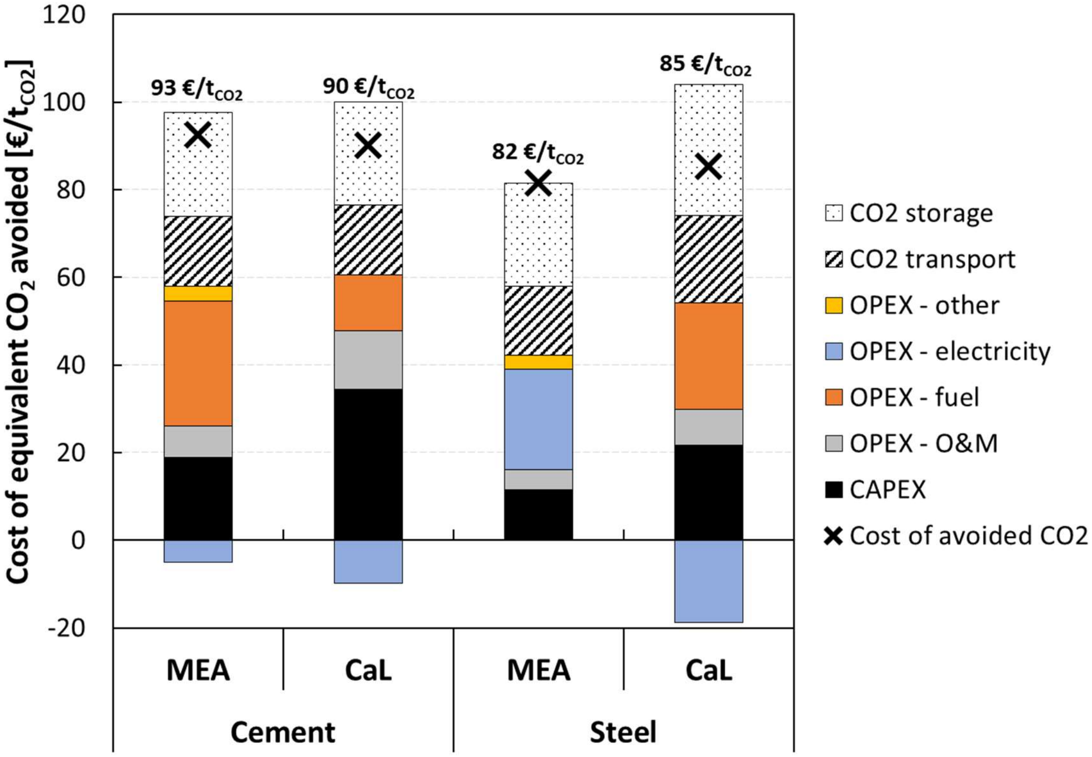

Figure 2 – Comparison of the cost of equivalent avoided CO_2 between MEA and CaL for CO2 capture in the cement and steel

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