

Optimization of Energy Transition Pathways in the Lime Industry: A Superstructure Approach

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Abstract:

Lime manufacturing is a hard-to-abate industry, owing to high-temperature heat requirements and process-related CO₂ emissions from limestone calcination. Although numerous mitigation technologies have been proposed, existing studies generally evaluate individual options or rely on predefined economic scenarios, providing limited guidance for technology selection under uncertain future energy and carbon prices. This study presents a systematic techno-economic assessment of multiple decarbonization options, including fuel switching, electrification, and CO₂ capture (CC) with storage or utilization. A unified superstructure model is coupled with scenario analysis and a parameter sweep of key energy and CO₂ prices to assess robustness under market volatility. Results show that the fuel switching alone achieves only 18% CO₂ emission reduction, making CC implementation inevitable for deep decarbonization. Implementing CC enables up to 78% emission reduction for fossil-based routes and net-negative emissions down to -0.22 tCO₂/t_{lime} for biomass-based configurations, at the expense of an energy penalty of 1.4–6.2 GJ/t_{lime}. Current economic conditions favor unabated and bioenergy-based production (€147–176/t_{lime} vs. €257–380/t_{lime} with CC), whereas CC becomes competitive only under high CO₂ pricing, achieving cost reductions up to 45% compared to the base case. Electrification and hydrogen-based production require very low-cost (≤€62/MWh) low-carbon energy to become competitive, whereas CCU remains constrained by its high energy demand (12.2 GJ/t_{lime}). Finally, oxycombustion appears as the most promising decarbonization pathway, as it consistently provides the best trade-off between energy penalty, CO₂ emissions, total cost, and robustness to market fluctuations, outperforming amine-based capture across all pricing scenarios.

Keywords: Lime industry; Industrial decarbonization; Energy transition; Superstructure optimization; Techno-economic assessment

1. Introduction

The ever-increasing greenhouse gases (GHG) emissions from human activities, inducing an atmospheric CO₂ concentration rise from 278 ppm in 1750 [1] to more than 424 ppm in 2024 [2], are reportedly responsible of climate change. To meet the Paris Agreement climate targets, global warming mitigation has become a major concern for many countries including Belgium. In 2024, industry represented 29% of the Belgian GHG emissions, whereas energy production accounted for 15% [3]. While the decarbonization of the power sector is progressing, with renewable sources representing 35% of the total electricity generation in Belgium in 2024 [4], hard-to-abate industrial sectors, such as steel, glass, lime or cement, representing approximately 20% of the global CO₂ emissions [5], are facing more challenges in terms of CO₂ emissions reduction due to high-temperature heat requirements and process-related emissions. However, addressing emissions in hard-to-abate industries is key for reaching the Fit-for-55 package [6] and European Green Deal [7] reduction targets.

Lime is an essential product used in a wide variety of applications [8]: construction (treatment of soils, hot mix asphalt, mortars, plasters), iron and steel-making (sinter strand process, impurity removal during the steelmaking process, desulfurization of pig iron), effluent treatment (water pH adjustment, acidic gases removal from flue gases), agrifood (insecticides and fungicides, sugar beet and sugar cane refining), chemicals production (source of calcium, causticizing agent, flocculant, hydrolyzing agent), etc. However,

the lime sector is a major CO₂ emitter, which represents alone around 1% of the global anthropogenic CO₂ emissions [9]. In 2024, the European CO₂ emissions of the lime industry amounted to approximately 21.5 MtCO₂, 6.5% of which can be attributed to Belgium [10].

Lime manufacturing is an energy-intensive process, with more than 90% of the energy demand associated with limestone calcination [11]. To date, significant effort has been dedicated to enhancing process efficiency by investing in best available kiln technologies and optimizing fuel consumption [12], reaching a European average thermal efficiency for lime production of 88% in 2023 [13]. However, with the calcination reaction alone emitting about 0.8 tCO₂/t_{lime}, significant efforts are still required to achieve net-zero or net-negative emissions in the lime industry, as noted by the European Lime Association (EuLA). State-of-the-art decarbonization strategies, identified by Simoni et al. [14], include fuel switching, electrification, and CO₂ capture (CC).

Different alternative fuels are envisaged to substitute fossil fuels like coal and natural gas, namely waste-derived fuels (plastics, paper or textiles [15]), biomass (grape seeds, olive stones, almond shells [15] [16], coconut cores, sugar can, rice hull [17], biodiesel, biogas, biomethane [18]), e-fuels, and hydrogen [12] [13]. About 16 lime kilns in Europe are currently known to operate using finely ground wood as fuel [17]. Electrification of cement and lime kilns is also gaining interest [13] [19]. Indeed, the patented Electric Arc Calciner (EAC) technology, developed by SaltX and relying on a plasma generator providing high-temperature heat (>1600°C), has already been demonstrated on a 300 kW pilot-scale in 2022. It has been upscaled to a 2 MW electric kiln pilot commissioned in Sweden in November 2023 in the framework of the ZEQL project [20]. Following successful results, SaltX and SMA Mineral are aiming for full-scale production by 2027. The project reached technology readiness level (TRL) 7 [17], while the construction of a 40,000-ton-per-year pilot plant is expected for 2026 [21] [22]. Nevertheless, due to the fact that the majority of CO₂ emissions are intrinsic to the calcination reaction, fuel switching and electrification alone are not sufficient for significant emissions abatement, thus, implementation of CO₂ capture (CC) seems unavoidable.

Various CC technologies are studied for lime kilns, including absorption, membrane separation, adsorption, direct separation, oxy-fuel combustion, and cryogenic separation [14]. The absorption-based CO₂ capture process entails contacting a gaseous effluent with a liquid solvent, the so-called absorbent, in a gas-liquid contactor. The selective dissolution of CO₂ in the absorbent leaves a CO₂-lean gas at the top of the column. A regeneration step of the CO₂-rich solvent enables the release of the captured CO₂ (which can then be transported for geological sequestration or used) and the recycling of the solvent back to the absorption column [23]. Absorption is characterized by a capture efficiency of ≥90% and a recovery of >99% pure CO₂ [24] [25]. Amine-based CO₂ capture is studied by Lhoist, Arcelor Mittal, TotalEnergies and IFP Energies Nouvelles in the DINAMX project, in which lower energy requirements for the regeneration step have been achieved by using a special de-mixing amine blend. A lab scale pilot has been validated for lime kiln flue gases, reaching TRL 7 [17]. The use of selective permeable membranes for post-combustion CO₂ capture is an interesting alternative to absorption thanks to its low CAPEX and OPEX, slow performance degradation, and easy installation and transport. Membrane-based separation is still at research or development stages. [26]. Even if this technology has not been tested yet in a lime plant, the Norcem CO₂ capture project (2013-2017, in Brevik, Norway) demonstrated at pilot scale the possibility of CO₂ capture from cement plant flue gases (similar in composition to lime kiln fumes [14]) with a polyvinylamine hollow fiber membrane [26] [27]. Adsorption processes for CC consist in contacting a gaseous effluent with solid adsorbents, leading to selective (physical or chemical) CO₂ adsorption on the adsorbent's surface [26]. Typical adsorbents include activated carbon, (natural or synthetic) zeolites, and metal-organic frameworks [24]. Once saturation is reached, the captured CO₂ is released by temperature or/and pressure swing, thus regenerating the adsorbent. Typical capture efficiency of adsorption-based CC lies between 70 and 95% [24]. CC by adsorption, with polyethyleneimine loaded on silica, was studied at the Brevik cement plant in 2016 by the Research Triangle Institute, demonstrating capture rates of 80–90% [26]. Meanwhile, oxycombustion, i.e., fuel combustion in pure oxygen instead of air, is considered as one of the most promising decarbonization routes for the lime sector [18]. Oxy-fired lime production was investigated in the Zero-Carbon Lime (ZERCAL) pilot plant. The increased CO₂ concentration in the flue gases (>80 vol%)

enables an easier CO₂ capture with a cryogenic CO₂ purification unit (CPU) [12] [26] [28]. The ZERCAL pilot plant (3000 t_{lime}/y), located at Singleton Birch's Melton Ross site, reportedly operated under oxycombustion conditions and captured all the CO₂ generated during lime production process [16]. Oxycombustion is also being studied in the Butterfly project, which aims to reach TRL 8 by 2026 [17]. In 2024, Carmeuse commissioned an in-house oxyfuel pilot kiln in Seilles, Belgium [17]. Following encouraging results, Carmeuse's ambition is to capture CO₂ at all its production sites by the end of 2028 [29]. Within the framework of the EVEREST project, involving Rheinkalk GmbH and Air Liquide, oxyfuel kilns concentrating CO₂ will be developed, which will reduce energy consumption and increase capture efficiency. The EVEREST project is planned to enter into operation in September 2031 in Flandersbach, Germany. It targets achieving TRL 8 and the capture of more than 1,000,000 tCO₂/y [30]. Finally, cryogenic CO₂ capture consists in cooling flue gases at low temperature to exploit differences in condensation or sublimation points and separate CO₂ from other gases. The rising interest in cryogenic CO₂ capture can be explained by the absence of chemical solvents, the high capture efficiency (90–99%) and the high product purity (>99%) associated with such processes [31] [32]. Within the CalCC project, Lhoist targets capturing and sequestering 600 ktCO₂/y thanks to Air Liquide's Cryocap™ FG cryogenic separation technology [13] [33]. The CalCC project will cover CO₂ capture, transport, and offshore geological storage, and is expected to enter into operation by March 2029 at Lhoist Group's site in Réty, France [34]. TRL 8 is targeted [17]. End-of-pipe cryogenic CO₂ capture is also investigated in the Saturn project, through a mobile CO₂ capture pilot. The project, launched in 2024, is funded by the European Union and involves Aperam, AGC, Prayon, CRM Group, Vocsens, UMONS, and ULiège [35] [36]. TRL 7 is targeted.

More recently, hybrid solutions are also investigated. Carmeuse's LEOPARD project, which started in April 2026, will combine an oxy-fired lime kiln (for CO₂ pre-concentration in the fumes) with a membrane-based CO₂ capture unit [37]. By using bioenergy (biogenic carbon) and permanent sequestration, negative emissions are expected. The demonstration pilot of 80,000 t_{lime}/y will be located in Aisémont, Belgium, and is expected to enter into operation by the end of 2031 [38]. The ambitious CARBON HUB CPT01 project will combine end-of-pipe pressure swing adsorption (PSA) and cryogenic carbon capture [39]. Its key innovation is a first-of-a-kind shared system that simultaneously treats flue gases from cement and lime production facilities. This integrated configuration is expected to reduce electricity demand and achieve more than 30% savings in capital expenditure compared with standalone installations. Located in Câmpulung, Romania, the project targets the annual production of approximately 2,000,000 tons of near-zero cement and 200,000 tons of near-zero lime. Its entry into operation is planned for the end of 2031 [40] [41].

Although CO₂ is typically captured for geological sequestration, some CO₂ Capture and Utilization (CCU) projects have also been launched over the years: LOWCO₂ (2019–2022, involving Lointek and Calcinor, and investigating captured CO₂ conversion towards methane or methanol), Neutral Kero Lime (2022–2026, involving industrial (such as Lhoist) and academic partners (such as ULiège and UMONS) aiming at producing e-kerosene from CO₂ captured from lime kilns), CO₂ncrEAT (2023–2033, involving Lhoist, Prefer, Orbix, and Fluxys, and aiming at CO₂ mineralization for sustainable building blocks production), or Columbus (involving Engie, Carmeuse, and John Cockerill, and aiming at converting captured CO₂ into e-methane) [16]. The latter has been cancelled in 2024 due to high energy costs and regulatory uncertainties [42].

Based on the numerous projects previously mentioned, the lime industry is faced with a wide variety of CO₂ emission mitigation pathways. However, these studies focus on isolated solutions or predefined economic scenarios. As a result, there is a lack of techno-economic assessments that systematically evaluate and compare competing decarbonization options for the lime sector while considering uncertainties associated with future energy and carbon prices. This limitation is particularly important for decision-makers, as pathway attractiveness may vary significantly depending on developments in the global geopolitical landscape and regulatory shifts.

To address this gap, the present study offers a comprehensive techno-economic comparison across multiple options, namely fuel switching, electrification, CO₂ capture and storage (CCS), and CO₂ capture and utilization (CCU). Unlike previous assessments that typically examine individual technologies or a limited set of predefined scenarios, this work integrates all candidate options within a common superstructure framework based on the methodology developed by Salman et al. [43]. This approach enables a consistent evaluation and comparison of alternative configurations using key performance indicators such as energy demand, CO₂ emissions, and costs, thereby offering a more robust basis for selecting emission mitigation pathways. Moreover, while techno-economic studies are typically derived from predefined scenarios regarding energy and carbon prices, the present work explicitly investigates the impact of energy and CO₂ cost volatility on economic performance and configuration ranking through a parameter sweep analysis. This enables the identification of optimal energy transition pathways, from an economic point of view, under a wide range of market conditions, aiming at the selection of resilient and cost-effective decarbonization strategies.

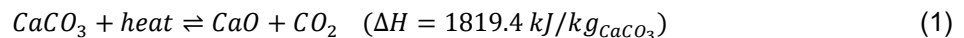
The objectives of this study are therefore: (i) to compare fuel switching, electrification, CCS, and CCU options for the lime industry based on technical, environmental, and economic indicators; and (ii) to evaluate the impact of energy and carbon price variability on pathway selection in order to support resilient and cost-effective decision-making by industrial stakeholders and policymakers. In addition, this work contributes to the development of INDECATE (indecate.com), a web-based decision-support tool for industrial decarbonization in sectors such as glass, cement, lime, and fertilizers.

2. Methodology

The methodology applied in this work consists of three main steps, namely (i) data collection, (ii) model development and validation, and (iii) superstructure optimization and analysis. First, a thorough literature review and data collection from open literature, including academic papers, institutional reports, e.g., International Energy Agency (IEA), European Lime Association (EuLA), Mineral Products Association (MPA), and the Best Available Techniques (BAT) reference document for lime sector [44], aim at collecting knowledge on the studied production process and the applicable emission mitigation pathways. These include energy efficiency improvement, fuel switching, process electrification, CCS, CCU, and bioenergy with CO₂ capture and storage (BECCS). The collected data are then used to develop detailed blueprints (BP) for lime production. BPs are equation-oriented models written in Lua language, consisting of detailed mass and energy balances, as well as economic considerations such as annualized investment and operating costs. Furthermore, model validation is conducted through the industry, ensuring physically informed, consistent results regarding the order of magnitude of several process KPIs including heat and electricity demand, as well as process emissions. Finally, the OSMOSE tool, developed by the IPESE group of École Polytechnique Fédérale de Lausanne (EPFL) [45], is used to evaluate and optimize the superstructure encompassing all the identified energy transition strategies. A systematic techno-economic comparison of the various lime production configurations is performed, based on technical, economic, and environmental aspects, using various key performance indicators (KPI) including specific energy demand (GJ/t_{lime}), CO₂ emissions (kgCO₂/t_{lime}), CAPEX (€/t_{lime}), and total cost (€/t_{lime}). Moreover, the impact of market volatility is assessed through a systematic parameter sweep analysis.

2.1. Lime production process description

After being extracted and processed, limestone, a natural mineral found widely around the world and consisting mainly of calcium carbonate (CaCO₃), is fed to the lime kiln where its calcination, i.e. thermal decomposition [8], according to reaction (1), produces quicklime (CaO), also called lime.



Limestone calcination, releasing $0.786 \text{ tCO}_2/\text{t}_{\text{lime}}$, is performed at high temperature ($900\text{--}1100^\circ\text{C}$), usually reached by fossil fuel combustion. Total energy requirements range from 3200 to 9200 MJ/t_{lime} [44], resulting in specific CO₂ emissions between 1 and 1.8 tCO₂/t_{lime} [14], and depend on the implemented kiln technology.

Common types of lime kilns include Parallel Flow Regenerative Kilns (PFRK), Annular Shaft Kilns (ASK), Mixed Feed Shaft Kilns (MFSK), Long Rotary Kilns (LRK), and Rotary Kilns with Preheater (PRK). Some less frequent kiln technologies include double-inclined shaft kilns, central burner shaft kilns, external chamber shaft kilns, multi-chamber shaft kilns, beam burner shaft kilns, flash calciner kilns, internal arch shaft kilns, rotating hearth kilns, and ‘topshaped’ kilns [8] [44]. According to a 2013 report of the European Commission [44], 90% of lime kilns installed in Europe were shaft kilns (551 kilns). From these 551 kilns, 158 were PFRK (29%), 116 were MFSK (21%), 74 were ASK (13%), and the remaining 203 kilns (37%) were “other” kilns.

The PFRK design is the predominant type of kiln used across the EU, combining maximal energy efficiency and minimal emissions. Fuel injection and conveyor belt operation require 20–40 kWh/t_{lime} of electricity, while heat use ranges from 3200 to 4200 MJ/t_{lime} [44] which represents specific CO₂ emissions between 1 and 1.2 tCO₂/t_{lime} [14]. The PFRK design depicted in Figure 1 consists of two shaft kilns connected by a cross-over channel. Each shaft kiln consists of three zones: the preheating zone (where limestone is preheated by direct contact with kiln gases, i.e., the products of combustion and excess air), the burning zone (where the calcination reaction takes place) and the cooling zone (where produced lime is cooled down to 100°C with cooling air, to avoid conveyor belt damage [46]). The operation of such a kiln takes place in two stages of 8–15 minutes. During the first stage, fuel is injected into the left shaft, through lances at the top of the burning zone, and its combustion takes place in a counter-current fashion with the cooling air being blown at the bottom of the shaft. Limestone calcination occurs at temperatures between 950°C and 1050°C . A mixture of off-gases and cooling air at around 1050°C is transferred through the crossover channel towards the right shaft, before being mixed with the cooling air from the bottom of this shaft and allowing the heating of the limestone in the preheating zone. The second stage (inversion) then begins and fuel is injected into the right shaft while flue gases are vented at the top of the left shaft [14]. Flue gas exits the kiln at relatively low temperature (120°C [44] [46]) and moderate CO₂ content (21 mol% [14]).

