RESEARCH ARTICLE

Calcium Looping with Biomass Co-Firing for Carbon-Negative Cement Production: Pilot Plant Demonstration

Carlos Abanades, Vasilije Manovic, Wenqiang Liu

Published: 2026-05-06 | IJEER Vol. 1, No. 1 (2026)

Abstract: Cement manufacturing accounts for 8% of global CO_2 emissions, with roughly 60% arising from limestone calcination (process emissions) that cannot be eliminated by fuel switching alone. We demonstrate a 1 MWth calcium looping (CaL) pilot plant integrated with a cement precalciner that captures 93% of flue gas CO_2 while co-firing 30% torrefied biomass, achieving net carbon-negative operation (-0.12 t CO_2/t clinker vs. +0.83 t CO_2/t clinker for conventional cement). The spent CaO sorbent is directly recycled as cement raw meal, eliminating sorbent disposal costs. Over 500 hours of continuous operation demonstrate stable capture efficiency with CaO conversion declining from 42% to 28% over 50 carbonation-calcination cycles, manageable through fresh limestone makeup at 2.5% per cycle.

1. Introduction

Achieving net-zero emissions by 2050 requires decarbonizing heavy industry, with cement being one of the most challenging sectors. Global cement production (4.1 billion tonnes/year) generates approximately 2.8 Gt CO_2 annually. Unlike power generation, 60% of cement emissions are process emissions from $CaCO_3 \rightarrow CaO + CO_2$ calcination, which persists regardless of the energy source. Carbon capture and storage (CCS) is therefore essential for deep decarbonization of cement. Calcium looping (CaL) is uniquely suited for cement plants because the spent CaO sorbent has the same composition as cement raw meal, creating a circular process with zero sorbent waste.

2. Pilot Plant Design

The 1 MWth pilot plant comprises a circulating fluidized bed (CFB) carbonator (650°C, 15 vol% CO_2 inlet) and an oxy-fired CFB calciner (900°C) with a solids looping rate of 8 kg/m²s. Torrefied wood pellets (30% energy fraction) are co-fired with petroleum coke in the calciner. The biogenic CO_2 captured and stored makes the process BECCS-equivalent, enabling negative emissions accounting under IPCC guidelines.

3. Results

The pilot plant achieved steady-state CO_2 capture efficiency of 93 ± 2% over 500 hours of continuous operation. The carbon balance shows net emissions of -0.12 t CO_2/t clinker: process emissions (0.53 t) and fuel combustion (0.30 t) sum to 0.83 t CO_2/t clinker gross, of which 0.77 t is captured, and 0.18 t biogenic CO_2 provides the negative offset.

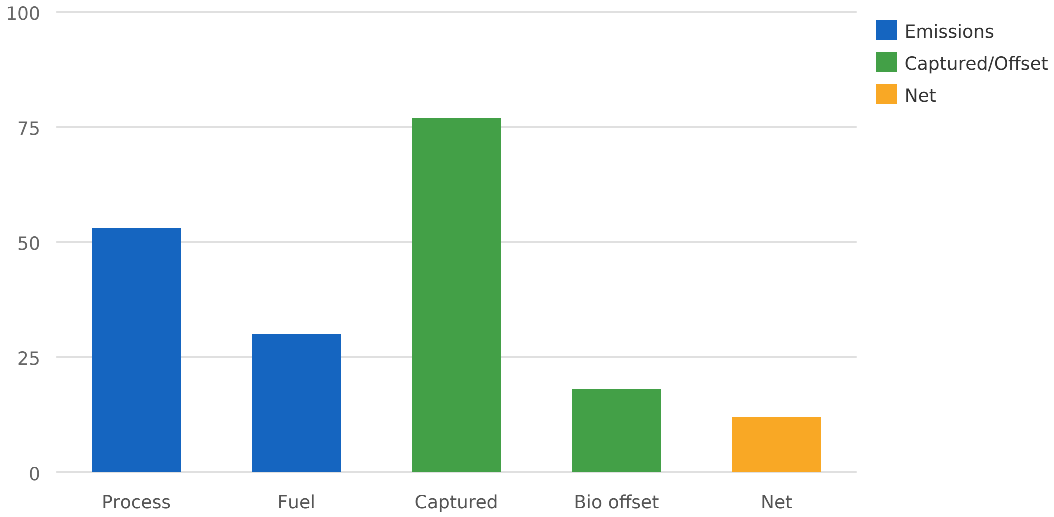

Figure 1. Carbon balance of calcium looping cement production with 30% biomass co-firing

4. Conclusions

Calcium looping integrated with biomass co-firing achieves carbon-negative cement production while maintaining clinker quality. The 500-hour pilot demonstration at 1 MWth scale provides engineering confidence for scale-up to commercial 50 MWth units. With an estimated CO_2 avoidance cost of $45-60/t CO_2, CaL-BECCS cement is economically viable under the EU Emissions Trading System carbon price and represents a critical technology for reaching net-zero industrial emissions.

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