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Carbon Capture vs. Electrification for Decarbonizing Ceramic Tile Manufacturing

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Abstract

The ceramic industry is characterized by an energy-intensive production process, which currently relies on the use of natural gas (NG) to reach high temperatures ($> 1000^{\circ}\text{C}$) in a series of different heating processes, thus generating an annual CO_2 emission of about 200 Mt/y, about 0.4% of global CO_2 emissions. The EU sector is responsible for the production of 25% of the global ceramic products and is already regulated by the EU-ETS regulation, even if, for the current period (up to 2030), it is rewarded by free allocation of allowances for the direct CO_2 emissions, being a sector exposed to the risk of carbon leakage. The Italian ceramic industry is almost entirely located in the Emilia-Romagna region, which hosts one of the largest manufacturing clusters in Europe and accounts for about 3 $\text{Mt}_{\text{CO}_2}/\text{y}$ (direct emissions). In the context of the ceramic sector targeting a 55% reduction in CO_2 emissions by 2030, several process modifications are being implemented, including fuel substitution, electrification, energy efficiency improvements, and the implementation of carbon capture, utilization, and storage processes. CCS4CER (www.ccs4cer.it) is an Italian research project aiming to study different decarbonization options based on CCS and electrification, while demonstrating the possibility of exploiting residual materials from the production process for a CO_2 mineralization process. The project partnership is composed of universities and research centers and includes several companies operating in the Emilia-Romagna region.

This work will present the conceptualization, modeling approach, and results related to the techno-economic competitiveness of electrification and CO_2 capture processes implemented to decarbonize a ceramic tile production plant. The selected ceramic plant has a production capacity of about $10'000 \text{ m}^2_{\text{tiles}}/\text{d}$ (tile thickness: 1 cm), with a NG consumption of $10.3 \text{ MW}_{\text{LHV}}$, corresponding to CO_2 emissions of about 18 kt/y. The plant (Figure 1) is composed of a raw material pre-processing section (grinding, mixing, and washing to obtain the ceramic slip) and a spray drier reactor, where hot flue gases ($\sim 550^{\circ}\text{C}$, produced by a NG-fired burner) are used to convert the ceramic slip into a dried granular powder. The material is then pressed to obtain the ceramic pieces and delivered to a low-temperature

drier (fed by a second NG combustion), and to a decoration and glazing section. Finally, the pieces are fed to the ceramic kiln, where the material is sintered at high temperature ($> 1000^{\circ}\text{C}$) and then cooled by a controlled airflow, used as combustion air in the previous plant sections. The large excess of air introduced into the process results in low CO_2 concentrations in the effluents, which pose a challenge for all CO_2 capture technologies. After a preliminary evaluation, Molten Carbonate Fuel Cells (MCFCs) have been selected as a promising CCS system. MCFCs generate electricity by directly converting natural gas (internally reformed at the anode) via electrochemical oxidation and, simultaneously, separate CO_2 from effluents generated by the ceramic production process, which are fed to the MCFC cathode. The power generated by the MCFC depends on the conversion efficiency (voltage) and the overall amount of CO_2 separated at the cathode. Several integration options of MCFC and its balance-of-plant to the ceramic production process have been proposed and simulated, including modifications to the host plant. Figure 2 shows a configuration in which the kiln exhaust gas is recycled to the hot spray drier to increase CO_2 concentration. All the effluents are then delivered to the CO_2 capture, purification, and compression section, where they are preheated (also using electrified heaters) and fed to the MCFC cathode, which separates 84% of CO_2 while generating a gross power of $1.4 \text{ MW}_{\text{el}}$. Overall, considering all auxiliary consumption of the capture unit (including CO_2 purification and compression), the ceramic plant reduces its thermal input from 10.3 to $9.4 \text{ MW}_{\text{LHV}}$, while increasing its electricity consumption from 1.6 to $2.7 \text{ MW}_{\text{el}}$.

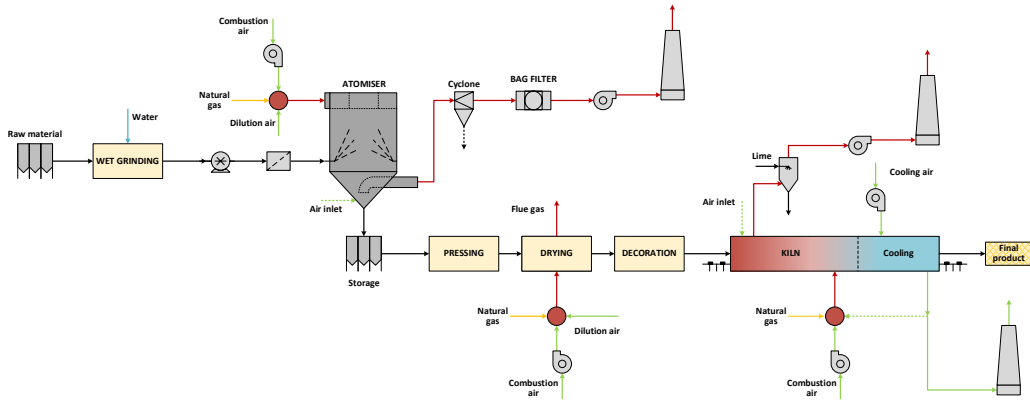


Figure 1: Reference ceramic tiles production plant without carbon capture.

