

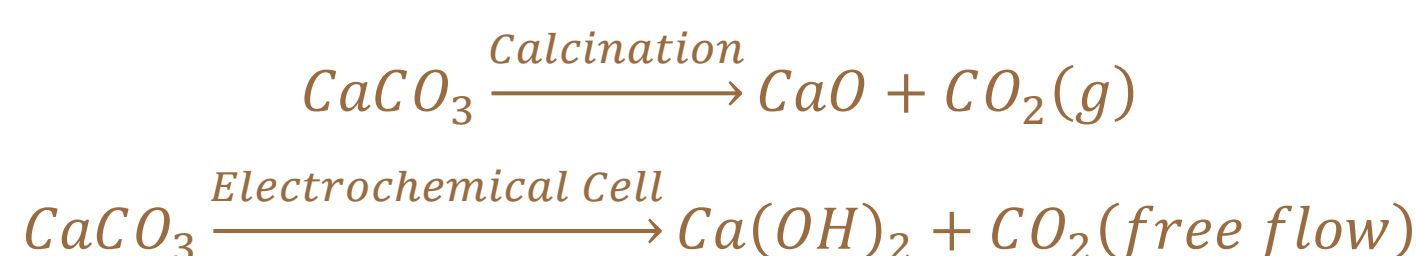
Replacing Calcination with Electrochemical Decarbonation: A Life Cycle Perspective for Cement Production

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INTRODUCTION & AIM

The clinker production process accounts for approximately 8% of global CO₂ emissions. In the conventional CaCO₃ calcination process, around 525–550 kg of CO₂ are released per ton of clinker, the main constituent of cement. This CO₂ generated is intrinsic and non-recoverable in the calcination reaction [1–5]. In recent years, electrochemical manufacturing has emerged as a promising pathway to decarbonize traditional high-temperature processes in the chemical industry, offering routes that integrate CO₂ recovery and renewable-powered electrochemical conversion [3,6]. Therefore, it has been proposed to replace the thermal calcination of CaCO₃ with an electrochemical reaction that produces H₂ (energy carrier) and CO₂ (recoverable stream) [3,4].



The research aims to evaluate, from a life cycle analysis perspective, the replacement of calcination process by the electrochemical decarbonation route for CaO production in clinker manufacturing.