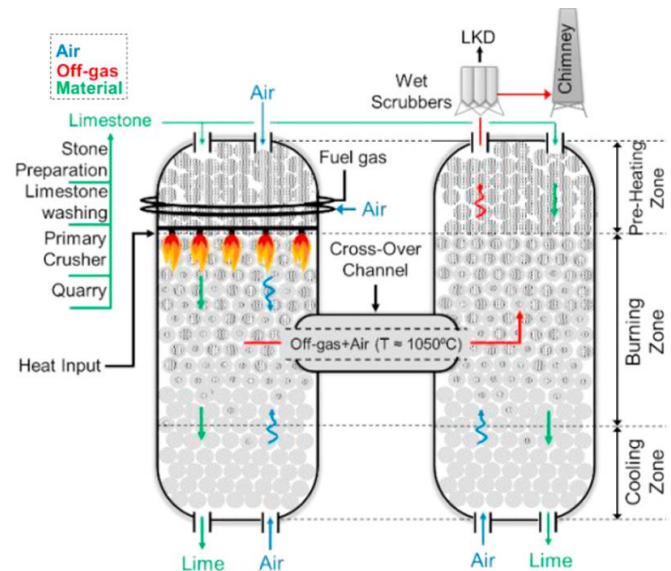


Figure 1: Schematic representation of a Parallel Flow Regenerative Kiln (Adapted from [14] under CC-BY license).

In Table 1, the model parameters used for the base case simulation, i.e., a natural gas-fired PFRK, can be seen.

Table 1: Model parameters for limestone calcination (base case).

Parameter	Value
Production capacity	240,000 t _{lime} /y
Limestone-to-lime ratio	1.94 kg _{CaCO3} /kg _{lime}
Limestone inlet temperature	25°C
Reaction temperature	1000°C
Flue gas temperature	120°C
Lime outlet temperature	100°C
Fuel type	Natural gas
Heat demand	3.49 MJ/kg _{lime}
CO ₂ generated by reaction	0.786 kg _{CO2} /kg _{lime}
CO ₂ generated by fuel combustion	0.172 kg _{CO2} /kg _{lime}
CO ₂ concentration	21 mol%
Electricity requirement	30 kWh/t _{lime}

2.2. Superstructure development

This decarbonization study focuses solely on the Parallel Flow Regenerative Kiln (PFRK) design, the most prevalent type of kiln in the EU, combining high efficiency (3200–4200 MJ/t_{lime} [44]) and minimal emissions (1–1.2 tCO₂/t_{lime} [14]). Several emission mitigation options for the lime sector are considered, including fuel switching towards low-carbon alternatives, kiln electrification, and CO₂ capture, use and sequestration. These transition pathways are consolidated within a single superstructure, illustrated in Figure 2, in which each colored dotted box represents a decision point.

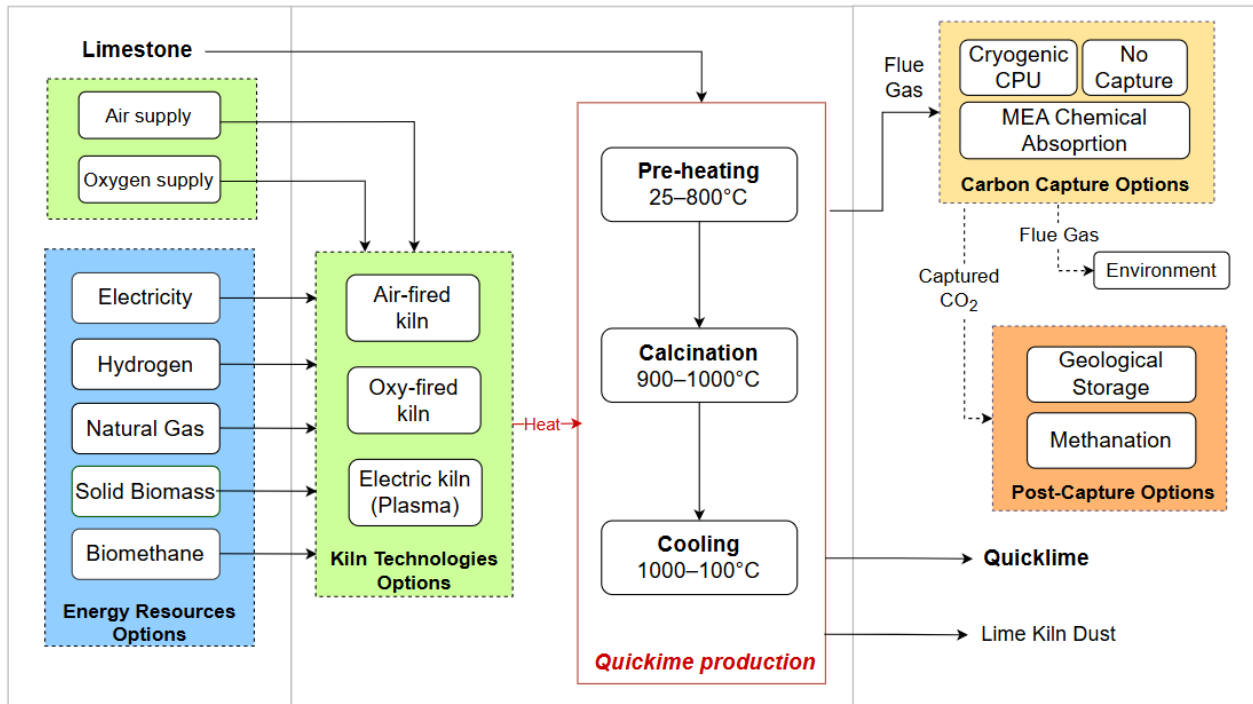


Figure 2: Superstructure of lime production encompassing fuel switching, electrification, CCS, and CCU routes.

The first decision relates to the energy resource used for heat supply to the lime kiln. The lime production base-case considers a natural gas air-fired kiln. To further reduce CO₂ emissions, kiln electrification with CO₂-based plasma torches can be investigated. An average thermal efficiency of 80% is considered in the plasma-based model [19]. Other fuel switching options include:

- *Biomethane* obtained by biogas upgrading or by biomass thermal gasification and methanation [47]. It can substitute natural gas in lime kilns without significant technological changes [18]. In this case, a 100% substitution of fossil gas is considered.
- *Hydrogen* utilization, instead of natural gas, avoids the fuel-related CO₂ emission. A typical hydrogen-fired kiln efficiency of 85% is considered [48] [49] .
- *Solid biomass* firing, instead of natural gas, avoids fuel-related (scope 1) CO₂ emissions. In this case, a 3% energy input increase, compared to a lignite-fired kiln (requiring typically 3.7 GJ/t_{lime}), is considered for a 100% fossil fuel substitution [18].

The second decision concerns the combustion mode for non-electric kilns. While fuel combustion in air is conventionally implemented, lime kilns can also be operated in oxycombustion mode, yielding higher CO₂ concentration in the flue gases (>80 vol%) [28], owing to the absence of inert nitrogen ballast, and enabling an easier subsequent CO₂ capture. However, additional electricity requirement for oxygen production by an Air Separation Unit (ASU) must be included, amounting to 226 kWh/t_{O₂} [50].

The third decision point deals with whether to emit CO₂ into the environment ('No capture' option) or to capture it via a suitable technology. The most mature CC technology is chemical absorption using amines such as monoethanolamine (MEA). In this work, the energy requirement and investment cost for CO₂ capture with amine (90% efficiency) and CO₂ compression up to 150 bar are based on correlations developed by Kim & Léonard [51]. Details are available in Supplementary Material (section S1). On the other hand, the cryogenic CPU, i.e. an electricity-driven cold box, is designed for highly concentrated flue gas streams. Therefore, it is chosen only for oxycombustion and electric kilns. It facilitates the CO₂ capture process, although entails an energy penalty of 0.35 kWh/kgCO₂ for 90% capture and further compression up to 150 bar [50].

Finally, post-capture CO₂ storage and utilization are also considered. Captured CO₂ can be permanently stored in geological formations, such as depleted gas fields and aquifers [52]. However, it can be also combined with hydrogen, produced on-site through water electrolysis, to produce e-methane (via methanation) substituting fossil fuel in the lime kiln. The lime kiln operates in oxyfiring mode and is supplied with oxygen coming from the electrolyzer.

The 12 steady-state lime production configurations studied are summarized in Table 2. More information about configuration selection is provided in Supplementary Material (section S2).

Table 2: Proposed configurations for lime production decarbonization.

Abbreviation	Configuration details
NG (base case)	Natural gas air-fired kiln without CC
NG-CC	Natural gas air-fired kiln with CC (chemical absorption)
NGOxy-CC	Natural gas oxy-fired kiln with CC (CPU)
Plasma-CC	Electric kiln with CC (CPU)
BioCH ₄	Biomethane air-fired kiln without CC
BioCH ₄ -CC	Biomethane air-fired kiln with CC (chemical absorption)
BioCH ₄ Oxy-CC	Biomethane oxy-fired kiln with CC (CPU)
H ₂ Oxy-CC	Hydrogen oxy-fired kiln with CC (CPU)
Biomass	Solid biomass air-fired kiln without CC
Biomass-CC	Solid biomass air-fired kiln with CC (chemical absorption)
BiomassOxy-CC	Solid biomass oxy-fired kiln with CC (CPU)
CCU	E-methane (from captured CO ₂ in CPU and electrolytic H ₂) oxy-fired kiln

2.3. Key performance indicators

In order to rank the proposed decarbonization pathways, the lime production routes are compared based on thermodynamic, environmental and economic key performance indicators (KPI), namely total energy demand, CO₂ emissions, initial investment, and total cost.

2.3.1. Energy demand

The specific energy demand (GJ/t_{lime}), calculated by Equation (2) represents the total energy required for producing one ton of lime for a given configuration. The metrics includes both fuel and electricity requirements for easier comparison across different production routes. However, the exact share of each energy vector is clearly represented in all figures. Depending on the studied configuration, energy demand may stem from kiln operation, as well as CC unit operation, oxygen production (ASU), and e-methane production.

$$\text{Spec. energy demand} = \frac{\sum_{u \in \text{units}} (Q_u + P_u)}{\text{ton of lime}} \quad (2)$$

where, Q_u and P_u represent, respectively, the fuel consumption and the electricity demand of unit u .

2.3.2. Direct and total CO₂ emissions accounting

During the lime production process, CO₂ is emitted from both the calcination reaction (“process emissions”) and fuel combustion for heat supply (“fuel-related emissions”). The sum of the process- and fuel-related emissions represents the direct (scope 1) CO₂ emissions of the lime production process. To evaluate this environmental indicator, the captured fossil CO₂ and the emitted biogenic CO₂ (e.g., from biomethane or solid biomass combustion) do not contribute to direct emissions, whereas captured biogenic CO₂ is accounted as negative emissions. Direct emissions can thus be computed according to Equation (3).

$$\text{Direct emissions} = \sum_{u \in \text{units}} (\dot{m}_{\text{NCF} \text{CO}_2, u} - \dot{m}_{\text{CBCO}_2, u}) \quad (3)$$

where $\dot{m}_{\text{NCF} \text{CO}_2, u}$ represents fossil CO₂ emitted by unit u that has not been captured and $\dot{m}_{\text{CBCO}_2, u}$ represents biogenic CO₂ that has been captured by unit u .

It should be noted that additional CO₂ emissions arise from limestone quarrying, and energy production and procurement. While indirect CO₂ emissions due to resource extraction (i.e., limestone, natural gas, and biomass supply chains) and biomethane production are assumed unchanged by 2050, the emission factor of electricity and hydrogen is expected to vary from 2025 to 2050. The Ecoinvent database [53] as well as scenarios for future European electricity mix [54] and global hydrogen production [55] are used to determine the indirect emissions of these supply chains. Further details are provided in Supplementary Material (section S3). Finally, total emissions combine both direct and indirect emissions.

$$\text{Total emissions} = \text{Direct emissions} + \text{Indirect emissions} \quad (4)$$

2.3.3. Capital expenditure and total cost

The Capital Expenditure (CAPEX) considers a greenfield situation without retrofitting costs and encompasses the equipment cost, as well as other additional necessary expenses such as installation, land exploitation and engineering design [51].

For each configuration, CAPEX related to the kiln, the ASU, the CC, and the methanation unit are added up. The specific CAPEX (€/t_{lime}) is computed according to Equation (5). The reference CAPEX ($\text{CAPEX}(u_{ref})$) is scaled up and updated to 2025 values through the Chemical Engineering Plant Cost Index (CEPCI) [56]. The scaled-up and updated CAPEX is finally annualized (€/y) and normalized with respect to annual lime production (t_{lime}/y). The parameters used for CAPEX estimation are provided in Supplementary Material (section S4).

$$Spec. CAPEX = \frac{\sum_{u \in units} \left[\left(CAPEX(u_{ref}) \cdot \left(\frac{S_u}{S_{u_{ref}}} \right)^{0.6} \cdot \frac{CEPCI_{2025}}{CEPCI_{ref}} \right) \cdot \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) \right]}{t_{time}/year} \quad (5)$$

where $CAPEX(u_{ref})$ is the reference cost of the unit, i is the discount rate, n is the project lifetime, and $S_{u_{ref}}$ and S_u are the reference and actual size of the units, respectively.

Moreover, Operational Expenses (OPEX) like electricity, fuel, cooling water, raw material, and CO₂ emission allowances are considered in the present study. The specific OPEX (€/t_{lime}) can be computed according to Equation (6). Although CO₂ emissions reduction by CC implementation reduces the respective emission costs, no additional revenue is considered when negative emissions are achieved. Furthermore, no free emission allowances are taken into account, assuming that the entirety of CO₂ emitted is subject to payment.

$$Spec. OPEX = \frac{[\sum_{u \in units} (\sum_{e \in en} (C_e \cdot \dot{Q}_{e_u}) + (C_{CO_2} \cdot \dot{m}_{em_u}) + \sum_{m \in mat} (C_m \cdot \dot{m}_{m_u})) + C_{T\&S} \cdot \dot{m}_{CC}] \cdot \Delta t}{\left(\frac{t_{time}}{year} \right)} \quad (6)$$

where C_e , C_{CO_2} , C_m , and $C_{T\&S}$ represent, respectively, the energy resources costs (i.e., natural gas, electricity, biomethane, biomass, and hydrogen), the European Emissions Trading System (EU ETS) CO₂ cost, the raw material prices (i.e., limestone, water), and the CO₂ transport and storage cost. The latter assumes onshore pipeline transport to the Belgian Zeebrugge terminal and offshore pipeline transport to the geological storage sites located in the North Sea [57] [58]. In addition, $\dot{Q}_{e_u}$ represents the energy demand of unit u (kW), $\dot{m}_{em_u}$ represents the net direct emissions of unit u (tCO₂/h), $\dot{m}_{m_u}$ represents the raw material demand of unit u (t/h), $\dot{m}_{CC}$ represents the captured CO₂ flow (tCO₂/h), and Δt represents the number of operating hours (8760 h/y).

For an economic comparison of the different CO₂ mitigation options, the specific total cost (STC, €/t_{lime}) is also introduced. This economic indicator accounts for both CAPEX and OPEX contributions. It should be noted that STC only provides an estimate of lime production costs for comparison between different decarbonization configurations and should not be interpreted as a prediction of current or future lime costs.

$$STC = spec. CAPEX + spec. OPEX \quad (7)$$

2.4. Energy and CO₂ costs

In the context of the energy transition, it is essential to select a technology that is not only cost-effective today but also remains viable in the future. To this end, a scenario-based analysis for present and future energy prices and CO₂ costs, and a combination of those prices to generate a set of economic conditions, have also been proposed.

2.4.1. Scenarios

First, each option is assessed for several pricing scenarios, reflecting present and future market conditions. Three different scenarios are explored: (i) the 2025 scenario which considers the current energy and CO₂ costs for a plant located in Belgium; (ii) the “ideal” scenario, where access to cheap electricity and bioenergy is combined with high CO₂ ETS price, representing the ideal driving force for industrial decarbonization; and (iii) the “competition” scenario which considers high CO₂ costs combined with increased bioenergy costs, reflecting the competition for limited bio-based energy vectors [59]. Energy and CO₂ costs in the different scenarios are summarized in Table 3. Other economic parameters assumed to be identical between all scenarios can be found in Table 4. Further details of cost estimation for CO₂ transport and storage (T&S) can be found in Supplementary Material (section S5).

Table 3: Commodities costs adopted for different pricing scenarios.

Costs	2025	Ideal	Competition
Electricity (€/MWh) ^a	194 [60] [61]	95	111

Hydrogen (€/MWh) ^b	83 [62]	81	135
Natural gas (€/MWh) ^c	50 [63]	55	55
Biomethane (€/MWh) ^d	84 [64]	54	168
Biomass (€/MWh) ^e	27 [65]	27	66
CO ₂ emission (€/t) ^f	75 [66]	300	200
CO ₂ T&S (€/t)	50	50	50

^a Cost estimates for the “ideal” and “competition” scenarios are sourced from [67]

^b The 2025 scenario assumes grey hydrogen. The “ideal” scenario considers the lowest estimate for green hydrogen price by 2050 according to [65], while the conservative 2050 estimate is considered for the “competition” scenario

^c Stable prices are assumed for natural gas

^d The “ideal” scenario considers the lowest cost estimate for biomethane according to [64]. The “competition” scenario assumes a twofold price increase reflecting the strong competition for bio-based resources in the future [59]

^e The 2050 estimates for local biomass and biomass imports are considered for, respectively, the “ideal” and the “competition” scenarios [65]

^f The CO₂ emission allowance cost is expected to drastically increase compared to current levels [65]

Table 4: Limestone, cooling water, and water costs.