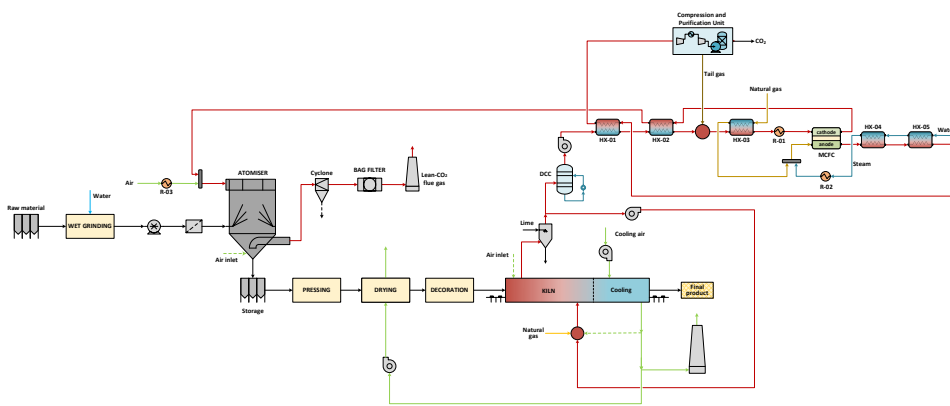


Figure 2: Ceramic tiles production plant integrated with an MCFC-based solution for process decarbonization.

An alternative process decarbonization solution is to adopt electrified heaters to generate the hot gases required for drying and sintering. This solution increases the electricity output to $11.3 \text{ MW}_{\text{el}}$ while achieving a CO_2 avoidance rate

of 94%. This solution avoids the need to (i) feed NG and (ii) post-process the CO₂ captured, resulting in lower capex and a simplified retrofit work. The techno-economic analysis of the proposed solutions shows that the best option depends primarily on the economic boundary conditions, namely the cost of natural gas and electricity. Compared to CCS applications in other hard-to-abate industrial processes (e.g., steel and cement), the application of CO₂ capture technologies is also affected by the ceramic plant's lower CO₂ flow rate, which leads to unfavorable economies of scale. For the MCFC case the resulting cost of CO₂ avoided (CCA) is 280 €/t_{CO2} (with a cost of electricity of 100 €/MWh_{el} and a cost of natural gas of 55 €/MWh_{LHV}) and appears promising when compared with the estimated cost for the reference amine-based system, which amounts to 440 €/t_{CO2}. The electrified process is characterized by lower capex, and its economic attractiveness is defined by electricity costs: in the baseline scenario (100 €/MWh_{el}) the resulting CCA is 220 €/t_{CO2}.

Figure 3 shows the breakeven conditions for natural gas and electricity costs (black line), where the CCS and electrification solutions yield the same incremental specific cost for the produced ceramic tile, expressed in €/m². In addition, for the two technologies, several iso-increment lines of the specific cost are reported. The bottom-right corner of the chart, corresponding to low natural gas prices and high electricity costs, is dominated by the CCS-MCFC solution, while the top-left corner, with low electricity and high natural gas prices, is a favorable context for the plant's electrification retrofit. Overall, the specific cost increment of the ceramic tile is in the order of magnitude of 0.7-1.2 €/m², which corresponds to around 8.4-22.1% of the actual direct production costs (OPEX) of the final product, depending on the quality of the product itself.

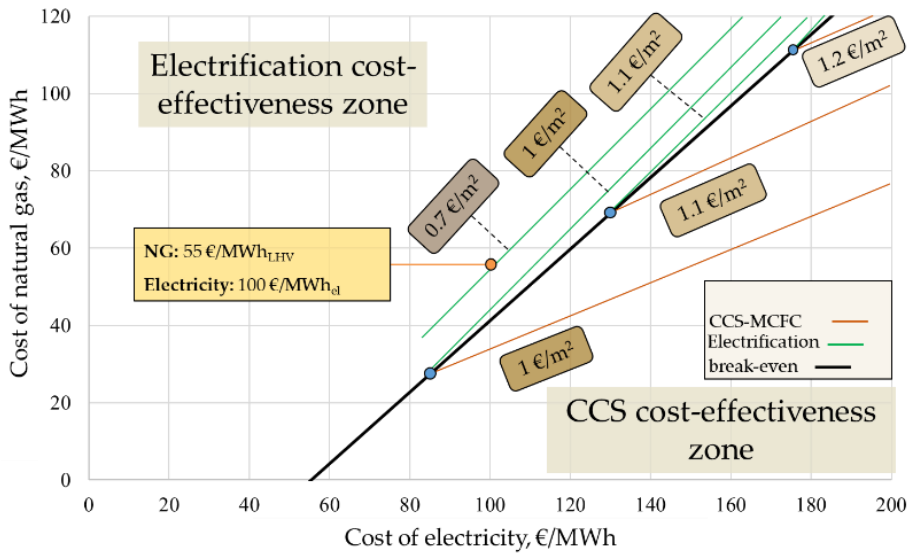


Figure 3: Breakeven line for the MCFC and electrification solutions for the decarbonization of the ceramic tile production plant, and iso-increments of specific cost line for the electrification retrofit (green) and for the MCFC (orange).

Acknowledgements

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Keywords: CCS4CER; CCUS chain; Molten Carbonate Fuel Cells; Low-carbon materials; Cost of CO₂ avoided