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Electrifying Post Combustion Carbon Capture: How Future Energy Scenarios Reshape Techno-Economic Performance

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Abstract

Post-combustion carbon capture (PCCC) using amine-based solvents, particularly monoethanolamine (MEA), has long been considered the industry benchmark for CO_2 mitigation in energy-intensive sectors. Despite its technical maturity and demonstrated capture efficiencies, the MEA process remains inherently constrained by its high energy intensity, specifically the low-grade thermal energy required for solvent regeneration. This energy penalty often necessitates additional fossil fuel combustion, commonly natural gas, leading to increased operational expenditures (OPEX) and additional CO_2 emissions. As a result, mitigating emissions through MEA scrubbing inadvertently exacerbate fuel demand and carbon intensity, thus challenging the long-term sustainability of this approach in decarbonization strategies for hard-to-abate industries.

This study explores a transformative alternative: electrification of PCCC, grounded in the hypothesis that leveraging low-carbon electricity could significantly reduce both the energy penalty and direct and indirect emissions associated with conventional post-combustion capture. The aim of this work is to determine the impact of the electrification on the feasibility of PCCC. To contextualize this investigation, the cement industry is selected as a reference case, representing one of the most carbon- and energy-intensive sectors globally. Cement plants not only demand high-temperature thermal energy, but also produce substantial process-intrinsic CO_2 emissions from calcination [1], making them an archetypal example of industrial decarbonization complexity. Insights derived from this sector can thus inform broader applications across other energy-intensive industries such as lime, steel, and glass.

A comprehensive suite of electrified PCCC pathways is systematically evaluated and compared, including:

- Electrically powered steam generation via high-efficiency electric boilers for MEA solvent regeneration;
- Integration of high-performance heat pumps for low-grade heat recovery and valorization within the MEA cycle;

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- Oxy-combustion processes with downstream cryogenic CO_2 purification units (CPU);
- Cryogenic CO_2 capture using renewable electricity-powered refrigeration cycles;
- Adsorption-based capture processes, including Vacuum Pressure Swing Adsorption (VPSA) and Vacuum Temperature Swing Adsorption (VTSA), utilizing electrically driven compressors and vacuum pumps;
- Membrane-based separation units with electricity-based compression systems.

To ensure a comprehensive and robust evaluation, the decision support framework developed by Salman et al. [2] was utilized. For this purpose, equation-oriented models were developed in Lua code, incorporating detailed mass and energy balances as well as techno-economic parameters. These models were informed by process simulations developed in Aspen Plus®, complemented by additional data from literature to capture the performance and cost characteristics of the various capture options. Once the necessary data was integrated, the OSMOSE platform [3] was used to implement the process integration and optimization, enabling a comparative assessment using different performance indicators. This approach allows the simultaneous evaluation of multiple decarbonization pathways under consistent boundary conditions and supports adaptive scenario analysis. The performance of each configuration is assessed using three key techno-economic indicators: Specific primary energy consumption per ton of CO_2 avoided (SPECCA), the specific cost of CO_2 avoided (€/tCO_2), and the levelized cost of clinker (€/t clinker). Furthermore, to evaluate the feasibility of electrified carbon capture under evolving energy markets, prospective scenarios were constructed using projections and studies from European energy distributors and research institutes such as Elia [4], ENTSO-E [5], EnergyVille [6], Climact [7] and others. These scenarios account for uncertainties in electricity and natural gas prices, CO_2 taxation evolution, and emerging policy support for electrification and carbon capture technologies.

The study aims to articulate strategic insights for policymakers, industrial stakeholders, and researchers. It sheds light on the threshold conditions under which electrified carbon capture pathways can outperform conventional ones. Other important aspects include the value of grid decarbonization in enabling viable low-emission industrial processes, the role of process integration and thermal recovery in boosting overall efficiency, and the potential trade-offs between capital intensity and operational flexibility inherent in electrified systems. It contributes to the emerging paradigm shift from fossil-driven carbon capture toward integrated, electrified, and low-carbon process systems.

Keywords: Electrified carbon capture; Cement industry decarbonization; Techno-economic analysis; Cryogenic separation; Heat pumps; Electrification pathways; Scenario analysis.

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