Commodities	Cost
Limestone	0.02 €/kg [68]
Cooling water	0.4 €/GJ [51]
Water	6 €/m ³ [69]

Naturally, in the 2025 scenario, 2025-specific emission factors are considered. By contrast, the “ideal” and the “competition” scenarios adopt 2050 projections for emission factors, as these scenarios represent potential future economic and technical conditions.

2.4.2. Parameter sweep

The previous scenario-based analysis is subject to the assumed commodities prices. However, the high uncertainty about energy prices, due to changing global political landscape, availability limitations, and regulatory shifts, prevents the accurate identification of future optimal production routes. To avoid the limitations of predefined prices, a parameter sweep is also performed, which helps explore a broader set of economic conditions and identify the zones of economic optimality, i.e., minimal STC associated with each configuration. Economic parameters, such as energy prices, ETS price, and CO₂ transport and storage (T&S) cost, are systematically varied within ranges based on energy distributors and research institutes reports such as IEA [47], ENTSOE and ENTSG [54], EnergyVille [70], Elia [71], Clean Air Task Force [72], IRENA [73], Eurostat [60] [63], and the European Hydrogen Observatory [74]. The final parameter sweep values considered for analysis can be found below:

Electricity cost:	[10, 25, 50, 75, 100, 125, 150, 175]	€/MWh
Hydrogen cost:	[10, 25, 50, 75, 100]	€/MWh
Natural gas cost:	[10, 35, 55, 75, 100]	€/MWh
Biomethane cost:	[30, 50, 70, 90, 110]	€/MWh
Biomass cost:	[20, 35, 50, 65, 80]	€/MWh
CO ₂ cost:	[75, 100, 150, 200, 250]	€/t
CO ₂ T&S cost:	[25, 50, 75, 100]	€/t

For each of the 100,000 combinations resulting from the aforementioned pricing sets, a Mixed-Integer Linear Programming (MILP) optimization is performed to identify the configuration that minimizes the specific total cost (Equation (7)). To enable a concise visualization of the results, decision-rule tables are derived from a supervised machine-learning approach. These tables summarize the commodity price conditions under which each configuration is economically optimal and highlight the most robust solutions

(i.e., the configurations offering a high flexibility regarding energy prices and appearing as optimal under moderate conditions), which result in more confidence for future investment and deployment. Details about the development of decision-rule tables are provided in Supplementary Material (section S6).

3. Results and Discussion

In this section, the base-case and alternative lime production routes are first compared based on different thermodynamic, environmental, and economic indicators. A ranking of the most suitable configurations is established for three different energy and CO₂ pricing scenarios (i.e., 2025, ideal, and competition scenarios). Next, a parameter sweep approach provides insights on the robustness of each decarbonization route for volatile market conditions.

3.1. Energy demand and CO₂ emission reduction potential

The specific energy demand, and the direct and total CO₂ emissions for the base-case and the alternative lime production routes are depicted in Figure 3. More details of the reported values can be found in Supplementary Material (section S7). The breakdown of the specific energy demand shown in Figure 3 highlights the relative importance of the kiln and CC units, compared to the ASU. Accordingly, the total energy demand required to produce one ton of lime varies between 3.60 GJ/t_{lime} for the base case and 12.21 GJ/t_{lime} for the CCU-based configuration. These values encompass both heat and electricity requirements to facilitate a straightforward comparison between configurations using different energy sources. Auxiliary operations, such as fuel injection and conveyor belt operation (labeled 'Elec kiln' in Figure 3), require about 30 kWh_e/t_{lime}. This electricity demand is assumed identical for all configurations.

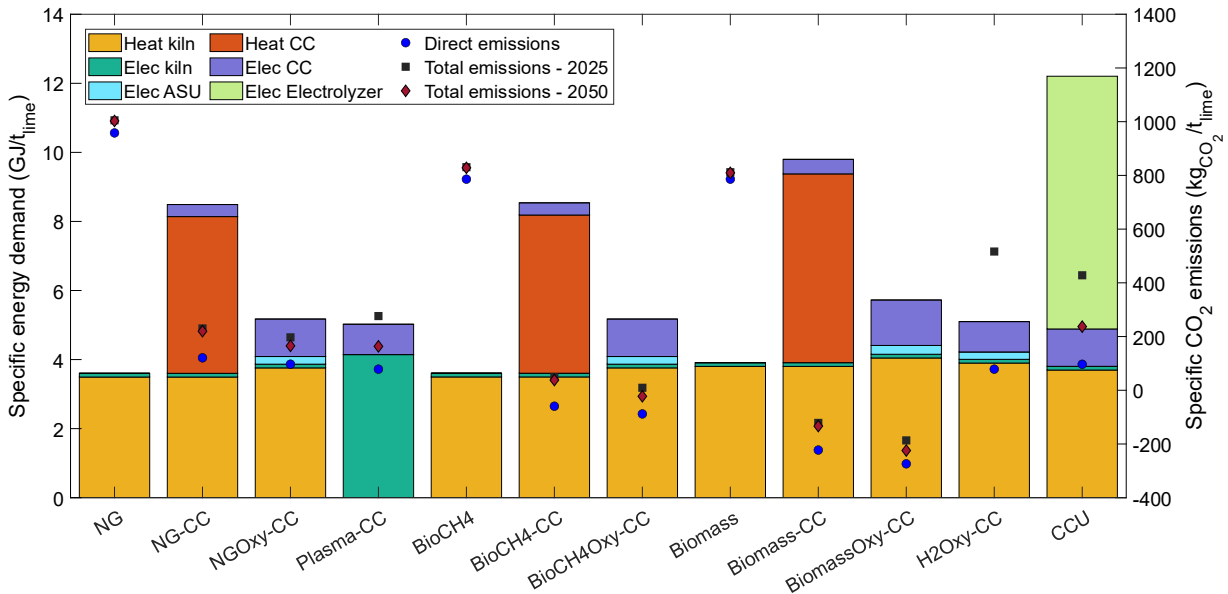


Figure 3: Specific energy demand breakdown, and direct and total CO₂ emissions for different lime production routes. The difference between total and direct emissions are indirect emissions associated to the energy supply chains.

Since natural gas substitution with biomethane does not entail a major technical challenge [18], the kiln heat requirement in the base case ('NG'), estimated as 3.5 GJ/t_{lime}, is equivalent to that of 'BioCH4' case. In contrast, other fuel switching options may reduce kiln efficiency and, consequently, lead to higher fuel consumption. For instance, when solid biomass is fed to the air-fired kiln, heat requirement slightly

increases up to 3.8 GJ/t_{lime} due to higher moisture content. These values are in line with the ranges reported in the Best Available Techniques (BAT), namely 3.2–4.2 GJ/t_{lime} [44].

Despite reduced nitrogen ballast, additional wall heat losses in the oxy-firing mode and lower TRL result in an increased fuel demand of approximately 7% compared to the air-fired counterpart. In fact, heat requirements for oxy-fired natural gas, biomethane, and biomass kilns amount to 3.8, 3.8, and 4.1 GJ/t_{lime}, respectively, representing conservative estimates as the technology is not yet fully optimized. Similar performance is observed for the 'H₂Oxy-CC' configuration, where heat requirement reaches 3.9 GJ/t_{lime}. Moreover, when oxycombustion is implemented, additional electricity is necessary for oxygen production (ASU). The minor contribution of the ASU to the total energy demand ranges from 0.21 GJ/t_{lime} (~59 kWh/t_{lime}) to 0.25 GJ/t_{lime} (~71 kWh/t_{lime}) depending on the specific oxygen demand of the fuel.

Regarding fully electric plasma-based kilns, the total energy demand for the kiln amounts to approximately 1151 kWh_e/t_{lime}, or equivalently 4.14 GJ/t_{lime}, which is larger than other fuels due to the average electrical-to-thermal efficiency of 80%.

Moreover, when MEA-based CC and subsequent CO₂ compression are implemented to capture CO₂ from diluted flue gases (~21 mol%), a high energy penalty is observed. Indeed, when comparing MEA-based configurations with their counterparts without CC, the total energy demand heavily increases, depending on the capture capacity, adding between 4.89 and 5.89 GJ/t_{lime} for natural gas-fired and biomass-fired kilns, respectively, the latter leading to larger CO₂ flowrates. This additional energy demand stems mainly from the solvent regeneration step that consumes steam produced by natural gas boilers. It should be noted that additional CO₂ emissions from CC boilers are also captured by the CC unit.

On the other hand, when a cryogenic CPU is implemented to capture CO₂, the corresponding energy penalty is much lower than with chemical absorption (303–437 kWh_e/t_{lime}) representing an energy demand increase between 42% (for process-related emissions of hydrogen-fired kilns) and 59% (for process- and fuel-related emissions of solid biomass-fired kilns) compared to base case 'NG'. This difference should be considered carefully, as it is partially due to the larger exergy content of electricity compared to heat. Indeed, MEA-based CC relies mainly on natural gas, while the CPU-based option fully relies on an electric process. The other main reason is related to the high CO₂ concentration in the flue gases (>90 mol% CO₂, dry basis) enabling a facilitated CO₂ capture. Expressed per ton of CO₂ captured to enable comparison with the literature, the energy penalty previously mentioned ranges from 1.48 to 1.54 GJ/tCO₂, which is consistent with the value of 1.6 GJ/tCO₂ reported by Simoni et al. [14].

The 'CCU' configuration consists of a e-methane lime kiln operated in oxycombustion mode. The kiln heat requirements are thus identical to the 'NGOxy-CC' and 'BioCH₄Oxy-CC' cases. After being captured with a CPU, CO₂ is combined with hydrogen (produced on-site with an alkaline electrolyzer) to produce e-methane. The electrolyzer represents the major contributor to the energy demand and requires 2033 kWh_e/t_{lime} (~7.3 GJ/t_{lime}). Notably, no energy requirement stems from an ASU in the 'CCU' configuration, since oxygen production from the electrolyzer is sufficient to fully cover the oxygen requirements of the lime production process. The 'CCU' route is by far the most energy-intensive one, characterized by an energy demand that is more than triple that of the base case (+239% compared to 'NG').

In Figure 3, direct process and energy-related CO₂ emissions, i.e., both CO₂ emitted from the calcination reaction and from fossil fuel combustion, are presented for all configurations. The maximum emission reduction potential relative to the base case for fuel switching alone is 18% due to the intrinsic process reaction emissions (786 kgCO₂/t_{lime}). Specific direct emissions for configurations not implementing CC vary between 786 kgCO₂/t_{lime} (for 'Plasma', 'BioCH₄', 'Biomass', and 'H₂Oxy') and 958 kgCO₂/t_{lime} (for 'NG'). The emission level of the base-case configuration 'NG' is representative of current industrial practice and agrees well with the 1–1.2 tCO₂/t_{lime} reported by Simoni et al. [14] for a PFRK. Lower CO₂ emissions can be achieved by implementing CC, in exchange of higher natural gas or electricity demand, as discussed previously. An emission reduction potential of about 90% can be reached when producing lime via the 'NG-CC', 'NGOxy-CC', 'Plasma-CC', 'H₂Oxy-CC', or 'CCU' routes. Negative direct emissions can be achieved

when biogenic CO₂ is captured. In this case, the CO₂ emissions reduction potential amounts to 106%, 109%, 123%, and 129% for 'BioCH₄-CC' (i.e., -59 kgCO₂/t_{lime}), 'BioCH₄Oxy-CC' (i.e., -88 kgCO₂/t_{lime}), 'Biomass-CC' (i.e., -222 kgCO₂/t_{lime}), and 'BiomassOxy-CC' (i.e., -274 kgCO₂/t_{lime}) options, respectively. The emission reduction potential of configurations implementing MEA-based CC is slightly lower than their counterparts implementing CPU, due to the additional CO₂ emitted during natural gas combustion for steam generation (reboiler duty).

Total emissions, encompassing both direct (i.e., resulting from fossil fuel combustion and the calcination reaction) and indirect emissions (i.e., stemming from the upstream energy production and supply chains of commodities), are also depicted in Figure 3, and the corresponding breakdown can be found in Figure 4. For pathways excluding CC, CO₂ produced by the calcination reaction constitutes nearly all of the total emissions. On the other hand, for CC-based configurations, indirect emissions increase in absolute values due to the additional energy demand for CC, but also in relative terms as they contribute for more than 40% of the total emissions, e.g., between 48% (for 'NG-CC' route) and 85% (for 'H₂Oxy-CC' route) in the 2025 scenario. Moreover, those values range between 41% ('NGOxy-CC' route) and 74% ('H₂Oxy-CC' route) in the 2050 scenario, emphasizing the need to consider both direct and indirect emissions for a comprehensive CO₂ emissions accounting. While indirect emissions associated with limestone, biomethane, and biomass supply chains have little impact, natural gas represents up to 35% of total CO₂ emissions when MEA-based CC is implemented. For large electricity and hydrogen consumers, including oxy-fired kilns, plasma-based kilns, and 'CCU' route, electricity and hydrogen supply chains contribute to 28–84% of total emissions in the 2025 scenario. This share drops down to 14–72% in the 2050 scenario, owing to a higher share of renewables in the electricity and hydrogen production mixes. This large contribution is attributable to the higher emission factors associated with electricity (Belgian estimate for 2025 and European projection for 2050) and hydrogen (global estimate) compared to other energy sources. Moreover, it can be observed that, in the 2025 scenario, switching to hydrogen leads to an overall higher CO₂ emission ratio (0.516 tCO₂/t_{lime}) than other CC-based options, since the current global hydrogen production is almost entirely based on unabated fossil fuels [75]. Indeed, in 2025, natural gas reforming without CC accounted for approximately 62% of the global hydrogen production, while coal-based production without CC contributed 20%. In contrast, only about 0.7% and 0.2% of the global production originated from fossil fuels with CC and electricity, respectively [76]. Despite optimistic scenarios for hydrogen production by 2050, i.e., with a global share of only 25% of fossil-based hydrogen production without CCUS, the hydrogen-based lime kiln remains among the configurations with the highest carbon intensity (0.299 tCO₂/t_{lime}). Similar trends can be observed for the 'CCU' configuration, heavily relying on electricity for water electrolysis implementation.

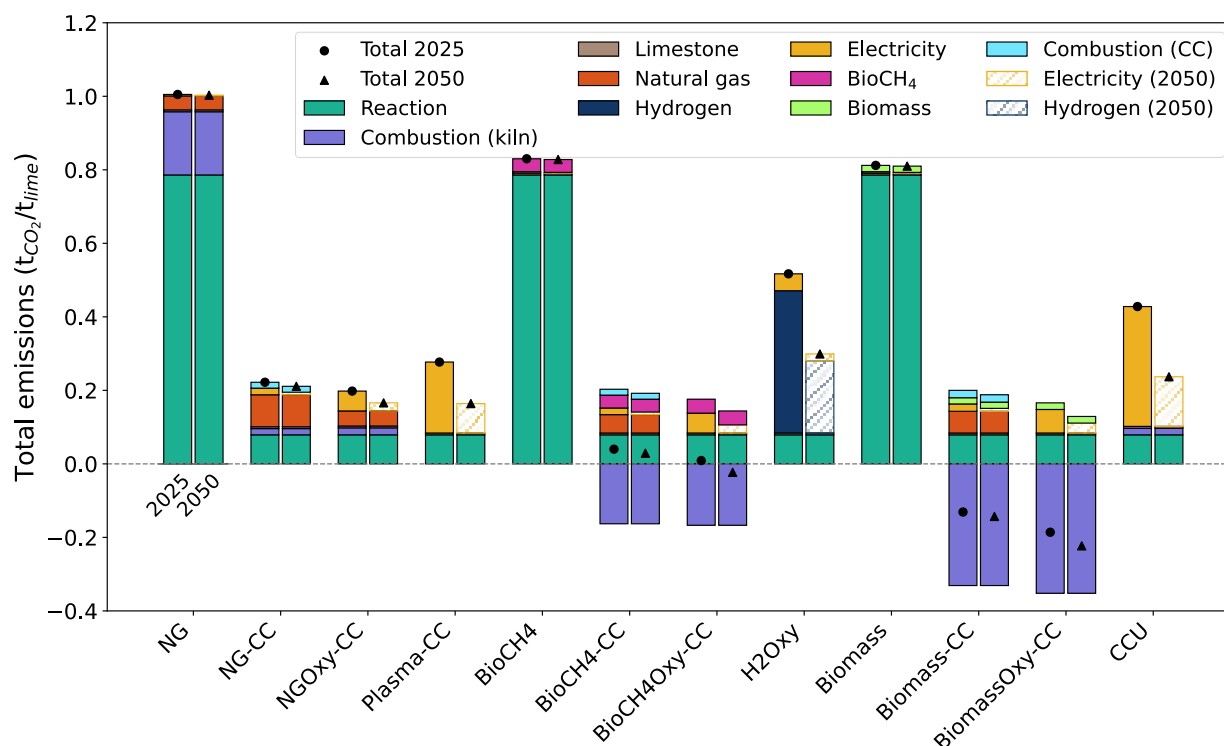


Figure 4: Total emissions breakdown by source for different lime production routes. For each production route, the left bar corresponds to the 2025 scenario and the right bar corresponds to the 2050 estimates.

