CO_2 capture, liquefaction, and storage: Evaluation of a pilot-scale CO_2 value chain at a cement plant

Introduction

Denmark aims to achieve net-zero emissions by 20245, setting an ambitious benchmark for the decarbonization of energy-intensive industries. Cement production represents one of the most challenging sectors due to its CO_2 emissions originating from limestone calcination and fuel combustion. Even with energy efficiency improvements, a significant fraction of the CO_2 emissions remains unavoidable. Carbon capture and storage (CCS) is therefore a critical technology for deep carbonization of the cement industry and for meeting the national climate target.

Successful large-scale CCS deployment requires not only efficient CO_2 capture but also reliable integration of the entire value chain. In this context, CO_2 quality management has emerged as a key technical and regulatory consideration. Impurities originating from flue gas composition, solvent degradation, and process interactions may affect the CO_2 value chain from liquefaction to transport to storage. Despite this importance, limited experimental data exists on impurity evolution across an integrated CCS chain operated under real cement plant conditions.

The CASPER project (Cement cArbon Storage Pilot for Emission Reduction) addresses this knowledge gap by demonstrating, for the first time in Denmark, a complete pilot-scale CCS value chain applied to a cement production facility. The project aims to generate high-resolution operational and compositional data to support the design, optimization, and scale-up of CCS systems. A central objective is the systematic evaluation of CO_2 purity from the point of capture through liquefaction and intermediate storage.

Method

An integrated pilot-scale CO_2 capture and liquefaction system was installed at the cement facility Aalborg Portland, Denmark. The flue gas from Aalborg Portland is characterized by approximately 18 vol% CO_2, and impurities such as NOx, SOx, CO, and dust.

The capture unit is a mobile amine-based thermal system with a capacity of up to 1 t CO_2/day (Figure 1A), which has a proven track record of capturing CO_2 from various sites such biogas, waste-to-energy plant, biomass combustion site, and cement production and of reducing the energy consumption [1-11]. The process employs a modified CESAR1 solvent consisting of 27 wt% 2-amino-2-methyl-1-propanol (AMP) and 6-7 wt% piperazine (PZ). The solvent formulation was selected to prevent solid formation during process operation. CESAR1 is known for its favorable kinetics, and relatively low regeneration energy demand compared to 30 wt% monoethanolamine (MEA).

Flue gas is first conditioned and cooled before entering the absorber column, where CO_2 is selectively absorbed into the solvent. The CO_2-rich solvent is regenerated in a stripper column, releasing high-purity CO_2. The regenerated lean solvent is recycled to the absorber, enabling continuous operation.

Following desorption, the CO_2 stream is directed to a liquefaction unit (Figure 1B) with a production capacity of 15 kg h^{-1}. The liquefaction process involves multi-stage compression, cooling, and phase separation to produce liquid CO_2. The liquefied CO_2 is stored in a 2-tonne intermediate storage tank (Figure 1C) under controlled temperature and pressure conditions.

This configuration enables evaluation of impurity behavior not only immediately after capture but also after phase change and during storage. Sampling points were established upstream and downstream of the liquefaction unit, as well as at the storage tank outlet, to allow tracking of impurity across process stages.

Figure 1 *Overview of the process equipment included in the test unit located at Aalborg Portland. A) CO_2 capture pilot plant, B) CO_2 liquefaction, and C) temporary CO_2 storage.*

Results

In this work, we report results from more than 2,000 hours of continuous operation at the Aalborg Portland cement production plant. The campaign provides comprehensive insight into the fully integrated operation of a pilot-scale CO_2 capture unit combined with downstream liquefaction and intermediate CO_2 storage. The study therefore demonstrates critical components of a complete CCS value chain under real industrial conditions, where process fluctuations, flue gas variability, and operational constraints reflect those expected in full-scale cement production.

The performance of the modified CESAR1 solvent is systematically assessed with emphasis on long-term operational stability, degradation pathways, solvent management, and atmospheric emissions from the depleted flue gas. Attention is given to understanding degradation mechanisms under cement-specific flue gas compositions and their inferences for solvent lifetime and operational reliability. In parallel, detailed CO_2 impurity profiles are established across the capture, liquefaction, and storage stages to evaluate the suitability of the CO_2 stream for transport and permanent storage. Trace components in both the treated flue gas and the CO_2 product stream are continuously monitored using Fourier-transform infrared spectroscopy (FTIR) and proton-transfer-reaction time-of-flight mass spectrometry (PTR-TOF-MS), enabling high-resolution tracking of volatile and semi-volatile species.

The results demonstrate stable long-term solvent performance and effective emission control. Importantly, solvent-related carry-over from the CESAR1 system into the CO_2 product stream is found to be negligible. This confirms the robustness of the capture process and the effectiveness of downstream liquefaction and conditioning in delivering a CO_2 stream that meets quality requirements for transport and storage applications.

Conclusions

The CASPER project delivers Denmark's first pilot-scale demonstration of a CCS value chain applied to cement production. Through more than 2,000 hours of integrated operation at Aalborg Portland, the project provides unique and comprehensive data on solvent performance, emission control, and CO_2 impurity evolution from capture through liquefaction and intermediate storage.

These results represent an important step toward enabling large-scale CCS deployment as part of Denmark's pathway to climate neutrality by 2045.

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