Research Article - Peer Reviewed Conference Proceeding
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

Transition Pathways for the Belgian Industry: Application to the Case of the Lime Sector

Rafailia Mitraki[a]*, Muhammad Salman[a], François Maréchal[b], Grégoire Léonard[a]

[a] University of Liège, Department of Chemical Engineering, Sart Tilman, Liège, Belgium
[b] Federal Polytechnic School of Lausanne, IPESE group, Sion, Switzerland
* Corresponding Author: rafailia.mitraki@uliege.be.

ABSTRACT

This study aims to analyze various pathways achieving CO_2 emission reduction in the lime industry, responsible for 1% of global anthropogenic emissions. A Blueprint (BP) model is developed, incorporating a superstructure of various energy transition pathways such as fuel switching, kiln electrification, and CO_2 capture (CC). Furthermore, the OSMOSE tool, developed at EPFL, is used to evaluate the superstructure for different years and energy scenarios impacting utilities and CO_2 emissions costs. Finally, a comparison between all alternative routes is performed on the basis of three key performance indicators: specific energy demand, specific CO_2 emissions, and specific total cost. From results, it comes that CC coupled with natural gas oxy-combustion, biomass- or biogas-fired lime kilns are the most cost-effective pathways for CO_2 emission mitigation, while hydrogen-firing represents one of the most expensive solutions for the lime sector.

Keywords: Lime Industry, Energy Transition, Superstructure Optimization

INTRODUCTION

The lime industry contributes significantly to CO_2 emissions, emitting 1–1.8 tCO_2/t_{lime} [1] and accounting for about 1% of global anthropogenic emissions [2]. The calcination reaction ($CaCO_3 + heat \rightarrow CaO + CO_2$) emits 0.786 tCO_2/t_{lime} and requires high temperatures (900–1100°C), typically achieved by fossil fuels combustion.

METHODOLOGY

This study aims to analyze various CO_2 emission reduction pathways for the lime sector. For this purpose, a Blueprint (BP) model is developed, consisting of detailed mass and energy balances as well as economic considerations, based on data from scientific literature and the lime sector Best Available Techniques reference document [1]. This BP model incorporates a superstructure (**Figure 1**) of various energy transition pathways: fuel switching (hydrogen ('H2'), biogas, solid biomass), natural gas oxy-combustion ('NGOxy'), kiln electrification ('Plasma') and CO_2 capture (CC) (i.e., chemical absorption with MEA, except for 'NGOxy' and 'Plasma' where cryogenic separation is considered).

The OSMOSE tool (an optimization framework developed at EPFL) is utilized to evaluate the superstructure for different scenarios from the PATHS2050 study [3] –whose assumptions are provided in the Supplementary Material– impacting utilities and CO_2 emissions costs. Finally, all alternative routes and the base case 'NG' (natural gas-fired kiln) are compared based on three key performance indicators (KPI): specific total cost (€/t_{lime}), specific scope 1 CO_2 emissions ($kgCO_2/t_{lime}$) and specific energy demand (kWh/t_{lime}). Results are reported in **Figure 2** and **Figure 3** for 2030 and 2050 respectively. Please note that presented costs should not be taken as predictions, but rather as results of sensitivity studies.

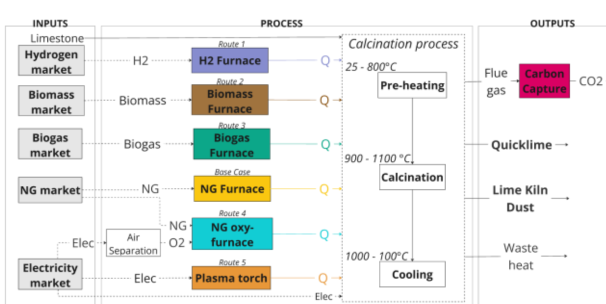

Figure 1. Superstructure of the lime sector.

RESULTS

The lime sector's CO_2 emissions range from -0.033 tCO_2/t_{lime} ('Biogas-CC') to 0.958 tCO_2/t_{lime} ('NG'). The CO_2 emission reduction potential of fuel switching without CC is bounded to 18% compared to 'NG', due to the calcination reaction-related emissions. Larger CO_2 emission reductions (69% ('NG-CC')—92% ('Plasma-CC')) are possible with CC, even enabling net negative emissions when combined with biofuels. However, this comes at the expense of significantly increased energy demand. Fuel switching without CC increases energy demand due to higher heat losses at the stack, while a 5% reduction is observed for 'NGOxy' due to the avoided nitrogen inert ballast.