3.2. Economic analysis

The economic performance of different energy transition pathways is evaluated through a comprehensive cost analysis, focusing on both CAPEX and OPEX contributions to the specific total cost (STC, €/t_{lime}). This section presents a breakdown of key cost components for different scenarios and the results of a parameter sweep analysis, highlighting the impact of energy and CO₂ pricing variations on economic feasibility and ranking of the pathways.

3.2.1. CAPEX breakdown

In Figure 5 is depicted the specific CAPEX breakdown for different configurations, assuming an annual plant production capacity of 240,000 t_{lime}/y and a greenfield scenario. CAPEX values are assumed to be identical for the different pricing scenarios. More details about the reported values can be found in Supplementary Material (section S8).

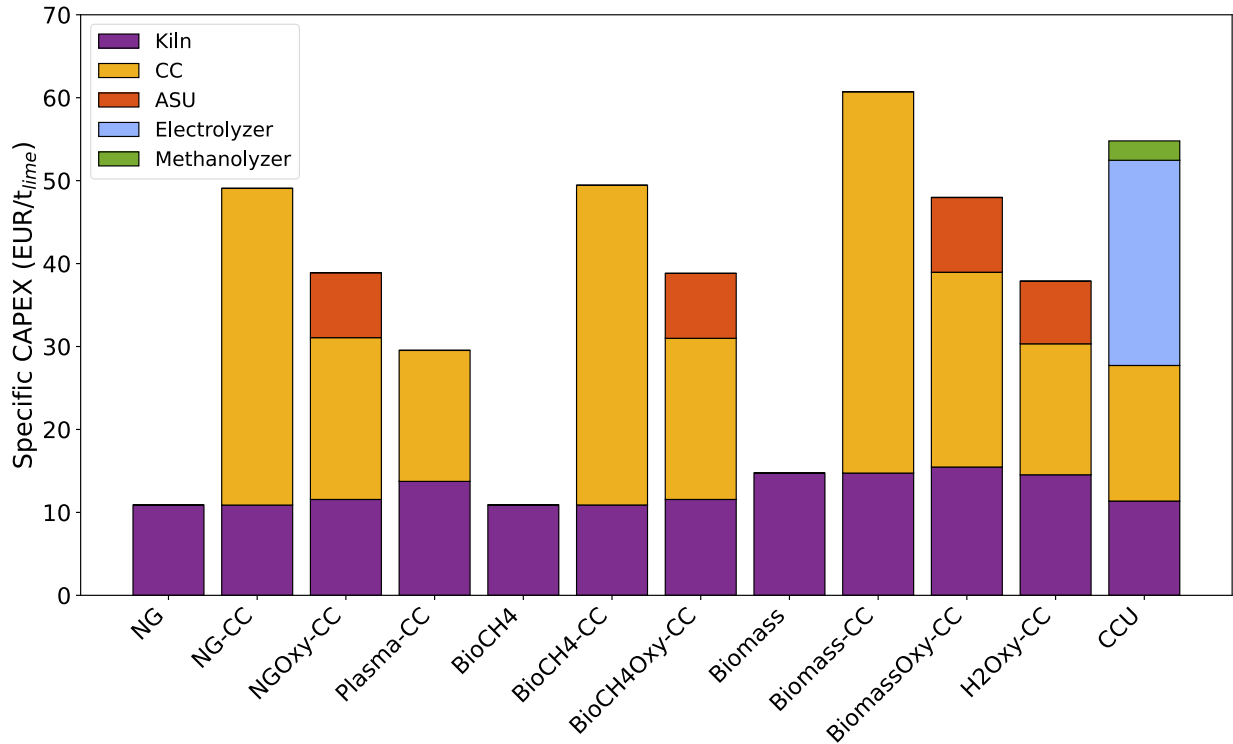


Figure 5: CAPEX breakdown for different lime production routes.

The specific kiln CAPEX varies between €11/t_{lime} and €15/t_{lime} depending on the energy vector used for heat supply. These results are consistent with values reported by EuLA [77] (around €7–15/t_{lime}). Fuel switching alone results in CAPEX increase below 35% compared to the base case due to burner modifications and increased capacity, whereas a CAPEX increase of 26% is expected for kiln electrification.

On the other hand, while sharply reducing CO₂ emissions, deploying CO₂ capture in lime facilities drives a CAPEX increase of 171–458% above the base-case level, depending on the implemented CC technology and the capture capacity. Indeed, implementing MEA-based CC leads to a more than fourfold increase (+ €38–45/t_{lime}) in specific CAPEX compared to the respective non-CC options, due to the CO₂ capture unit equipment and subsequent CO₂ compression train. These configurations result in specific total CAPEX values between €49–61/t_{lime}. For oxy-fired kilns, around €8/t_{lime} must be added for ASU investment, whereas for cryogenic CPU the additional investment ranges between €16/t_{lime} (for 'Plasma-CC' and 'H2Oxy-CC' routes, capturing process emissions only) and €23/t_{lime} (for 'BiomassOxy-CC' route, capturing process and biogenic energy-related emissions). Thus, total CAPEX values for CPU-based configurations vary between €30/t_{lime} and €48/t_{lime}. Beyond reducing energy requirements for performing CO₂ capture, oxycombustion combined with CPU appears also less capital-intensive than amine-based CO₂ capture. This observation stems from a more compact unit enabled by higher CO₂ concentration and smaller flue gas volumes to be treated in the former case.

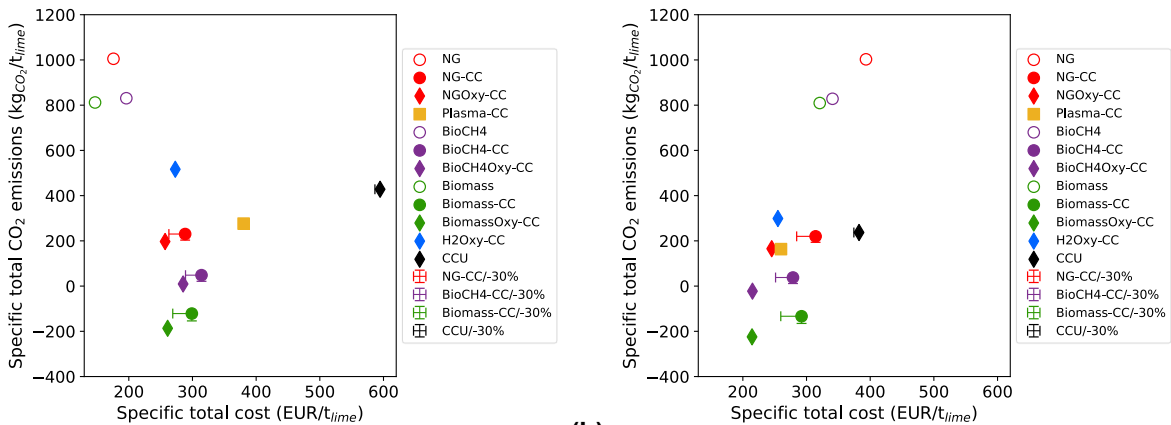
Finally, regarding the 'CCU' route, roughly 45% of the total CAPEX can be attributed to the electrolyzer, while the contribution of the methanation unit is less significant. Moreover, since the electrolyzer covers both hydrogen and oxygen requirements of the process, no ASU investment is necessary. In this case, the total specific CAPEX amounts to €55/t_{lime}. Consequently, besides being the most energy-intensive configuration and one of the most carbon-intensive CC-based options, 'CCU' is also among the most capital-demanding decarbonization routes.

3.2.2. Scenario-dependent cost ranking of production pathways

In this section, twelve different lime production configurations are compared based on their specific total cost (STC, €/t_{lime}), encompassing both investment (CAPEX) and operating expenses (OPEX). Aiming to identify configurations that are viable in both near and long terms, this economic comparison will be conducted under three distinct energy pricing scenarios, namely the 2025 scenario, the ideal scenario, and the competition scenario. The first scenario accounts for current energy prices, the second one represents the ideal incentive for industrial decarbonization (i.e., cheap electricity and bioenergy, and high CO₂ price), while the latter reflects competition for bio-based energy vectors.

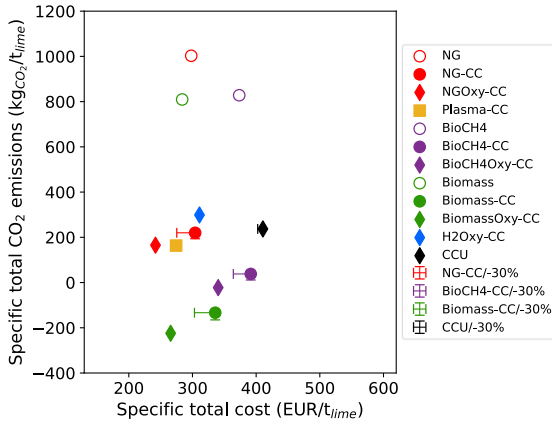
Pareto plots for specific total cost vs. specific CO₂ emissions are illustrated in Figure 6 for the three scenarios. The cost values provided are not intended to be predictive, but rather should be used for comparison between the different options. In these graphs, hollow symbols correspond to configurations where CO₂ is directly emitted to the environment, leading to higher specific emissions. On the other hand, solid symbols represent configurations where CC is implemented. Finally, air-fired kilns are represented by circles, oxy-fired kilns by diamonds, and electric kilns by squares.

MEA-based CC is a high-TRL option that is typically included in studies. However, the use of alternative solvents may reduce heat requirements for solvent regeneration by up to 30% [78] [79]. This improvement potential is represented by error bars (labeled “xx-CC/-30%”). The impact of heat demand reductions on the breakdown of energy demand, CO₂ emissions, and CAPEX is elaborated further in Supplementary Material (section S9). Moreover, since CCU is a low-TRL configuration, it is also associated with a higher CAPEX uncertainty. Hence, a scenario with a 30% lower CAPEX is introduced through an error bar for the corresponding configuration (labeled “CCU/-30%”).



(a)

(b)



(c)

Figure 6: Specific direct emissions and total cost for different lime production routes in the (a) 2025 scenario, (b) ideal scenario, and (c) competition scenario. Circles, squares, and diamonds denote air-fired, electric, and oxy-fired kilns, respectively. Hollow and filled markers represent configurations without and with CC, respectively. Colors distinguish configurations according to the energy resource used.

From Figure 6a, the total cost of the base case configuration ('NG' route) reaches €176/t_{lime} in the 2025 scenario, which is slightly higher than that of the 'Biomass' case (€147/t_{lime}), but lower than that for the 'BioCH₄' configuration (€196/t_{lime}). Although they are the most cost-efficient configurations in 2025 scenario, the corresponding CO₂ emissions of the cases without CO₂ capture are relatively high (ranging between 0.812 and 1.005 tCO₂/t_{lime}) since only fuel-related emissions are addressed. Hence, for the relatively low CO₂ ETS prices currently observed (<€75/tCO₂), there are few incentives for implementing CC technologies.

A trade-off between low CO₂ emissions and moderate total costs can be found in the 'NGOxy-CC' (€257/t_{lime} or 46% higher STC compared to the base case), 'BiomassOxy-CC' (€261/t_{lime} or 48% higher STC), and 'BioCH₄Oxy-CC' options (€285/t_{lime} or 62% higher STC). These configurations are closely followed by MEA-based configurations: 'NG-CC' (€288/t_{lime}), 'Biomass-CC' (€299/t_{lime}), and 'BioCH₄-CC' (€314/t_{lime}).

Despite the increased total energy demand of the 'Biomass' route (+9%) compared to the base case ('NG'), lower CO₂ emissions and lower fuel costs (€31/MWh_{Biomass} vs. €50/MWh_{NG}) result in a STC reduction of 14% compared to 'NG' configuration. Meanwhile, the 'BiomassOxy-CC' route exhibits a modest 1% increase in specific total cost compared to the 'NGOxy-CC' case. Likewise, the 'Biomass-CC' configuration becomes more expensive than its natural gas-based counterpart ('NG-CC') owing to a higher CC unit capacity required for capturing both fossil and biogenic CO₂. This leads to a higher CAPEX, electricity demand, and amount of CO₂ to be transported and stored. Despite the similar energy demand and reduced CO₂ emissions of the biomethane-fired options compared to the gas-fired counterparts, higher fuel costs of biomethane (€84/MWh_{BioCH₄} vs. €50/MWh_{NG}) result in higher specific total costs for 'BioCH₄' option (+11%) compared to 'NG' route. This is also the case for the 'BioCH₄Oxy-CC' option (+9%) compared to the 'NGOxy-CC' configuration, and for 'BioCH₄-CC' (+11%) compared to 'NG-CC' route.

Reducing heat requirements for CC solvent regeneration enables STC reduction between €25/t_{lime} (for 'BioCH₄-CC' option) and €26/t_{lime} (for 'Biomass-CC' option) compared to the initial estimates. The cost difference between configurations can be attributed to different capture capacities required. Moreover, the total CO₂ emissions can be reduced by 0.03 tCO₂/t_{lime}. However, even if energy demand for solvent regeneration can be reduced, oxy-fired options remain cheaper than their air-fired counterparts coupled with absorption-based CC. This result stems from lower total energy demand, lower CAPEX, and lower specific emissions characterizing oxycombustion options, which are consistent with observations from the literature [14].

The 'H2Oxy-CC' case is characterized by a moderate STC increase relative to 'NG'. Its STC reaches €273/t_{lime}, which is comparable to the values observed for other oxy-fired configurations. However, because current hydrogen production remains predominantly fossil-fuel-based [76], the carbon footprint of the 'H2Oxy-CC' case exceeds 516 kgCO₂/t_{lime}, which represents a more than 162% increase compared to other oxy-fired configurations. If electrolytic hydrogen is used instead of grey hydrogen, the STC of the 'H2Oxy-CC' is significantly increased, reaching €475/t_{lime}. This observation is attributable to the availability of electrolytic hydrogen at a very high price (€269/MWh in Belgium [74]). Hence, hydrogen is currently not a competitive decarbonization option from either an environmental or an economic perspective.

Furthermore, elevated electricity prices are detrimental for lime kiln electrification as 'Plasma-CC' ranks among the most expensive configurations. The corresponding STC amounts to €380/t_{lime}, which is 116% higher than the one observed for the base case 'NG'. Despite a lower energy penalty than oxy-fired configurations (+39% compared to 'NG' vs. +44–59% for 'NGOxy-CC' and 'BiomassOxy-CC', respectively), 'Plasma-CC' is 46–48% more expensive than 'NGOxy-CC' and 'BiomassOxy-CC', owing to much pricier energy resource (€194/MWh_e vs. €27/MWh_{Biomass} and €50/MWh_{NG}).

Finally, the most expensive lime production route in the 2025 scenario is 'CCU' (€595/t_{lime}), whose cost is 238% higher than that of the base case configuration and 56% more expensive than the 'Plasma-CC' option. This significant cost increase is the result of increased CAPEX (+403%), higher energy demand (+239%, mostly due to the electrolyzer), and higher electricity cost (€194/MWh_e) compared to natural gas (€50/MWh_{NG}). Moreover, as the error bar in Figure 6 shows, even under a scenario of 30% CAPEX reduction [80], the improved economic condition cannot offset the significantly higher investment and operating expenses compared to the other configurations. This observation is consistent with the challenges highlighted by industrial CCU projects [42].

In Figure 6b, specific total cost is plotted against the corresponding specific CO₂ emissions for each configuration in the "ideal" scenario. In this scenario, lower bio-energy and electricity costs, as well as higher CO₂ allowance costs compared to 2025 are considered, as can be seen in see Table 3. In particular, the CO₂ cost for 2025 (€75/tCO₂) is assumed to reach €300/tCO₂, which is in line with the upward trend in future ETS prices [81]. These future assumptions result in a decreased specific total cost for CC-based options, whereas configurations without CC are penalized. Indeed, when no CO₂ capture is adopted, the specific total cost for lime production varies between €320/t_{lime} (for 'Biomass' option) and €393/t_{lime} (for 'NG' option). Meanwhile, lower total costs between €214/t_{lime} and €314/t_{lime} can be reached when CCS is implemented, and up to €382/t_{lime} when CCU is considered. Provided that CO₂ transport and storage infrastructure is available, all CC-based configurations (excluding 'CCU') become more cost-effective than the configurations without CC under the economic conditions of the "ideal" scenario. More interestingly, the specific total cost of the base case increases by 124% compared to 2025 (reaching €393/t_{lime}), making it more expensive than any alternative production pathway, including 'CCU'. Consequently, high CO₂ ETS price and access to cheap low-carbon energy are strong incentives for long-term CC implementation in the lime industry.

In the "ideal" scenario, the top five cost-beneficial lime production routes are 'BiomassOxy-CC' (€214/t_{lime} or 45% cheaper than the base case), 'BioCH4Oxy-CC' (€215/t_{lime}), 'NGOxy-CC' (€245/t_{lime}), 'BioCH4-CC' (€251/t_{lime}, if energy efficiency improvements are considered), and 'H2Oxy-CC' (€255/t_{lime}). The use of electrolytic hydrogen and the access to a decarbonized electricity grid strongly improves the environmental ranking of 'H2Oxy-CC' and 'Plasma-CC' configurations. Moreover, the access to cheap green hydrogen and electricity renders these cases economically viable: 34–35% cheaper than the base case 'NG', and only 19–21% more expensive than the cost-optimal (i.e., 'BiomassOxy-CC' case). It is assumed that cost reductions between €27/t_{lime} and €33/t_{lime} can be achieved by reducing heat requirements related to chemical absorption CC. However, this action is insufficient to outperform their oxy-fired counterparts, highlighting again the economic advantage of CPU-based configurations over amine-based CC options, owing to lower CAPEX, lower energy demand, favorable electricity costs, and lower direct emissions subject to CO₂ pricing, as previously discussed. Finally, similar to the 2025 scenario, CCU remains the most expensive decarbonization solution. However, despite slightly lower total costs compared to the 'NG' case

(€382/t_{lime} for 'CCU' vs. €393/t_{lime} for 'NG'), the access to a decarbonized electricity grid enables a carbon footprint in the 'CCU' case of 237 kgCO₂/t_{lime} which is 76% lower than the base case.