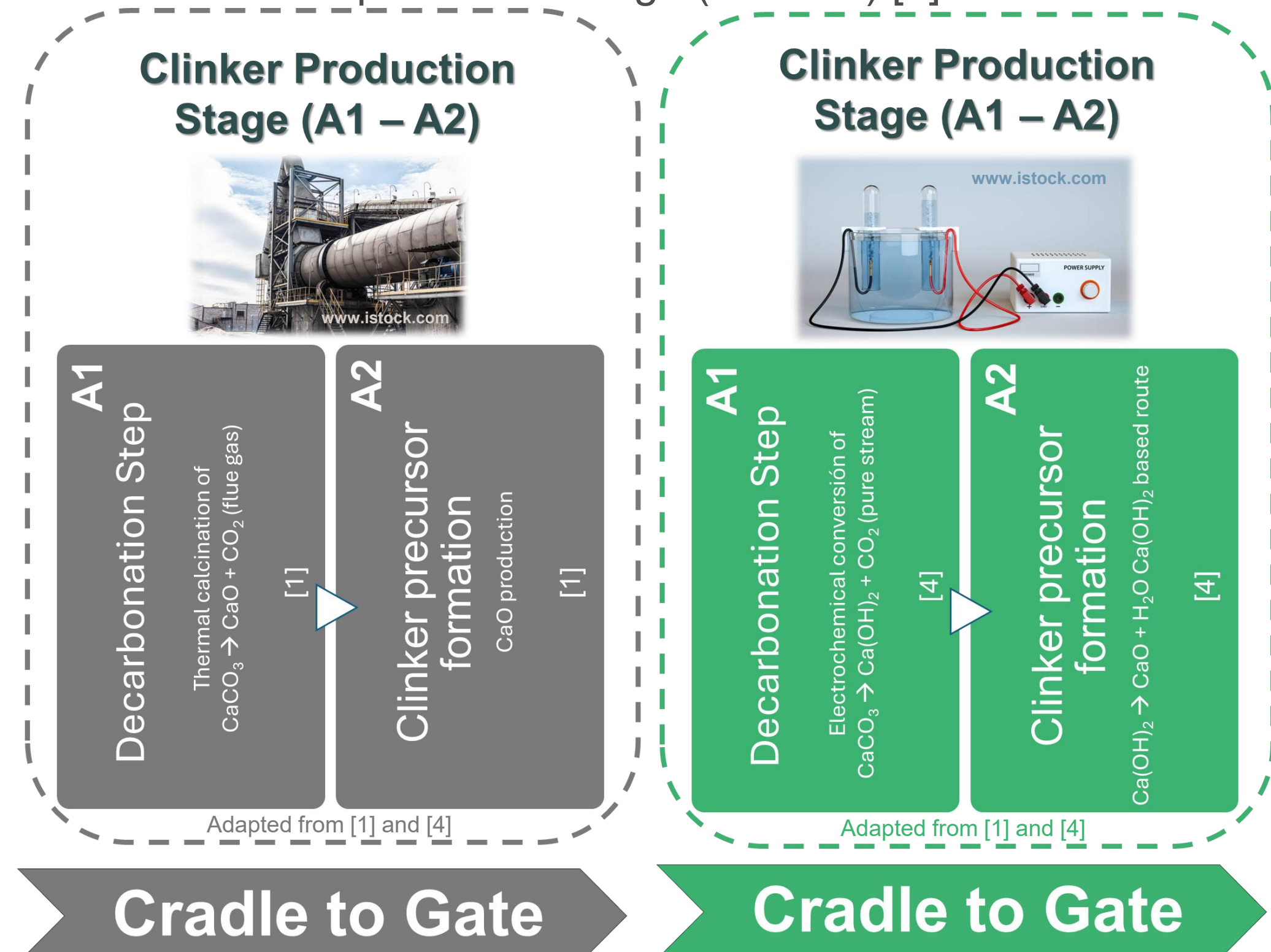
METHOD

System Boundaries and Inventory Assumptions

The analysis considers the Clinker production stage (A1–A2) within a cradle to gate system boundary. Three routes were compared: conventional calcination, electrochemical decarbonation, and a Ca(OH)₂ – based pathway. The functional unit is 1 ton of Clinker. Only process – and energy – related CO₂ emissions were included. Data from Ellis et al. [1] and Martínez et al. [4] were used, with yields (CHy 52 – 80%) and CO₂ reduction efficiencies (52 – 90%) applied.

Energy demand for the electrochemical route was scaled from laboratory data [1] to an industrial adjusted value of 3.2 MWh t^{−1} clinker, using efficiency benchmarks from mature electrochemical industries such as chlor – alkali [6,7] and molten – oxide electrolysis [8]. Only process and electricity – related CO₂ emissions were included, considering a constant energy carbon intensity of 0.1 kg CO₂ kWh^{−1}. System boundaries and inventory assumptions for the clinker production stage (A1–A2) are illustrated below.

Figure 1. System boundaries for the clinker production stage (A1 – A2) [9]