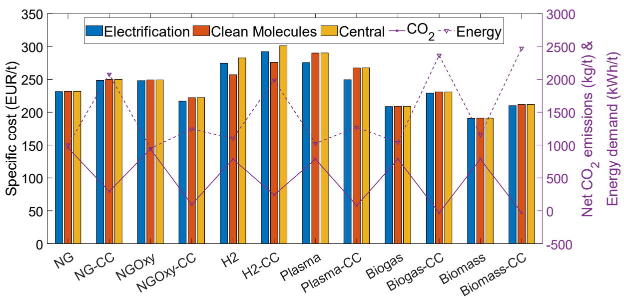

Figure 2: Comparison of different technologies in 2030.

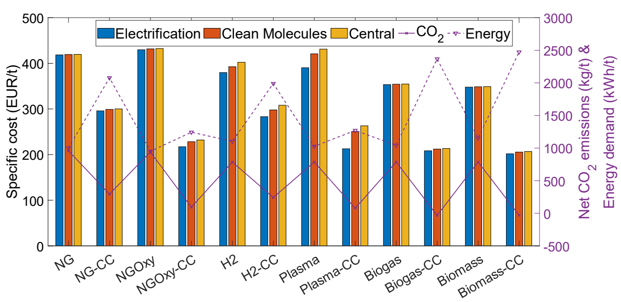

Figure 3: Comparison of different technologies in 2050.

In 2030, the optimum pathways appear to be 'Biomass-CC' and 'NGOxy-CC'. Significant CO_2 emissions reduction due to CC and lower fuel costs result in a specific total cost (STC) reduction of 9% compared to 'NG' (€232/t_{lime}) for 'Biomass-CC', despite increased total energy demand (+147%). 'NGOxy-CC' reduces CO_2 emissions by 90%, enabling a STC reduction of 4–6% compared to 'NG', despite a 24% higher energy demand. Conversely, plasma- and hydrogen-based configurations are the most expensive routes due to higher energy demand (between 3% ('Plasma') and 99% ('H2-CC')), CAPEX (between +9% ('Plasma') and +405% ('H2-CC') compared to 'NG'), and fuel cost.

In 2050, the STC of 'NG' reaches €419/t_{lime} and, with a carbon price of €350/tCO_2, all CC-based configurations are characterized by a lower STC than the cheapest configuration without CC (i.e., 'Biomass'). 'Biomass-CC' remains the optimal route, with a STC reduction of 51% compared to 'NG', closely followed by 'Biogas-CC' and 'NGOxy-CC', reducing STC by 49% and 45-48% respectively, depending on the scenario. 'Plasma-CC' comes 4th in the clean molecules and central scenarios (respectively 40% and 37% lower STC than 'NG'), and 3rd in the electrification scenario (49% lower STC than 'NG') due to favorable electricity prices. Despite lower hydrogen prices in 2050, hydrogen-firing in lime kilns remains one of the most expensive transition pathways for the sector, for the same reasons as previously mentioned.

CONCLUSION

This study offers a foundation for decision-making based on specific KPIs for future scenarios. CC coupled with biomass- or biogas-fired kilns and oxy-combustion configuration represent the most cost-effective routes for emissions reduction in the lime sector. However, biomass availability problems should not be overlooked.

DIGITAL SUPPLEMENTARY MATERIAL

Supplementary material (including energy demands and CO_2 emissions for each configuration, and commodities prices) can be accessed here: LAPSE:2025.0003

ACKNOWLEDGEMENTS

This paper is supported by the Belgian Fund for Scientific Research (FRS-FNRS) through a FRIA grant.

REFERENCES

1. Schorcht F., Kourti I., Scalet B. M., Roudier S., and Delgado Sancho L. Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide. *Publications Office of the European Union* (2013). DOI: 10.2788/12850.
2. Laveglia A., Luciano S., Ukrainczyk N., De Belie N., and Koenders E. Hydrated lime life-cycle assessment: Current and future scenarios in four EU countries. *J. Clean. Prod.* 369 (2022) https://doi.org/10.1016/j.jclepro.2022.133224
3. EnergyVille. Paths2050 scenarios, 2023. https://perspective2050.energyville.be/