In Figure 6c, specific total and CO₂ emissions are represented for each configuration in the “competition” scenario. In this scenario, favorable electricity and hydrogen prices are considered, whereas competition for bio-based resources induces a drastic increase in biomethane and biomass prices. The ETS price is fixed at €200/tCO₂, which is higher than current levels but reflects a less aggressive incentive than in the “ideal” scenario.

These assumptions render biomethane-based options less economically attractive than the base case. The STC of the former lies between €340/t_{lime} (for 'BioCH₄Oxy-CC' case) and €391/t_{lime} (for 'BioCH₄-CC' case). Moreover, except for the 'Biomass' case, high biomass prices lead to biomass-based configurations that are more expensive than their natural gas-fired counterparts. For example, 'BiomassOxy-CC' and 'Biomass-CC' are 10% more expensive than, respectively, 'NGOxy-CC' and 'NG-CC'. This observation can be attributed to the larger capture capacity required to capture both fossil and biogenic CO₂. On the contrary to the previous scenarios, the high biomass prices considered in the “competition” scenario do not compensate anymore for the increased energy demand and higher CAPEX associated with the biomass-based options. Moreover, despite similar electricity prices in the “ideal” and “competitive” scenarios (respectively €95/MWh and €111/MWh), with the latter being only 17% higher, the 'CCU' option is now 38% more expensive than the 'NG' case. This result highlights the critical influence of the ETS price on the decarbonization of the lime industry.

Finally, in the “competition” scenario, the cost-optimal production pathways are 'NGOxy-CC' and 'BiomassOxy-CC' provided that CO₂ transport and storage infrastructure is available. These options are characterized by STCs of €242–266/t_{lime}, which are 11–19% less expensive than 'NG' (€298/t_{lime}). The aforementioned configurations are closely followed by 'Plasma-CC' (€274/t_{lime}), 'NG-CC' (€275–304/t_{lime}), and 'Biomass-CC' (€303/t_{lime} if lower heat requirements are assumed for solvent regeneration). Access to low-cost green hydrogen results in a STC for the 'H₂Oxy-CC' case that is 4% higher than the one observed for the 'NG' case.

The specific cost breakdown for different lime production routes in the 2025, the ideal, and the competition scenarios can be seen in Figure 7, Figure 8, and Figure 9 respectively. In these figures, the relative shares of specific CAPEX and OPEX, including raw materials (limestone and water), fuel (i.e., natural gas, biomethane, solid biomass, and hydrogen), electricity, cooling water, as well as CO₂ emissions, and CO₂ transport and storage are depicted.

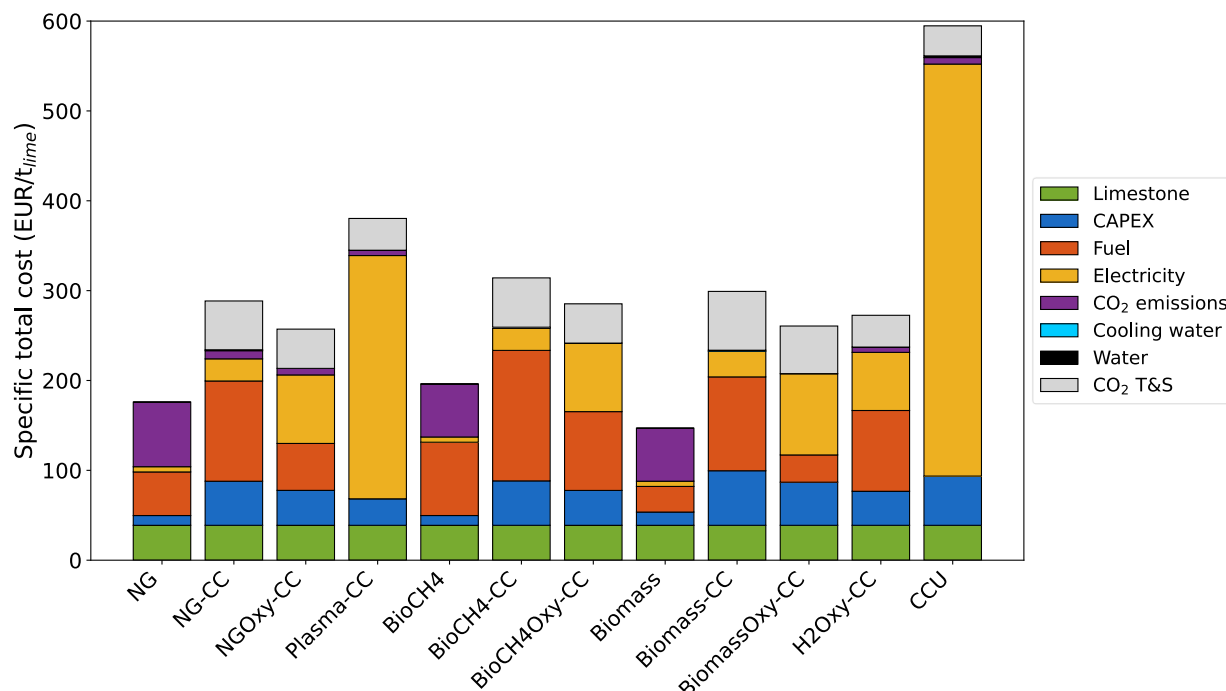


Figure 7: Specific total cost breakdown for different lime production routes in the 2025 scenario.

According to Figure 7, in 2025 scenario, total cost is mainly driven by OPEX, which ranges from €132/t_{lime} to €540/t_{lime} (i.e., 89–97% of the STC). Meanwhile, CAPEX contributes only between 6–20% to the total cost. Moreover, for configurations with no CC, the relative share of CO₂ costs varies between 30% (for ‘BioCH4’ option) and 41% (for ‘NG’ option). This share drops to values between 0% and 3% when a CC unit is implemented thanks to the sharp reduction in scope 1 CO₂ emissions.

On the other hand, electricity represents 71% of the specific total cost for ‘Plasma-CC’ option and 77% for ‘CCU’ option, attributable to the heavy reliance of these configurations on electricity consumption (1395 and 2334 kWh_e/t_{lime}, respectively). Moreover, no explicit fuel-related expenses are observed in these cases since ‘Plasma-CC’ is a fully electric configuration, while e-methane is produced on-site in the ‘CCU’ configuration.

In general, implementing chemical absorption CC leads to an increased relative share of fuel- and electricity-related expenses due to the additional natural gas and electricity consumption associated with the operation of CO₂ capture regeneration process and CO₂ compression train. When coupled with amine-based solutions, fuel-related expenses rise from €49/t_{lime} for ‘NG’ option to €112/t_{lime} for ‘NG-CC’ option (i.e., relative share increases from 28% to 39% of the STC). Comparatively, fuel consumption contribution for the biomethane-fueled route increases from €82/t_{lime} (42% of ‘BioCH4’ STC) to €145/t_{lime} (46% of ‘BioCH4-CC’ STC). When comparing ‘Biomass’ and ‘Biomass-CC’ options, fuel contribution rises from €28/t_{lime} to €104/t_{lime}, i.e., the fuel share goes from 19% to 35% of the specific total cost due to the additional natural gas consumption to fuel the CC process. When improved energy efficiency for solvent regeneration is considered, i.e., 30% less heat is required, the fuel-related cost penalty amounts to only €52/t_{lime}, €57/t_{lime}, and €84/t_{lime} for natural gas-, biomethane-, and biomass-fired kilns respectively. Moreover, MEA-based CC implementation results in a moderate increase (+€19–22/t_{lime}) of electricity expenses.

When oxycombustion is implemented, the relative share of electricity demand varies between 24% (for ‘H2Oxy-CC’ option) and 35% (for ‘BiomassOxy-CC’ option) mainly due to the electrified CO₂ capture via CPU. The additional OPEX associated to CPU-based configurations compared to their counterparts without

CC amounts to €53–81/t_{lime}. The difference in cost penalties between configurations implementing CPU stems from different capture capacities depending on the fuel that is used.

Finally, when comparing amine-based and CPU-based CC routes, it can be observed that CO₂ T&S expenses are higher in the former. This can be explained by higher CO₂ flows to be treated in case of amine-based CC, as CO₂ is emitted through both the lime production process and the CC auxiliary boilers, unlike the fully electrified CPU. CO₂ T&S expenses arise also for the 'CCU' configuration as e-methane production covers only the energy demand of the lime kiln, while the remaining captured CO₂ is permanently sequestered. Transport and storage represent between €33/t_{lime} (for 'CCU' option) and €65/t_{lime} (for 'Biomass-CC' option). This cost variation can be explained by differences in the amount of CO₂ transported and stored (e.g., 0.668 tCO₂/t_{lime} for 'CCU' option vs. 1.214 tCO₂/t_{lime} for 'Biomass-CC' option).

Despite kiln heat requirements in the 'H2Oxy-CC' configuration being only 12% higher, fuel-related expenses are almost double those of the base case 'NG' option. This observation can be attributed to the hydrogen price being almost twice that of natural gas (€83/MWh_{H2} vs. €50/MWh_{NG}). Plasma-based kilns exhibit a similar trend, with energy-related expenses almost five times those of 'NG' option, despite energy demand being only 19% higher, owing to higher electricity prices relative to natural gas prices (€194/MWh_e vs. €50/MWh_{NG}). On the other hand, although specific energy requirements are 9% higher in the 'Biomass' case than in 'NG' configuration, lower fuel-related costs can be observed due to biomass available at almost half the price of natural gas (€27/MWh_{Biomass} vs. €50/MWh_{NG}).

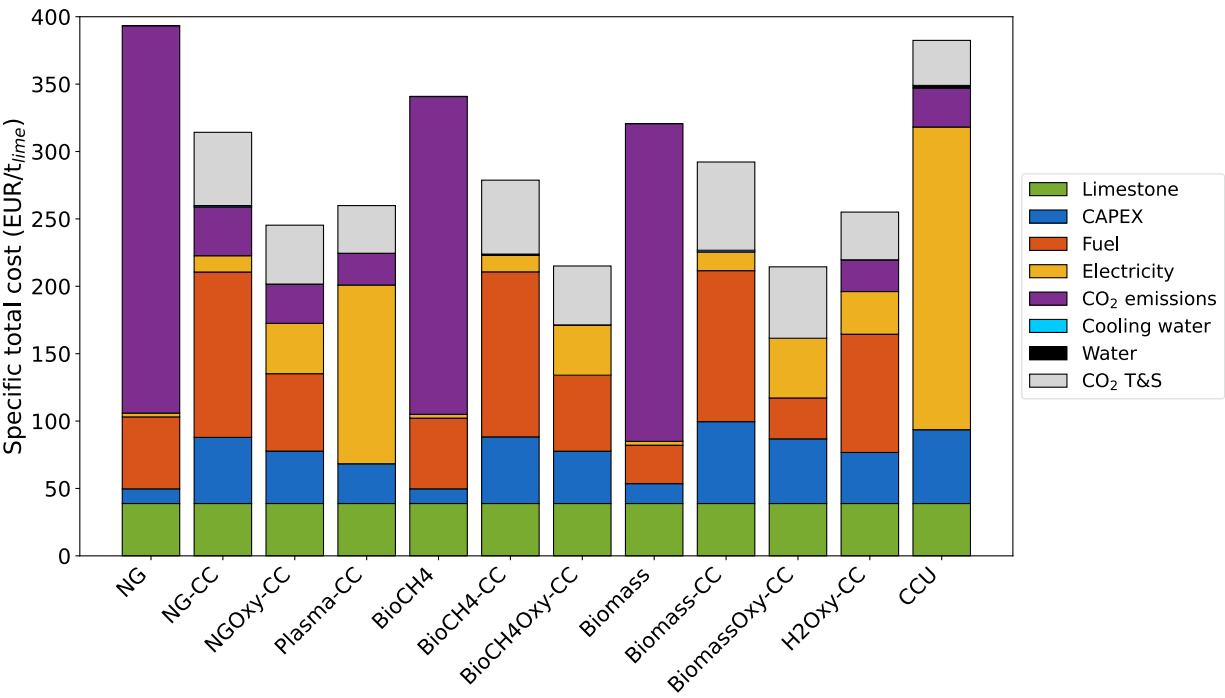


Figure 8: Specific total cost breakdown for different lime production routes in the ideal scenario.

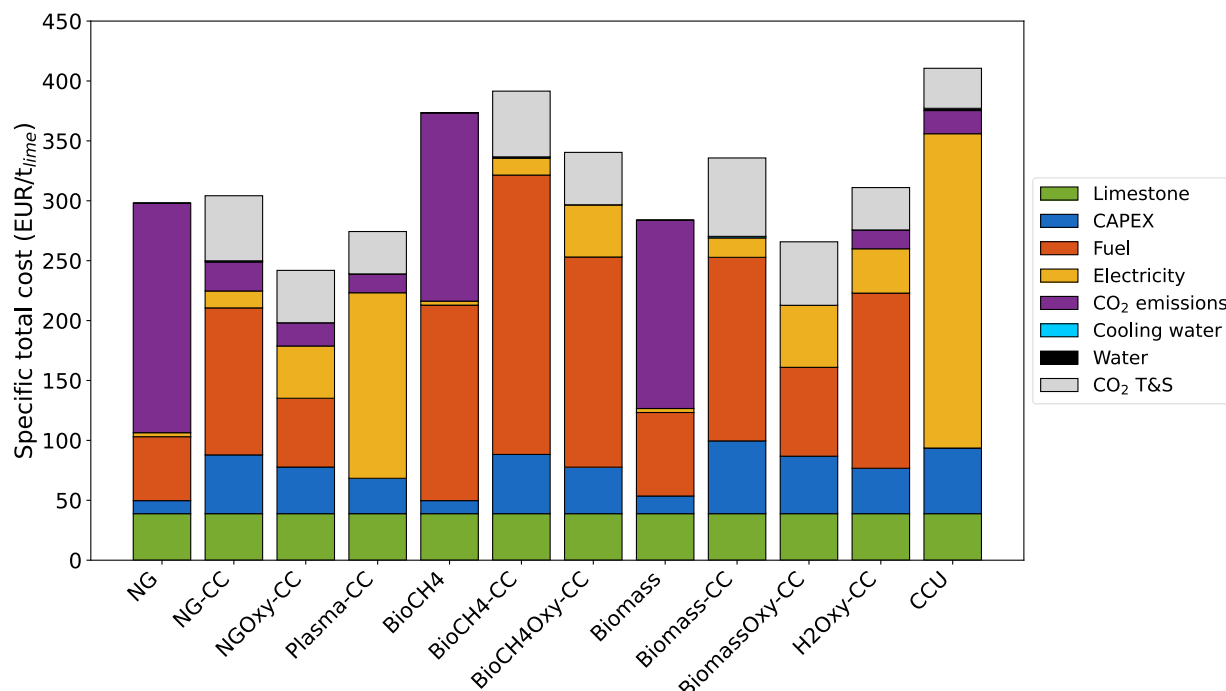


Figure 9: Specific total cost breakdown for different lime production routes in the competition scenario.

It is important to note that, in the “ideal” scenario, low-carbon energy prices are reduced while CO₂ cost sharply increases. Thus, the relative share of energy-related expenses decreases compared to 2025 scenario, while the opposite trend is observed for CO₂-related expenses. As it can be seen in Figure 8, when no CC is implemented, the specific cost related to CO₂ emissions is preponderant, representing between 69% (for ‘BioCH4’ option) and 74% (for ‘NG’ option) of the specific total cost. This share typically drops to between 0% and 12% when a subsequent CC step is included, although these values are still higher than in 2025 scenario. For CC-based configurations, specific total cost is primarily driven by energy use (i.e., fuel and electricity), which accounts for 35% for ‘BiomassOxy-CC’ option, and up to 59% for ‘CCU’ option. Meanwhile, CO₂ T&S contributions range from 9% in ‘CCU’ option up to 25% in ‘BiomassOxy-CC’ option.

Finally, in the “competition” scenario (Figure 9), bio-energy prices are sharply increased compared to the 2025 scenario, while CO₂ cost increases. The relative share of CO₂-related expenses increases (+3–23%) compared to 2025 scenario. Moreover, the contribution of energy-related costs in biomethane- and biomass-based configurations is increased by 1–9% compared to 2025 levels. Similarly to the previous scenario, the specific cost related to CO₂ emissions is preponderant for configurations without CC, representing a relative share of 42–64%. When CC is implemented, this share lies below 8%. In the ‘BioCH4’ case, the cost is almost equally distributed between fuel- and CO₂-related expenses (respectively 44% and 42%). The specific cost of ‘BioCH4Oxy-CC’ and ‘BioCH4-CC’ is primarily driven by fuel combustion, representing 52–60%. On the other hand, costs related to biomass combustion account for 25–46% of biomass-based options.

3.2.3. Economic optimality mapping of production pathways

The outcomes based on scenario analysis are valid solely for assumed energy and carbon prices, which are subject to significant uncertainty. Accordingly, it is essential to identify robust solutions over a wide range of energy prices and stringent environmental regulations in order to mitigate associated risks. The broader the price ranges acceptable for a solution to be optimal, the greater the flexibility of the configuration. Thus, a parameter sweep analysis is performed for the prices of electricity (p_E), hydrogen (p_{H_2}), natural gas (p_{NG}), biomethane (p_{BG}), and biomass (p_{BM}), as well as CO₂ emission (p_{CO_2}), transport and storage costs

(p_{TS}), aiming at the simulation of market volatility. The results of the parameter sweep are summarized in decision tables highlighting the commodity price conditions under which each configuration is the cost-optimal solution.