RESULTS & DISCUSSION

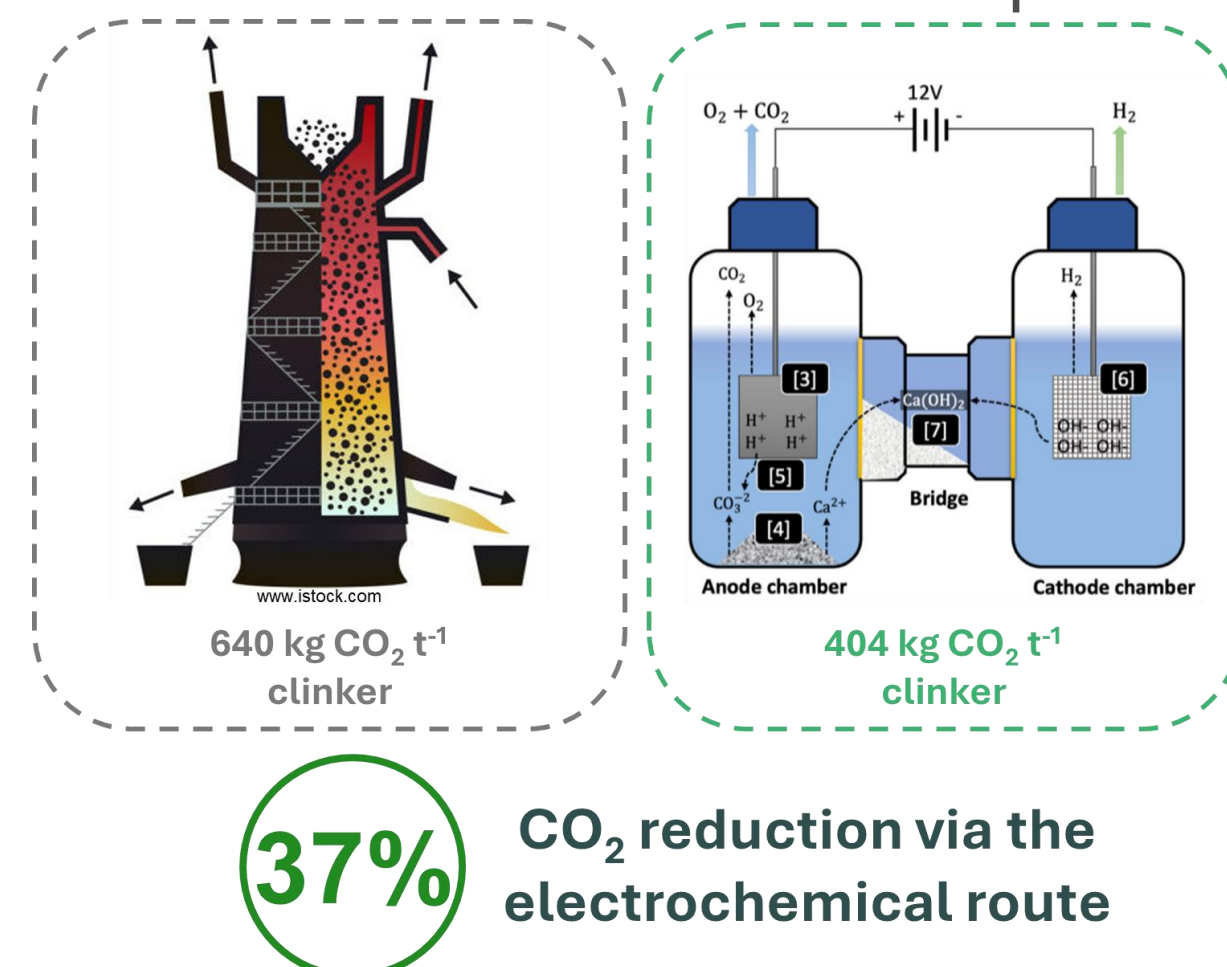
Industrial-adjusted estimates, which include the dehydration step (Ca(OH)₂ → CaO) were benchmarked using data from Martínez et al. [4], supported by insights from emerging electrochemical decarbonization technologies [6] and established high-temperature electrolysis systems [7,8]. The scaling assumes that the laboratory energy demand (10.04 MWh t^{−1} clinker) decreases proportionally with cell-efficiency improvements from ≈ 26% to 75–90%. This adjustment yields an estimated industrial consumption of ≈ 3.2 MWh t^{−1}, consistent with mature electrochemical benchmarks such as chlor-alkali and molten-oxide electrolysis [7,8]. The resulting energy and CO₂ emission estimates are summarized in Table 1.

Table 1. Energy demand and CO₂ emissions for conventional and electrochemical routes to produce CaO (per ton of clinker).

Process route	CO ₂ from reaction (kg t ^{−1})	CO ₂ from energy (kg t ^{−1})	Energy (MWh t ^{−1} Clinker)
Conventional Calcination	540	100	1.0
Electrochemical (industrial-adjusted)	54	350	3.5

Note: The residual CO₂ emissions reported for the electrochemical route (~54 kg t^{−1} clinker) originate from the partial decomposition of unreacted carbonate in the particulate material (PM), rather than from fuel combustion. The total includes the additional 0.3 MWh t^{−1} required for Ca(OH)₂ dehydration to obtain CaO [10–12].

Figure 2. CO₂ emission reduction potential of the electrochemical route in clinker production



Data adapted from Martínez et al. [4] and this study

Figure 2. Comparison of process-related CO₂ emissions for conventional calcination (gray) and the electrochemical decarbonation route (green). The electrochemical pathway, including the dehydration step (Ca(OH)₂ → CaO), achieves a 37% reduction per ton of clinker due to CO₂ recovery and the absence of fuel combustion.

CONCLUSION

The electrochemical decarbonation route demonstrated a 37% reduction in total CO₂ emissions compared to conventional calcination, even when including the dehydration of Ca(OH)₂ to CaO. This reduction is mainly attributed to the elimination of fuel combustion and the potential recovery of concentrated CO₂. While current energy requirements remain similar to thermal routes, further efficiency improvements and renewable electricity integration could enable a near-zero –carbon pathway for clinker production

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