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How to cost-effectively achieve net-zero CO_2 emissions for cement industry with CCS?

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Abstract

1. Introduction

Carbon capture and storage (CCS) units are traditionally designed to achieve ~90% carbon capture rate, leaving ~10% of direct CO_2 emissions as residual emissions[1]. While it is technically feasible to design CCS for higher capture rates to further reduce or eliminate residual emissions[2], doing so incurs increasing marginal costs. Achieving net-zero emissions requires compensating for residual and indirect emissions either through purchasing carbon offsets or by implementing carbon dioxide removal (CDR) technologies such as direct air capture (DAC). However, DAC technologies are currently expensive, with costs ranging from \$700–\$1000 per ton of CO_2, with future estimates varying between \$200–\$600per ton of CO_2 [3] . Given this uncertainty, it is crucial to evaluate the trade-offs between CO_2 capture levels, CO_2 offsets, and alternative approaches to achieving net-zero emissions in different carbon-intensive sectors.

This study assesses the costs associated with reaching net-zero emissions in a cement plant emitting flue gas with an 18% CO_2 concentration [4]. Three different mitigation pathways are considered (Figure 1):

Case 1: Combining CCS with the offsetting of residual emissions through CDR credits

Case 2: Operating CCS at a capture rate high enough to directly achieve net-zero emissions

Case 3: Integrating CCS and DAC, where the CCS outlet gas is processed through a DAC unit

While case 1 and 2 are well-established pathways, case 3 introduces a novel approach that leverages DAC's capability to separate CO_2 from dilute streams but at higher CO_2 concentrations than atmospheric air. This approach

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offers potential benefits in terms of kinetics and cost reduction. Additionally, a hybrid CCS-DAC design allows for on-site upscaling of DAC to capture CO_2 from CCS outlet gases while also removing additional CO_2 from air to compensate for indirect emissions.

2. Carbon Capture Technologies and Challenges

Regarding CCS technology, this study considers both membrane-based separation and amine scrubbing [5] . While amine scrubbing is the most mature CCS technology, it requires significant heat input, which is not available as excess heat on-site. To operate at high capture rates, an external heat source such as a boiler is needed, which might in turn reduces the total CO_2 avoided and increases the demand for CO_2 offsets. Although membrane-based separation is well-suited for cement plant emissions due to the relatively high CO_2 concentration in flue gas, membranes face limitations in achieving high capture rates[6] and require substantial electricity input, which can further increase CO_2 offset requirements if the electricity supply has a high carbon footprint.

Given these challenges, DAC technologies are explored as complementary solutions in options 1 and 3. Two of the most established DAC processes are considered in this study: solid sorbent DAC (S-DAC) [7]and liquid solvent DAC (L-DAC) [8].

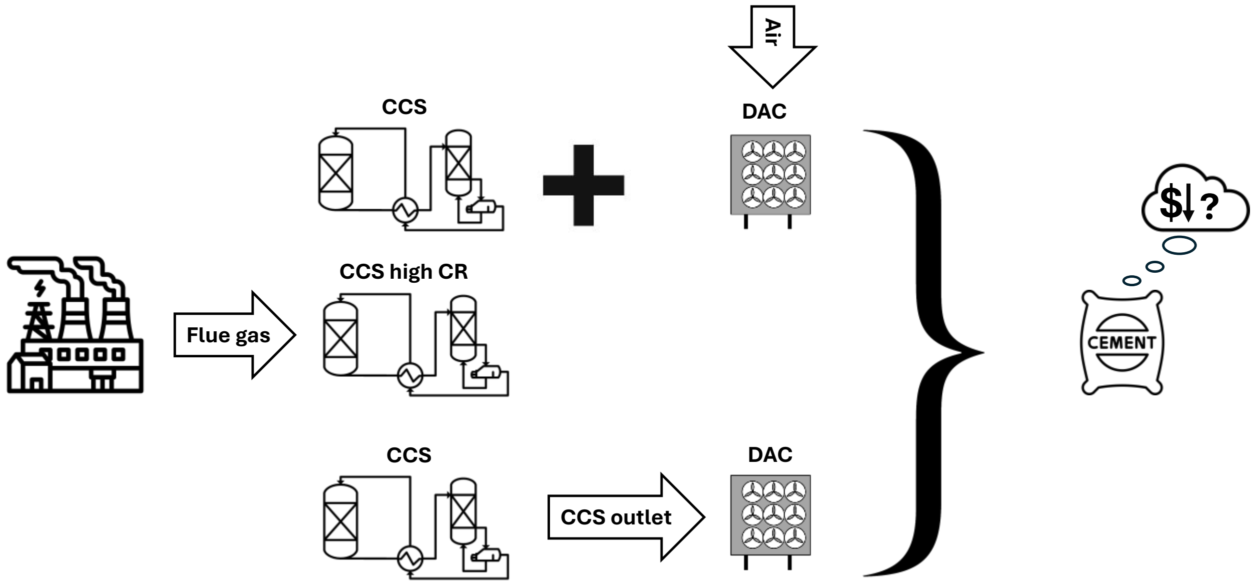

Figure 1: Pathways to net-zero emission cement production considered in this work.

3. Methodology

This work used a steady-state model to close mass and energy balances for amine scrubbing and L-DAC processes. A multi-stage membrane modelling framework was used to optimize membrane-based CCS design and evaluate mass and energy requirements [6]. Additionally, a dynamic model implemented in gPROMS was used to simulate mass, momentum, and energy balances for the S-DAC process. The CO_2 compression and liquefaction processes were also modelled to design layouts compatible with the requirements for CO_2 transport and storage in the Northern Lights project [9]. The steady-state models are developed using Aspen Plus.

To estimate the additional cost of cement production under net-zero CO_2 emissions, the study considers: i) The cost of capturing CO_2 from the flue gas stream. ii) The cost of offsetting residual and indirect emissions

For case 2, the capture rate is determined based on the CO_2 concentration in flue gas streams. For cases 1 and 3, the optimal CCS capture rate is established to minimize the additional cost of cement production. Sensitivity analysis is performed to account for the carbon footprint of heat and electricity supply, as these factors significantly influence cost optimization.

4. Expected results and Implications

The results provide insights into the cost-effectiveness of the three pathways for achieving net-zero CO_2 emissions in cement production. These findings can inform policies on the allocation of negative emissions and the eligibility of negative emission certificates. Furthermore, this study establishes a cost threshold for electrification technologies to become viable alternatives in the cement industry.

By assessing different pathways and considering the trade-offs between capture rates and offsets, this study contributes to the ongoing discussion on decarbonizing cement production and achieving net-zero emissions efficiently.

Keywords: Carbon capture and storage, direct air capture, carbon dioxide removal, technoeconomics, Net-zero, Cement.

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