Table 5: Conditions for cost-optimal electrified lime production. All prices are expressed in €/MWh, except p_{CO_2} and p_{TS} which are expressed in €/tCO₂.

Configuration	p_E	p_{NG}	p_{H_2}	p_{BG}	p_{BM}	p_{CO_2}	p_{TS}
Plasma	≤ 18					≤ 125	> 62
	$18 < p \leq 38$	> 22	> 18	> 40	> 28	≤ 125	
Plasma-CC	≤ 18					> 125	
	$18 < p \leq 38$		> 18		> 28	≤ 88	≤ 38
						$88 < p \leq 125$	≤ 62
						> 125	
	$38 < p \leq 62$	> 22	> 38	> 60	> 42	> 125	

According to Table 5, plasma-based options become economically competitive only for low electricity prices (≤ 62 /MWh), explained by their strong reliance on electricity. Aside from 'Plasma' option without CC, which requires low CO₂ costs (≤ 125 /tCO₂) and typically moderate to high CO₂ T&S costs (≥ 62 /tCO₂) to be competitive, 'Plasma-CC' route can feasibly operate even at lower CO₂ costs (≤ 88 /tCO₂) as long as CO₂ T&S cost remains also low (≤ 38 /tCO₂). Moreover, moderate to high biomethane and solid biomass prices are required to render plasma options attractive (e.g., > 40 /MWh_{BioCH₄} and > 28 /MWh_{Biomass} when electricity is priced at more than approximately 20/MWh; > 60 /MWh_{BioCH₄} and > 42 /MWh_{Biomass} when electricity costs more than 40/MWh).

Table 6: Conditions for cost-optimal hydrogen-based lime production. All prices are expressed in €/MWh, except p_{CO_2} and p_{TS} which are expressed in €/tCO₂.

Configuration	p_{H_2}	p_E	p_{NG}	p_{BG}	p_{BM}	p_{CO_2}	p_{TS}
H ₂ Oxy	≤ 18	$18 < p \leq 38$				≤ 125	> 62
		> 38	> 22		$28 < p \leq 42$	≤ 125	
	$18 < p \leq 38$	$38 < p \leq 88$	> 22	> 40	> 42	≤ 125	> 38
		> 88	> 22	> 40	> 28	≤ 175	> 88
H ₂ Oxy-CC	≤ 18					> 125	
	$18 < p \leq 38$	> 38	> 22	> 40	> 28	$125 < p \leq 175$	≤ 88
						> 175	
	$38 < p \leq 62$	> 62	> 22	> 60	> 58	> 125	

From Table 6, hydrogen-based options appear as suitable lime production routes only when low hydrogen prices are available (≤ 38 /MWh_{H₂} for 'H₂Oxy' and ≤ 62 /MWh_{H₂} for 'H₂Oxy-CC'). These thresholds are significantly lower than current green hydrogen prices, varying between 120–480/MWh_{H₂} in Europe in 2024 [74]. An additional condition is that electricity cost must exceed hydrogen cost, otherwise plasma-based kilns are favored over the hydrogen-fired systems. This constraint suggests that hydrogen used for heat supply must either be produced from fossil resources (e.g., derived from cheaper conventional natural gas reforming or even coal gasification), imported at significant low cost from large renewable hubs, or only produced when low-cost electricity is available, which makes unlikely a scenario entirely based on hydrogen combustion. It should be noted that the cost of indirect emissions is not considered in this analysis. Moreover, as the price of hydrogen increases, biomethane and biomass costs must lie within the upper

range to maintain economic attractiveness of hydrogen. As a result, unless more favorable economic conditions are achieved, fuel switching towards hydrogen seems improbable in lime kilns.

Table 7: Conditions for cost-optimal natural gas-based lime production. All prices are expressed in €/MWh, except p_{CO_2} and p_{TS} which are expressed in €/tCO₂.

Configuration	p_{NG}	p_E	p_{H_2}	p_{BG}	p_{BM}	p_{CO_2}	p_{TS}
NG	≤ 22	> 18	> 18		> 28	≤ 125	> 38
	$22 < p \leq 45$	> 38	> 38	> 60	> 42	≤ 125	
	$45 < p \leq 65$	> 38	> 38	> 60	> 58	≤ 125	
NGOxy-CC	≤ 22	$38 < p \leq 88$	> 38	> 60	> 42	> 125	
	$22 < p \leq 45$	> 62	> 62	> 80	> 58	> 125	
NG-CC	≤ 22	$38 < p \leq 88$			> 28	$88 < p \leq 125$	≤ 38
			> 38	$40 < p \leq 60$	> 42	> 125	
		> 88	> 38	> 60	> 42	> 125	

According to Table 7, the attractiveness of natural gas-based options relies mainly on natural gas availability at favorable prices. For 'NG' option to be selected, natural gas must be available at low to moderate prices (typically ≤ 65 /MWh), whereas electricity, biomass and biomethane should be more expensive than natural gas. Moreover, 'NG' option remains suitable only at low CO₂ costs (≤ 125 /tCO₂), owing to the high specific CO₂ emission levels associated to this energy vector. In other words, high natural gas prices combined with low electricity prices and high CO₂ costs render the base case ('NG') economically unattractive. Certainly, by achieving affordable decarbonized electricity and penalizing CO₂ emissions, the energy transition in the lime industry can be accelerated. Meanwhile, lower natural gas prices are required (≤ 45 /MWh) to make attractive the 'NGOxy-CC' configuration due to its higher energy demand compared to 'NG' option. Moreover, all other energy commodities must be more expensive than natural gas, while the CO₂ cost must be set above ≤ 125 /tCO₂ for 'NGOxy-CC' to be selected. Finally, 'NG-CC' option is the most restrictive configuration, requiring simultaneously inexpensive natural gas (≤ 22 /MWh), costly electricity, moderate to high CO₂ ETS cost, and bioenergy prices more than twice those of natural gas.

Table 8: Conditions for cost-optimal biomass-based lime production. All prices are expressed in €/MWh, except p_{CO_2} and p_{TS} which are expressed in €/tCO₂.

Configuration	p_{BM}	p_E	p_{NG}	p_{H_2}	p_{BG}	p_{CO_2}	p_{TS}
Biomass	≤ 28			> 18		≤ 125	> 62
	$28 < p \leq 42$	> 38	> 22	> 18	> 40	≤ 125	
						$125 < p \leq 175$	> 62
	$42 < p \leq 58$	> 38	> 45	> 38	> 60	≤ 125	
	> 58	> 38	> 65	> 38	> 80	≤ 125	
BiomassOxy-CC	≤ 28	$18 < p \leq 38$		> 18		> 125	
		> 38	> 22	> 38		> 175	
	$28 < p \leq 42$	$38 < p \leq 88$		> 38	> 40	$125 < p \leq 175$	≤ 62
						> 175	
	$42 < p \leq 58$	> 62	> 22	> 38	> 60	> 125	
	> 58	> 62	> 45	> 62	> 80	> 125	
Biomass-CC	≤ 42	> 88	≤ 22	> 38		> 125	

As can be seen in Table 8, 'Biomass' configuration is more robust in terms of energy prices than the systems previously mentioned, its economic attractiveness mainly requiring higher biomethane prices than biomass prices. For instance, when electricity price is higher than €38/MWh and natural gas price exceeds €45/MWh, biomass price can still go as high as €58/MWh, while maintaining a cost-competitiveness. Similar trends are observed for 'BiomassOxy-CC' option when CO₂ cost is above €125–175/tCO₂, depending on biomass cost. Finally, the main conditions for the 'Biomass-CC' configuration to become an economically attractive solution are (i) moderate to high electricity prices (€88/MWh or higher) to disfavor CPU-based CC; (ii) low natural gas prices ($\leq$ €22/MWh) attributable to the natural-gas-fired boilers used for solvent regeneration; (iii) low to moderate biomass price (less than approximately €40/MWh). Similar trends are observed for biomethane-based options, as can be seen in Table 9.

Table 9: Conditions for cost-optimal biomethane-based lime production. All prices are expressed in €/MWh, except p_{CO_2} and p_{TS} which are expressed in €/tCO₂.

Configuration	p_{BG}	p_E	p_{NG}	p_{H_2}	p_{BM}	p_{CO_2}	p_{TS}
BioCH₄	≤ 40	> 18	> 22	> 18	> 28	≤ 125	
	$40 < p \leq 60$	> 38	> 22	> 38	> 42	≤ 125 $125 < p \leq 175$	> 62
	$60 < p \leq 80$	> 38	> 65	> 38	> 58	≤ 125	
BioCH₄Oxy-CC	≤ 40	> 38	> 22	> 18	> 28	> 125	
	$40 < p \leq 60$	> 38	> 22	> 38	> 42	$125 < p \leq 175$ > 175	≤ 62
	$60 < p \leq 80$	> 62	> 22	> 62	> 58	> 125	
BioCH₄-CC	≤ 40	> 38	≤ 22	> 38	> 42	> 125	

3.3. Discussion: Implications, challenges, and future perspectives for lime industry decarbonization

3.3.1. Decarbonization roadmap for the lime sector

Lime is an essential material for numerous industrial value chains, including steelmaking, construction, and environmental applications. Consequently, decarbonizing lime production also contributes to the carbon-neutrality of downstream industries [17]. The present study consisted of a comprehensive comparative assessment of various energy transition pathways for the lime industry, including fuel switching (towards hydrogen, biomass, and biomethane), electrification, CCS, CCU, and BECCS. By combining thermodynamic, environmental, and economic analyses, the study provides a systematic comparison of the advantages, limitations, and deployment viability of each pathway.

CO₂ accounting performed in this study highlighted that fuel switching alone is insufficient to reach climate targets for lime production since the implemented calcination reaction is the major contributor to CO₂ emissions. Hence, fuel switching towards biomass, biomethane, or hydrogen can be considered as a potential short-term solution, but CO₂ capture implementation will become inevitable in the mid- and long-term, contributing to the largest share of emissions reduction. Moreover, net-negative emissions are achievable through combination of sustainable bioenergy with CO₂ capture and storage.

The conclusions drawn from this study are consistent with the roadmap towards climate neutrality established by the European Lime Association (EuLA). According to EuLA, CO₂ capture is expected to account for most of the CO₂ emission reductions (approximately 80% compared to 2019 levels). Meanwhile, fuel switching will cut emissions by about 13%, and the emission reduction potential of electrified kilns will lie around 4%. Finally, BECCS as well as enhanced and natural carbonation are expected to enable net negative emissions by 2050. While not included in the scope of this study, natural carbonation occurs when lime or lime-based products gradually reabsorb CO₂ from the atmosphere during the use stage. Hence, this

carbonation permanently captures approximately 33% of the CO₂ originally released during the process, with most of the reaction occurring within the first year. Enhanced carbonation relies on the same chemistry, but accelerates it by increasing CO₂ concentrations and optimizing process parameters. EuLA estimates that enhanced carbonation could deliver an additional 12% CO₂ removal by 2050 [13].

The different emission reduction strategies are currently at different stages of technological maturity (as can be seen in Table 10), impacting the timing of their large-scale deployment. Fuel switching is already commercially available [17], whereas electrified kilns and CO₂ capture technologies remain at demonstration scale (TRL 6–8). Among the capture technologies assessed, amine-based CC is currently the most mature technology. The techno-economic assessment highlighted that oxycombustion is the most attractive long-term option, owing to lower energy penalty and less stringent conditions for economic optimality compared to MEA-based CC. This observation is consistent with other studies [14], as well as institutional reports [17] [18]. However, oxycombustion requires further technological development before industrial deployment can be achieved. Advancing these decarbonization technologies to mature commercial systems (TRL 9) requires investment, combined with strong market signals and stable policy incentives that reduce the associated risk [17].

Table 10: Technology readiness level of different energy transition pathways for the lime industry [17] [82] [83].

Technology	TRL
Fuel switching	8-9
Kiln electrification	7-8
CO ₂ capture – amines	7-8
CO ₂ capture – oxycombustion	6-8
CCU – methanation	6-7

Hence, the decarbonization of the lime sector will be implemented progressively. In the short term, investing in best available kiln technologies and fuel switching can reduce combustion-related emissions. Over the medium and long-term, large-scale deployment of CC will become essential to mitigate unavoidable process emissions, while the net-negative emissions of BECCS offer the possibility to compensate the sector's residual emissions.

However, the energy transition in the lime sector is associated with specific challenges discussed in the following sections. These include adequate carbon pricing mechanisms, availability and cost-competitiveness of alternative energy vectors compared to fossil fuels, and CO₂ and hydrogen infrastructure deployment.

3.3.2. Kiln electrification: electricity supply and commercial scale-up

For electrified lime kilns to retain environmental and economic benefits over alternative routes, decarbonized electricity should be available at low costs ($\leq$ €62/MWh). This threshold is significantly lower than current electricity prices observed across Europe, which typically exceeded €100/MWh in 2025 [60].

Moreover, the electricity generation capacity or electricity imports should be sharply increased compared to current levels. Indeed, if the entire Belgian lime sector (i.e., 1 Mt_{lime}/y [84]) were to transition to plasma-based kilns, an additional yearly green electricity demand of 1.37 TWh would be necessary, corresponding to 1.7% of the annual electricity demand in Belgium [85]. Similarly, depending on the configuration, an increased capacity of 0.1–0.4 TWh_e/y would still be necessary for large-scale deployment of CC in Belgian lime production facilities.

From a technological perspective, conventional PFRKs typically have a daily production capacity of 100–600 tons [44]. The electrification of such kilns would represent an electric power demand of approximately 6–35 MW. SaltX has demonstrated its EAC technology at a scale of up to 2 MW [20], which is roughly three times lower than the smallest conventional PFRKs currently available. However, the

commissioning of its new 100-tons-per-day pilot [21] [22] represents a significant step towards large-scale electrification of lime production.

3.3.3. Competition for sustainable biomass available potential

Despite rising interest in biomass- and biomethane-based options, driven by their potential for net-negative emissions and higher resilience to fluctuations in energy prices, the main drawback remains the limited feedstock availability [59].

Biomass is a scarce and valuable resource. Current projections estimate a biomass demand exceeding availability by 40–140%. Hence, bioenergy use must be prioritized in applications with high economic, environmental, and societal value, such as hybrid solutions for high-temperature industrial heat. However, maximum biomass availability in Belgium amounts to 13.89 TWh/y according to Eurostat data [86], while the International Energy Agency (IEA) [87] reports a European biomethane production of roughly 38 TWh. Considering only Belgian production, the yearly biomass requirement for the lime industry would amount to 1.12 TWh, representing 8% of the Belgian biomass availability. If lime production originates from biomethane-fired kilns, the corresponding yearly demand would reach 1.04 TWh_{BioCH₄} which corresponds to 3% of the European biomethane production, while the entire European lime production, amounting to more than 20 million tons per year [88], would represent 55% of the European biomethane availability. Since several other industrial sectors rely on bioenergy for CO₂ emission mitigation or use biomass as a feedstock (e.g., pulp and paper industry), biomass- and biomethane-fired kilns are not expected to meet alone the entire lime production needs in Belgium.

While biomass can contribute to industrial energy transition, its sustainability depends on careful sourcing and management. Future biomass supply in Europe is expected to come from a combination of woody biomass (including wood removals, forestry residues, and industrial by-products), agricultural biomass (energy crops and agricultural residues), and recycled and waste streams such as paper waste, wood waste, or household waste [59]. Biomass delivers climate benefits when sourced sustainably and without generating an imbalance in the carbon cycle. For instance, the use of agricultural residues and short-rotation crops as fuel generally have favorable carbon balances as they regrow quickly. On the other hand, the impact of using forest residues is more complex. Harvesting them can increase CO₂ emissions, but sustainable forest management strategies and thinning can also accelerate forest growth and prevent wildfires, consequently reducing CO₂ emissions. Moreover, energy crops cultivated on surplus land contribute to emission reductions.

Bioenergy growth raises additional concerns including worsening of water scarcity (particularly in water-stressed regions), degradation of soil quality (through fertilizer use, or excessive extraction rates), reduction of biodiversity (from deforestation or excessive extraction rates), and competition with food production (contributing to higher food prices and food-security risks if not managed carefully). Consequently, biomass should be viewed as a limited strategic resource whose use must be carefully targeted to sectors where it provides the greatest decarbonization benefit, while taking into account trade-offs between greenhouse gases emissions, water use, soil health, and biodiversity [89].

3.3.4. Deployment of large-scale CCS: incentives and infrastructure availability

The implementation of CC is inevitable for the hard-to-abate lime sector. However, it comes with a variety of challenges, including sufficient economic and policy incentives, transport infrastructure planning, and access to storage capacity.

First, according to the results of the parameter sweep analysis, the energy transition in the lime industry can be accelerated by lower electricity prices and higher CO₂ allowance costs. However, current CO₂ ETS prices are too low to provide a strong incentive for CC implementation in lime production facilities. Indeed, after plummeting to around €55/tCO₂ in February 2024, the EU-ETS carbon price experienced a

slight increase, exceeding €70/tCO₂ in February 2026 [66]. These values are far below the ETS price that would be required to rule out natural gas-fired lime production with unabated emissions.

Even if economic conditions become favorable and CO₂ is captured at industrial scale, CO₂ transport and storage infrastructure will also be required. In Belgium, there are five lime production plants located in Aisémont, Seilles, Moha, Hermalle, and On-Jemelle (see Supplementary Material, Figure S1). When compared with the long-term vision of the Belgian CO₂ pipeline network (see Supplementary Material, Figure S2), four out of these five production facilities are located along the Charleroi-Liège axis, where a pipeline for CO₂ transport is planned. Capturing CO₂ emissions from all Belgian lime plants would require approximately 1 MtCO₂/y of transport and storage capacity, representing around 4% of Fluxys' planned transport capacity towards North Sea storage sites by 2030 [90].

However, the deployment of CO₂ transport and storage infrastructure is still facing a “chicken-and-egg” problem. Building pipelines, compression stations, shipping terminals, injection wells, and storage sites requires substantial upfront capital investment. Infrastructure developers are reluctant to invest without sufficient confidence about the captured CO₂ volumes, while capture facilities will not start operating unless reliable transport and permanent storage are guaranteed. This paradox is expected to create a mismatch between required and available transport and storage capacity, as the Clean Air Task Force (CATF) estimates that, by 2030, only half of the volume of captured CO₂ in Europe will be effectively stored [91].

For de-risking the implementation of CCS, permanent geological storage must be guaranteed, with sufficient storage capacity, adequate reservoir injectivity, and seal integrity ensuring long-term containment [92] [93]. Since several countries, such as Belgium, lack suitable geological sites for permanent CO₂ storage, large-scale implementation of CCS will depend on access to storage sites abroad. This reliance on cross-border storage is likely to increase competition among hard-to-abate sectors for access to limited CO₂ storage capacity [65], while regulatory and legal challenges associated with transporting CO₂ across national borders represent an additional obstacle to the deployment of CCS projects.

Nevertheless, important progress has been made towards the development of cross-border transport and storage in Europe. Belgium and the United Kingdom have signed a memorandum under the London protocol permitting the permanent storage of CO₂ captured from Belgian industries in UK's geological reservoirs. Such cooperation is expected to significantly reduce transport and storage costs for North-West European emitters (by up to 28% compared with scenarios without cross-border transport), while generating substantial revenues for the UK, estimated at approximately £2 billion annually by 2030 [94]. Moreover, several countries, including the United Kingdom, Denmark, Norway, Germany, Japan and the United States, have recently introduced funding programs, storage licensing rounds and regulatory reforms to accelerate the deployment of CO₂ transport and storage, recognizing that shared transport and storage infrastructure is essential for large-scale CCS deployment [95].

To address these barriers, the IEA identified three key priorities to accelerate the deployment of CO₂ transport and storage infrastructure. Firstly, as developing storage sites typically requires 3–10 years, geological storage resources should be assessed as early as possible using standardized methods, while permitting procedures should be simplified. Secondly, legal and regulatory frameworks should be reviewed to ensure the safe transport and permanent storage of CO₂, support CCUS business models, facilitate cross-border cooperation, and cover different transport modes. Finally, public policies should encourage private investment in shared CO₂ transport and storage infrastructure as well as multi-user CCUS hubs, enabling economies of scale and reducing investment risks [95].

3.3.5. Challenges for large-scale hydrogen deployment in the lime industry

CO₂ accounting revealed that, today, hydrogen-fired systems would exhibit considerably higher CO₂ emissions than other low-carbon alternative production routes, owing to the higher indirect emission factor

of hydrogen. Despite rapid growth in announced projects, the production of low-emissions hydrogen remains a challenge as electrolytic and CCUS-based hydrogen currently represent less than 1% of global hydrogen production. Indeed, although global electrolysis capacity doubled in 2025 to exceed 4 GW, the current production mix is dominated by unabated natural gas and coal-based production [96]. This observation is attributable to the high production cost of low-emissions hydrogen compared with conventional fossil-based production. According to the IEA [96], global fossil-based (without CCUS) hydrogen production costs lie between USD 1–4.5/kg H₂. On the other hand, CCUS-based production costs USD 1.6–5/kg H₂, while electrolysis results in hydrogen costs of USD 3.5–15/kg H₂. Electrolytic hydrogen production costs are driven by electricity prices, operating hours, and electrolyzer investment costs. The latter remain relatively high, typically ranging between USD 1900–2500/kW. Except in China, where electrolyzer manufacturing and installation amounts to USD 500–1100/kW [96], reductions in equipment costs are essential for a widespread deployment.

Although hydrogen production costs are expected to decline by 2030, projected ranges remain wide, especially for electrolytic hydrogen: USD 2–10/kg H₂ for wind onshore-based electricity, and above USD 12/kg H₂ if electricity is produced with offshore wind turbines or solar panels [96]. This large uncertainty reflects volatile electricity prices, and persistent uncertainty regarding technology costs and financing conditions, complicating investment decisions for energy-intensive industries considering hydrogen as a decarbonization pathway.

Moreover, as highlighted by the parameter sweep analysis, economic attractiveness of hydrogen-based configurations is also challenging, since electricity costs exceeding those of hydrogen are required. This suggests that hydrogen must either be produced from cheaper fossil resources (assuming that indirect emissions do not come with an additional cost), imported at low cost from large renewable hubs, or be produced only when low-cost electricity is available. These stringent conditions result in large-scale deployment of hydrogen-fired lime kilns that seems highly improbable.

Beyond economic considerations, fuel switching towards hydrogen in lime kilns is also constrained by the limited availability of hydrogen transport infrastructure. Similar to CCS, hydrogen deployment is affected by a "chicken-and-egg" dilemma: investors are reluctant to develop large-scale hydrogen production plants and transmission infrastructure without guaranteed industrial demand, while industrial consumers will not commit without reliable, affordable hydrogen supply and transport infrastructure.

This uncertainty is reflected in recent projections. In its 2026 report [96], the IEA reduced its estimate of announced hydrogen production capacity for 2030 from 37 Mt/y (reported in 2025) to 27 Mt/y, mainly due to high production costs, insufficient public support, permitting delays, regulatory uncertainty, and a lack of secured demand. Moreover, only 3.2 Mt/y (i.e., approximately 9% of announced capacity) has reached final investment decision (FID) or is currently under construction [96]. By comparison, complete fuel switching in the European lime industry would require approximately 0.65 Mt H₂/y, i.e., 2.4% of the announced production capacity by 2030 or equivalently 20% of the capacity beyond the FID stage, highlighting the gap between announced ambitions and projects likely to materialize.

Even if sufficient hydrogen production capacity becomes available, large-scale hydrogen supply will require substantial infrastructure development, including transmission pipelines, compression and liquefaction facilities, as well as import and export terminals.

For pure hydrogen, pipelines are usually the cheapest transportation mode where suitable routes are available and sufficient demand exists. While more than 40,000 km of hydrogen transport pipelines have been announced worldwide for completion by 2035, only around 9% of this network is operational, under construction, or has secured investment, highlighting the gap between announced ambitions and actual deployment. Nevertheless, major milestones have been reached in 2025, as the world's longest repurposing of a natural gas pipeline (400 km) was completed in Germany, and the construction of the world's longest hydrogen pipeline (1000 km) started in China [96].

Alternatively, where pipelines are not technically or economically feasible, hydrogen may be transported by ship either in liquid form or via alternative carriers, such as ammonia or liquid organic hydrogen carriers. However, this transport mode requires energy-intensive liquefaction and reconversion processes, consuming more than 30% of hydrogen's energy content. In addition, these alternatives have not yet reached commercial maturity, limiting their near-term potential for large-scale hydrogen supply [96].

3.3.6. Study limitations and future research directions

Several limitations should be considered when interpreting the results of this study. First, the analysis was restricted to the PFRK design, which represents the most performant and dominant technology for industrial lime production but do not capture the full diversity of kiln designs currently in operation. Second, the cost estimates focus solely on greenfield scenarios, excluding retrofitting that may present different technical and economic characteristics. Furthermore, learning curve effects, i.e., reductions in CAPEX that would occur once the technology becomes Nth-of-a-Kind (NOAK), are not considered. Finally, fixed operating and maintenance costs, infrastructure modification costs (e.g., electric grid capacity increase), and process units including flue gas pre-treatment and CO₂ polishing are neglected for the economic assessment. Hence, addressing these in future research would contribute to more accurate estimations and greater confidence in the techno-economic assessments.

In addition, this study focuses on industrial-scale lime production through thermal calcination of CaCO₃. While these technologies represent the most realistic options for achieving substantial emission reductions over the coming decades, alternative “cold” production routes, avoiding or reducing CO₂ emissions, are also investigated at lab scale (TRL 2–3 [97]). Among these emerging production routes, Ellis et al. [98] demonstrated an electrochemical process operating at ambient temperature, decarbonating CaCO₃ and precipitating Ca(OH)₂. During this process, a gaseous mixture of O₂ and CO₂ is produced at the anode, with a relatively high CO₂ concentration enabling a facilitated CO₂ capture process. The hydrogen produced at the cathode might be used to partially fulfill the process energy demand. The key benefit of this electrochemical production process is that it bypasses the production of the CaO intermediate when Ca(OH)₂ is the desired product, while Ca(OH)₂ dehydration to CaO is less energy-intensive than conventional thermal treatment. Alternatively, Hanein et al. [99] proposed a liquid-solid reaction between CaCO₃ and NaOH for Ca(OH)₂ production at room temperature. This process stores CO₂ in mineral form Na₂CO₃·xH₂O, thus, avoiding both fuel- and process-related emissions. Including these emerging technologies in future assessments could further complete the picture of decarbonization pathways in the lime sector.

Additional sensitivity analysis considering kiln efficiency improvement as well as alternative CC technologies (e.g., membrane- and adsorption-based processes or hybrid configurations) characterized by higher capture rates, and CCUS routes (e.g., CO₂ mineralization) should also be explored. Detailed Life Cycle Assessment (LCA) should be conducted to evaluate environmental impacts beyond CO₂ emissions accounting. Finally, further research should focus on an industrial cluster-level optimization approach, considering material and energy exchanges between industries.

Beyond its application to the lime sector, the methodological framework developed in this study provides a systematic approach for comparing alternative decarbonization pathways across multiple key performance indicators, and can thus be applied to other industrial sectors. By combining thermodynamic modelling with environmental and economic assessments, the framework enables consistent evaluation of competing technologies. The study offers estimates of the additional energy requirements for key components of the industrial energy transition such as process electrification and CO₂ capture. The results offer energy providers insights into potential infrastructure modification requirements, such as the need for increased electricity supply capacity and molecules transport infrastructure deployment. Moreover, the cost estimates presented in the economic analysis serve as a basis for comparison of the investigated options relative to one another, while identifying viable and robust strategies that support the decarbonization of the industry.

4. Conclusion

This study provides a systematic techno-economic analysis of a comprehensive set of decarbonization pathways for the lime industry, by integrating fuel switching (biomass, biomethane, hydrogen), electrification, CO₂ capture and storage (CCS, via MEA-based chemical absorption or electrified CO₂ purification unit (CPU)), and CO₂ capture and utilization (CCU, via e-methane production from captured CO₂ and electrolytic hydrogen) within a unified superstructure optimization framework. In addition to comparing alternative production routes using thermodynamic, environmental, and economic indicators, the proposed methodology accounted for uncertainty in future energy and carbon prices through scenario-based and parameter sweep analyses. This approach provides a more robust basis for technology selection than conventional assessments relying on a limited number of predefined market scenarios.

The base case 'NG', i.e., conventional natural gas-fired parallel flow regenerative kiln, is characterized by the highest carbon footprint and the lowest energy demand, amounting to 1 tCO₂/t_{lime} and 3.6 GJ/t_{lime}, respectively. According to the CO₂ accounting, fuel switching alone is insufficient to deeply decarbonize lime production, resulting in modest emissions reduction of approximately 18% compared to the base case. It can be explained by the dominance of the CO₂ emissions coming from the calcination reaction itself (0.786 tCO₂/t_{lime}). Consequently, implementing CO₂ capture (CC) becomes unavoidable to reduce process-related emissions at the expense of higher investments and increased energy demand. Among the pathways investigated, MEA-based CC is characterized by a CO₂ emission reduction potential of 73–116% but exhibits a significant energy penalty (+136–172%) stemming from solvent regeneration, mostly heat-related. Oxycombustion coupled with cryogenic CO₂ purification consistently demonstrated the best compromise between energy efficiency (energy penalty of 44–59% compared to 'NG'), capital investment (+€27–37/t_{lime} vs. +€38–50/t_{lime} with MEA), emission reduction (80–122%), and production costs. Furthermore, net-negative emissions are achievable through bioenergy combined with CO₂ capture and storage (BECCS), provided that sustainable biomass resources remain available. Conversely, hydrogen- and electricity-based production routes show promising long-term potential under decarbonized electricity and hydrogen supply chains, while the CCU pathway remains constrained by its high electricity demand (+8.6 GJ/t_{lime} or +239% compared to 'NG') stemming almost entirely from the electrolyzer operation.

The study also highlights the critical influence of future energy and CO₂ emission allowance prices on technology competitiveness. While conventional natural gas-fired production remains economically attractive under current market conditions, increasing CO₂ emission allowance prices and the availability of affordable low-carbon electricity substantially improve the competitiveness of CC-based options. The parameter sweep analysis, systematically exploring a broad set of economic conditions, further identified the ranges of energy and carbon prices under which each configuration becomes economically optimal, providing practical decision rules for selecting resilient strategies under market uncertainty. Overall, oxycombustion coupled with CC appears as the most promising emission mitigation pathway for the lime industry, offering the best compromise between environmental performance and economic competitiveness. However, the successful deployment of this pathway will require the rapid development of CO₂ transport and storage infrastructure, making its development a key priority for enabling industrial-scale CO₂ capture.

Beyond the lime industry, the methodology can readily be adapted to other industrial sectors facing similar challenges. Future work should improve economic assessments by incorporating brownfield scenarios and learning curve effects. Moreover, infrastructure modification, flue gas pre-treatment prior to CC, and CO₂ polishing to meet transport purity requirements should be included in the scope of the study. Additional CC technologies, low-TRL "cold" production pathways, as well as other CCUS routes should also be explored. Finally, detailed Life Cycle Assessment (LCA) should be conducted to evaluate environmental impacts beyond CO₂ emissions accounting.

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6. References

- [1] J. Chen, L. Duan and Z. Sun, "Review on the Development of Sorbents for Calcium Looping," *Energy & Fuels*, April 2020. DOI: 10.1021/acs.energyfuels.0c00682
- [2] J. Rowlatt and M. Poynting, "Planet-warming gas levels rose more than ever in 2024," BBC Climate & Science, 17 January 2025. [Online]. Available: <https://www.bbc.com/news/articles/c30dn5dn53jo>. [Accessed 4 April 2025].
- [3] Climat.be, "Emissions de gaz à effet de serre : émissions par secteur," 11 March 2026. [Online]. Available: <https://climat.be/en-belgique/climat-et-emissions/emissions-des-gaz-a-effet-de-serre/emissions-par-secteur>.
- [4] Statista, "Distribution of electricity generation in Belgium in 2024, by source," [Online]. Available: <https://www.statista.com/statistics/1234898/belgium-distribution-of-electricity-production-by-source/>. [Accessed 11 March 2026].
- [5] International Renewable Energy Agency - IRENA, "Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7," Abu Dhabi, 2024.
- [6] European Commission, "'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality," [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550>. [Accessed 01 August 2025].
- [7] European Commission, "The European Green Deal: Striving to be the first climate-neutral continent," 2019. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
- [8] J. A. Oates, *Lime and Limestone: Chemistry and Technology, Production and Uses*, Wiley-VCH Verlag GmbH, 1998.
- [9] A. Laveglia, S. Luciano, N. Ukrainczyk, N. De Belie and E. Koenders, "Hydrated lime life-cycle assessment: Current and future scenarios in four EU countries," *Journal of Cleaner Production*, vol. 369, 2022. DOI: <https://doi.org/10.1016/j.jclepro.2022.133224>

- [1 European Environment Agency, "EU ETS data viewer," [Online]. Available:
0] <https://www.eea.europa.eu/en/analysis/maps-and-charts/emissions-trading-viewer-1-dashboards>.
[Accessed 10 June 2025].
- [1 A. Sagastume Gutiérrez, J. B. Cogollos Martínez and C. Vandecasteele, "Energy and exergy
1] assessments of a lime shaft kiln," *Applied Thermal Engineering*, vol. 51, no. 1, 2013. DOI:
<https://doi.org/10.1016/j.applthermaleng.2012.07.013>
- [1 Mineral Products Association, "MPA Lime - Net Negative 2040 Roadmap," 2023.
2]
- [1 European Lime Association, "A pathway to negative CO₂ emissions by 2050: The contribution of the
3] lime industry to a carbon-neutral Europe," 2023.
- [1 M. Simoni, M. D. Wilkes, S. Brown, J. L. Provis, H. Kinoshita and T. Hanein, "Decarbonising the lime
4] industry: State-of-the-art," *Renewable and Sustainable Energy Reviews*, vol. 168, 2022. DOI:
<https://doi.org/10.1016/j.rser.2022.112765>
- [1 Lhoist, "Carbon Action 2030," 2023.
5]
- [1 European Lime Association, "CO₂ Innovation in the lime sector 3.0," 2022.
6]
- [1 European Lime Association, "CO₂ Innovation in the Lime Sector 4.0," 2025.
7]
- [1 H. Piringer and P. Bucher, "Is it sufficient to use renewable energy sources for lime kilns to achieve
8] the climate goals?," ZKG, 2022.
- [1 Fraunhofer ISI, "Direct electrification of industrial process heat: An assessment of technologies,
9] potentials and future prospects for the EU. Study on behalf of Agora Industry," 2024.
- [2 C. Blackman, "Electrification's promising path," *International Cement Review*, May 2024.
0]
- [2 SaltX Technology, "SaltX receives a \$1.5 million R&D grant from Frontier to support large-scale
1] electrified calcination project," [Online]. Available: <https://www.saltxtechnology.com/cision/saltx-receives-a-1-5-million-rd-grant-from-frontier-to-support-large-scale-electrified-calcination-project/>.
[Accessed 11 March 2026].
- [2 ZEQL, "Zero Emission Quicklime," [Online]. Available: <https://www.zeql.com/>. [Accessed 11 March
2] 2026].
- [2 U. Khan, C. C. Ogbaga, O.-A. O. Abiodun, A. A. Adeleke, P. P. Ikubanni, P. U. Okoye and J. A. Okolie,
3] "Assessing absorption-based CO₂ capture: Research progress and techno-economic assessment

overview," *Carbon Capture Science & Technology*, vol. 8, 2023. DOI: <https://doi.org/10.1016/j.ccst.2023.100125>

- [2] H. Hekmatmehr, A. Esmaeili, M. Pourmahdi, S. Atashrouz, A. Abedi, M. Ali Abuswer, D. Nedeljkovic,
- 4] M. Latifi, S. Farag and A. Mohaddespour, "Carbon capture technologies: A review on technology readiness level," *Fuel (Guildford)*, vol. 363, 2024. DOI: 10.1016/j.fuel.2024.130898
- [2] M. J. Regufe, A. Pereira, A. F. P. Ferreira, A. M. Ribeiro and A. E. Rodrigues, "Current Developments of
- 5] Carbon Capture Storage and/or Utilization—Looking for Net-Zero Emissions Defined in the Paris Agreement," vol. 14, no. 9, 2021. DOI: 10.3390/en14092406
- [2] M. G. Plaza, S. Martínez and F. Rubiera, "CO₂ Capture, Use, and Storage in the Cement Industry:
- 6] State of the Art and Expectations," *Energies*, vol. 13, no. 21, 2020. DOI: 10.3390/en13215692
- [2] M.-B. Hägg, A. Lindbråthen, X. He, S. Nodeland and T. Cantero, "Pilot Demonstration-reporting on
- 7] CO₂ Capture from a Cement Plant Using Hollow Fiber Process," in *13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland, 2017*.
- [2] W. Y. Hong, "A techno-economic review on carbon capture, utilisation and storage systems for
- 8] achieving a net-zero CO₂ emissions future," *Carbon Capture Science & Technology*, vol. 3, 2022. DOI: <https://doi.org/10.1016/j.ccst.2022.100044>
- [2] L'Echo, "Carmeuse pourra décarboner tous ses sites industriels d'ici fin 2028," [Online]. Available:
- 9] <https://www.lecho.be/entreprises/industries-de-base/carmeuse-pourra-decarboner-tous-ses-sites-industriels-d-ici-fin-2028/10624292.html>. [Accessed 10 March 2026].
- [3] Lhoist, "EVEREST: Decarbonizing our main lime plant," [Online]. Available:
- 0] <https://www.lhoist.com/en/everest>. [Accessed 17 June 2026].
- [3] M. Shen, L. Tong, S. Yin, C. Liu, L. Wang, W. Feng and Y. Ding, "Cryogenic technology progress for CO₂
- 1] capture under carbon neutrality goals: A review," *Separation and Purification Technology*, vol. 299, 2022. DOI: <https://doi.org/10.1016/j.seppur.2022.121734>
- [3] H. Enayatizadeh, A. Arjomand, T. Tynjälä and E. Inkeri, "Cryogenic carbon capture design through
- 2] CO₂ anti-sublimation for a gas turbine exhaust: Environmental, economic, energy, and exergy analysis," *Energy*, vol. 304, 2024. DOI: <https://doi.org/10.1016/j.energy.2024.132244>
- [3] Lhoist, "CALCC Project Summary," [Online]. Available: <https://www.lhoist.com/en/calcc>. [Accessed
- 3] 02 March 2025].
- [3] Innovation Fund, "CalCC - Project Factsheet," 2026.
- 4]
- [3] Walloon Region, "HECO₂ - Strategic Program for Industrial Circularity," [Online]. Available:
- 5] <https://ecosysteme-economiecirculaire.wallonie.be/en/action-plan/heco2-26-walloon-industrial-players-boost-innovation-in-circular-economy-and-energy-transition/>. [Accessed 10 March 2026].

- [3 Carmeuse, "CO2 Roadmap: Pathway to carbon neutrality," 2025.
6]
- [3 Circular Wallonia, "Leopard," [Online]. Available: <https://ecosysteme-economiecirculaire.wallonie.be/fiche-action/leopard/>. [Accessed 17 June 2026].
7]
- [3 Innovation Fund, "Leopard: Lime operation decarbonised - Project Factsheet," 2026.
8]
- [3 Holcim, "CARBON HUB CPT01," [Online]. Available: <https://www.holcim.com/what-we-do/green-operations/ccus/carbon-hub-cpt01>. [Accessed 17 June 2026].
9]
- [4 Innovation Fund, "CARBON HUB CPT01 - Project factsheet," 2026.
0]
- [4 Carmeuse, "Holcim Romania and Cinea sign grant agreement for CARBON HUB CPT01," [Online].
1] Available: <https://www.carmeuse.com/eu-en/newsroom/global/holcim-romania-and-cinea-sign-grant-agreement-carbon-hub-cpt01>. [Accessed 17 June 2026].
- [4 Carmeuse, "Engie et Carmeuse annoncent l'arrêt du projet Colombus pour des raisons économiques
2] et réglementaires," [Online]. Available: <https://www.carmeuse.com/eu-fr/newsroom/global/engie-et-carmeuse-annoncent-larret-du-projet-columbus-pour-des-raisons-economiques>. [Accessed 21 June 2025].
- [4 M. Salman, D. Flórez-Orrego, D. Coppitters, R. Mitraki, F. Maréchal and G. Léonard, "Decarbonising
3] the Glass Industry: A Comprehensive Techno- Economic Assessment of Low-Emission Pathways," *Computers & Chemical Engineering*, August 2025. DOI: 10.1016/j.compchemeng.2025.109329
- [4 F. Schorcht, I. Kourti, B. M. Scalet, S. Roudier and L. Delgado Sancho, "Best Available Techniques
4] (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)," Publications Office of the European Union, 2013.
- [4 D. Flórez-Orrego, M. Ribeiro Domingos and F. Maréchal, "A systematic framework for the multi-time
5] integration of industrial complexes and urban systems, in: 7th International Conference on Contemporary Problems of Thermal Engineering," in *CPOTE 2022*, Warsaw, 2022.
- [4 A. Bes, *Dynamic Process Simulation of Limestone Calcination in Normal Shaft Kilns*, PhD thesis, Otto
6] von Guericke Universität Magdeburg, 2005.
- [4 International Energy Agency (IEA), "Outlook for biogas and biomethane: Prospects for organic
7] growth," 2020.
- [4 Element Energy Limited, "Industrial Fuel Switching Market Engagement Study: Final report for
8] Business, Energy & Industrial Strategy Department," 2018.

- [4 H. Piringer, "New PFR lime kiln process with blast furnace gas and oxygen," *ZKG*, 2021.
9]
- [5 S. O. Gardarsdottir, E. De Lena, M. Romano, S. Roussanaly, M. Voldsund, J.-F. Pérez-Calvo, D. Berstad,
0] C. Fu, R. Anantharaman, D. Sutter, M. Gazzani, M. Mazzotti and G. Cinti, "Comparison of
Technologies for CO₂ Capture from Cement Production - Part 2: Cost Analysis," *Energies*, vol. 12, no.
3, 2019. DOI: 10.3390/en12030542
- [5 S.-M. Kim and G. Léonard, "CO₂ Capture Technologies and Shortcut Cost Correlations for Different
1] Inlet CO₂ Concentrations and Flow Rates. Part 1: Chemical Absorption," *International Journal of
Greenhouse Gas Control*, vol. 145, 2025. DOI: <https://doi.org/10.1016/j.ijggc.2025.104391>
- [5 S. Roussanaly, N. Berghout, T. Fout, M. Garcia, S. Gardarsdottir, S. M. Nazir, A. Ramirez and E. S.
2] Rubin, "Towards improved cost evaluation of Carbon Capture and Storage from industry,"
International Journal of Greenhouse Gas Control, vol. 106, 2021. DOI:
<https://doi.org/10.1016/j.ijggc.2021.103263>
- [5 Ecoquery, "Ecoinvent database," [Online]. Available: <https://ecoquery.ecoinvent.org/3.9.1/cutoff>.
3]
- [5 ENTSO-E & ENTSG, "TYNDP 2024: Scenarios Report - Final Version," January 2025.
4]
- [5 International Energy Agency (IEA), "Global Hydrogen Review," October 2024.
5]
- [5 Chemical Engineering, "The chemical engineering plant cost index," [Online]. Available:
6] [https://www.chemengonline.com/pci-](https://www.chemengonline.com/pci-home#:~:text=The%20CEPCI%20consists%20of%20a,weighted%20sum%20of%20several%20components.)
home#:~:text=The%20CEPCI%20consists%20of%20a,weighted%20sum%20of%20several%
20components. [Accessed 8 April 2024].
- [5 Fluxys, "CO₂ infrastructure for Belgium," [Online]. Available:
7] <https://www.fluxys.com/en/co2/activities/co2-transmission>. [Accessed 11 December 2024].
- [5 Fluxys, "CO₂ Hub in Zeebrugge," [Online]. Available: [https://www.fluxys.com/en/projects/co2-hub-](https://www.fluxys.com/en/projects/co2-hub-in-zeebrugge)
8] in-zeebrugge. [Accessed 11 December 2024].
- [5 Material Economics, "EU Biomass Use In A Net-Zero Economy - A Course Correction for EU Biomass,"
9] 2021.
- [6 Eurostat, "Electricity price statistics," [Online]. Available: [https://ec.europa.eu/eurostat/statistics-](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics)
0] explained/index.php?title=Electricity_price_statistics . [Accessed 4 November 2025].
- [6 SCPI & FPS Public Health, "Methodological appendix to the report "Additional investments in existing
1] net-zero emissions scenarios for Belgium", " 2025.

- [6 European Hydrogen Observatory, "Cost of hydrogen production," [Online]. Available:
2] <https://observatory.clean-hydrogen.europa.eu/index.php/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production>. [Accessed 2026].
- [6 Eurostat, "Natural gas price statistics," [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics . [Accessed 4 November 2025].
- [6 BIP Europe, "Insights into the current cost of biomethane production from real industry data.," 2023.
4]
- [6 EnergyVille, "Main Edition 2025 - Assumptions," [Online]. Available:
5] <https://perspective2050.energyville.be/results/main-edition-2025/assumptions>. [Accessed 18 June 2026].
- [6 Statista, "Daily European Union Emission Trading System (EU-ETS) carbon pricing from 2025 to
6] 2026," [Online]. Available: https://www.statista.com/statistics/1322214/carbon-prices-european-union-emission-trading-scheme/?srsltid=AfmBOoolIGRqkPnpq7M2PMSzeS7C8yf0Y_LeJtF-HlQdTlLgRWxiJve5.
- [6 Elia, "Belgian Electricity System Blueprint For 2035-2050.," 2024.
7]
- [6 C.-C. Cormos, "Economic evaluations of coal-based combustion and gasification power plants with
8] post-combustion CO₂ capture using calcium looping cycle," *Energy*, vol. 78, pp. 665-673, 2014. DOI: <https://doi.org/10.1016/j.energy.2014.10.054>
- [6 CILE, "Le prix de l'eau," [Online]. Available: <https://www.cile.be/facturation/le-prix-de-leau>.
9]
- [7 EnergyVille, "PATHS 2050 - Scenarios towards a carbon-neutral Belgium by 2050," Genk, 2023.
0]
- [7 ELIA, "Electricity Scenarios for Belgium Towards 2050: ELIA's Quantified Study on the Energy
1] Transition in 2030 and 2040," Brussels, 2017.
- [7 Clean Air Task Force, "The cost of carbon capture and storage in Europe - Interactive tool," 2025.
2] [Online]. Available: <https://www.catf.us/ccs-cost-tool/>.
- [7 International Renewable Energy Agency (IRENA), "Renewable Energy Technologies: Cost Analysis
3] Series - Volume 1: Power Sector," June 2012.
- [7 European Commission - European Hydrogen Observatory, "Cost of hydrogen production," [Online].
4] Available: <https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production>. [Accessed 13 June 2025].
- [7 International Energy Agency (IEA), "Towards hydrogen definitions based on their emissions
5] intensity," April 2023.

- [7 International Energy Agency (IEA), "Global Hydrogen Review," 2025.
6]
- [7 M. Stork, W. Meindersma, M. Overgaag and M. Neelis, "A Competitive and Efficient Lime Industry:
7] Cornerstone for a Sustainable Europe," July 2014.
- [7 Carbon Capture Journal, "Launch of Dinamx industrial CO₂ capture pilot in France," October 2020.
8] [Online]. Available:
<https://carboncapturejournal.com/news/launchofdinamx%20industrial%20co2capturepilot%20infrastructure/4440.aspx?Category=all>.
- [7 D. Verdonck, L. Dubois, G. De Weireld and D. Thomas, "Methodological Selection of Demixing
9] Liquid–Liquid Solvents Used in the Absorption–Regeneration Carbon Capture Process," *Industrial & Engineering Chemistry Research*, vol. 64, no. 9, pp. 4709–4724, 2025. DOI:
<https://doi.org/10.1021/acs.iecr.4c04342>
- [8 AACE, "AACE International Recommended Practice No. 104R-19: Communicating Expected Estimate
0] Accuracy, TCM Framework: 7.3 - Cost Estimating and Budgeting," 2021.
- [8 EnergyVille, "PATHS2050 Coalition: Belgian Energy System Pathways 2025 - Executive Summary,"
1] April 2025.
- [8 A. Gailani, S. Cooper, S. Allen, A. Pimm, P. Taylor and R. Gross, "Assessing the potential of
2] decarbonization," *Joule*, vol. 8, pp. 576–603, 2024. DOI: <https://doi.org/10.1016/j.joule.2024.01.007>
- [8 A. Robinson Medici, A. Giuliano, N. Pierro, I. de Bari and S. Papadokonstantakis, "Green-Hydrogen
3] Energy Share: An Intuitive Metric to Compare Energy Density and H₂ Efficiency in Biofuels and E-Fuels," *ACS omega*, vol. 11, no. 3, 2026. DOI: <https://doi.org/10.1021/acsomega.5c09592>
- [8 Statista, "Leading countries based on production of lime worldwide in 2024," [Online]. Available:
4] <https://www.statista.com/statistics/657049/production-of-lime-worldwide/>. [Accessed 12 August 2025].
- [8 Commission for the Regulation of Electricity and Gas (CREG), "Annual Report 2024," Brussels, April
5] 2025.
- [8 J. C. Laguna, A. Moglianesi, P. Vingerhoets, W. Nijs and P. Lodewijks, "PATHS 2050 - Scenarios towards
6] a carbon-neutral Belgium by 2050," EnergyVille, Genk, 2023.
- [8 International Energy Agency (IEA), "Outlook for Biogas and Biomethane: A global geospatial
7] assessment," 2025.
- [8 European Lime Association (EuLA), "La chaux, puits de carbone naturel," 2021.
8]
- [8 IRENA, "Global bioenergy supply and demand projections," 2014.
9]

- [9 Fluxys, "Zeebrugge offshore CO₂ pipeline," [Online]. Available:
0] <https://www.fluxys.com/en/projects/zeebrugge-offshore-co2-pipeline>. [Accessed 21 June 2026].
- [9 Clean Air Task Force, "Six things we learned at the Commission's 2022 CCUS Forum," 20 December
1] 2022. [Online]. Available: <https://www.catf.us/2022/12/six-things-we-learned-2022-ccus-forum/>.
[Accessed 21 June 2026].
- [9 Working Group III of the Intergovernmental Panel on Climate Change, "Chapter 5 - Underground
2] geological storage," in *IPCC Special Report on Carbon Dioxide Capture and Storage*, 2005, pp. 195-
277.
- [9 International Energy Agency (IEA), "Methods to assess geological CO₂ storage capacity: status and
3] best practice," 2013.
- [9 "Belgium and UK sign agreement on carbon capture and storage," 16 June 2026. [Online]. Available:
4] <https://www.carboncapturejournal.com/ViewNews.aspx?NewsID=7301>. [Accessed 20 June 2026].
- [9 Internal Energy Agency (IEA), "CO₂ Transport and Storage," 25 April 2024. [Online]. Available:
5] <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage>. [Accessed 20 June 2026].
- [9 International Energy Agency (IEA), "Global hydrogen review," 2026.
6]
- [9 A. Gailani, S. Cooper, S. Allen, A. Pimm, P. Taylor and R. Gross, "Assessing the potential of
7] decarbonization options for industrial sectors," *Joule*, vol. 8, no. 3, pp. 576-603, 2024. DOI:
<https://doi.org/10.1016/j.joule.2024.01.007>
- [9 L. Ellis, A. Badel, M. Chiang, R. Park and Y.-M. Chiang, "Toward electrochemical synthesis of cement:
8] An electrolyzer-based process for decarbonating CaCO₃ while producing useful gas streams,"
Proceedings of the National Academy of Sciences, vol. 117, no. 23, pp. 12584-12591, 2020. DOI:
10.1073/pnas.1821673116
- [9 T. Hanein, M. Simoni, C. L. Woo, J. Provis and H. Kinoshita, "Decarbonisation of calcium carbonate at
9] atmospheric temperatures and pressures, with simultaneous CO₂ capture, through production of
sodium carbonate," *Energy & Environmental Science*, vol. 14, no. 12, pp. 6595-6604, 2021.