BerkeleyHaas
2023 HAAS SUSTAINABLE RESEARCH BUSINESS PRIZE

Cost-efficient Decarbonization of Portland Cement Production

By Gunther Glenk, Anton Kelnhofer, Rebecca Meier,
and Stefan Reichelstein

We develop an economic model for identifying cost-efficient pathways for decarbonization. Applied to European cement plants, we find that a carbon price of €81 per ton, as observed on average in Europe in 2022, incentivizes firms to reduce their annual direct emissions by about one-third relative to current levels.

KEY FINDINGS

- We propose a generic abatement cost framework for identifying cost-efficient pathways toward substantial emission reductions.
- When calibrated to European cement plants, we find that a carbon price of €81 per ton, as observed on average in Europe in 2022, incentivizes firms to reduce their annual direct emissions by about one-third relative to the status quo.
- Yet, if carbon prices were to reach €126 per ton, firms would have incentives to abate their current emissions by almost 80%.
- Our findings provide multiple implications for policymakers regarding the incentives needed to accelerate climate action in the cement industry.

RESEARCH SUMMARY

In the discussion surrounding the timely transition to a net-zero economy, commentators frequently point to the obstacles of reducing the carbon dioxide (CO_2) emissions in hard-to-decarbonize industries, such as steel, cement, and chemicals[1,2]. These industries deliver products that are essential to economic development. Yet, large shares of their emissions are intrinsic process emissions that are not caused by the burning of fossil fuels. Among these industries, cement alone is responsible for about 8% of global annual CO_2 emissions[3]. Like their counterparts in other heavy manufacturing industries, major cement producers have recently embraced net-zero emission goals by the year 2050. Achieving these goals will require the adoption of abatement levers that drastically reduce the emissions associated with current production processes.

This paper first develops a generic economic model for identifying cost-efficient combinations of abatement levers a firm would need to implement to substantially reduce emissions. We then calibrate our model to new industry data[4] in the context of European cement plants. Our numerical analysis considers nine elementary abatement levers that are becoming technologically ready for deployment (Figure 1). These levers include process improvements, input substitutions, such as the use of supplementary cementitious materials (SCMs), and the installation of carbon capture technologies. Since most of these elementary levers can be combined freely, there are potentially up to $2^9 = 512$ combined abatement levers. Importantly, the resulting abatement and cost analysis is not separable across the constituent

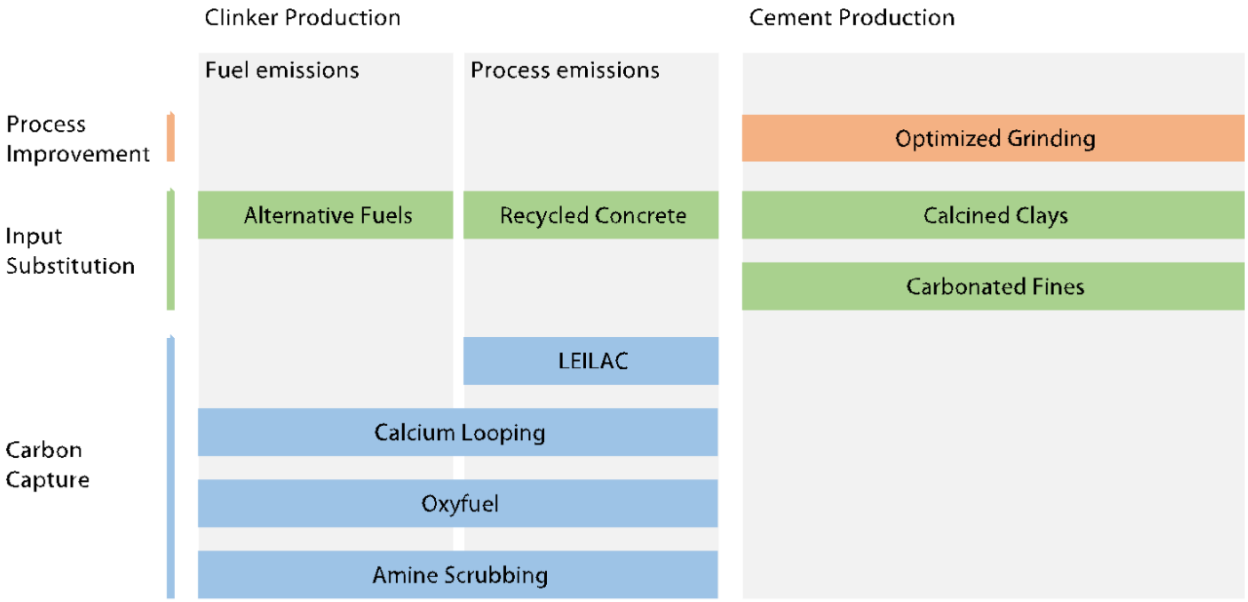

Figure 1: Elementary abatement levers. *This figure illustrates the nine elementary abatement levers considered in our analysis.*

elementary levers. For instance, the abatement impact of SCMs varies depending on whether the use of these materials is combined with a carbon capture installation.

The central economic concept examined in this paper is an abatement cost curve, conceptualized as the life-cycle cost of reducing annual CO_2 emissions to some target level. Relative to a status quo level of emissions, the abatement cost of reducing emissions to a target level thus represents the minimal lump-sum payment a firm would require for the corresponding emissions abatement in future time periods. The cost curves emerging from our model framework are generally not convex. Specifically, for abatement increments of a given size, the corresponding incremental abatement cost is generally not increasing for more ambitious abatement targets. This feature stands in contrast to *marginal abatement cost curves* popularized by McKinsey[5] and studied in numerous contexts[6-8]. A key assumption of traditional marginal abatement cost curves is that the abatement effects of different levers are separable (independent), allowing for elementary levers to be ordered according to their (incremental) marginal cost. Such ordering is not possible in the context of our model, precisely because the joint costs and emission levels corresponding to different combined levers are not separable across the constituent elementary levers.

Our numerical analysis examines the incentives for European cement producers to adopt combinations of elementary abatement levers in response to alternative carbon prices that might prevail under the European Emissions Trading System (EU ETS). We find that if prices were to continue at their 2022 average value of €81 per ton of CO_2 in future years, firms would have incentives to abate their annual direct (Scope 1) CO_2 emissions by 34% relative to the status quo (Figure 2). At the same time, our analysis demonstrates that optimal abatement levels are highly sensitive to carbon prices in the range of €90-140 per ton. Specifically, cement producers would optimally reduce their emissions by 78% at a carbon price of €126 per ton of CO_2, while €141 per ton would provide incentives sufficient for near-full decarbonization.

Our findings lend economic support to the recent surge in market activity for low-carbon cement products and the 2030 emissions targets articulated by leading cement producers. Compared to earlier studies, we project lower costs for decarbonizing cement production[9-11]. These

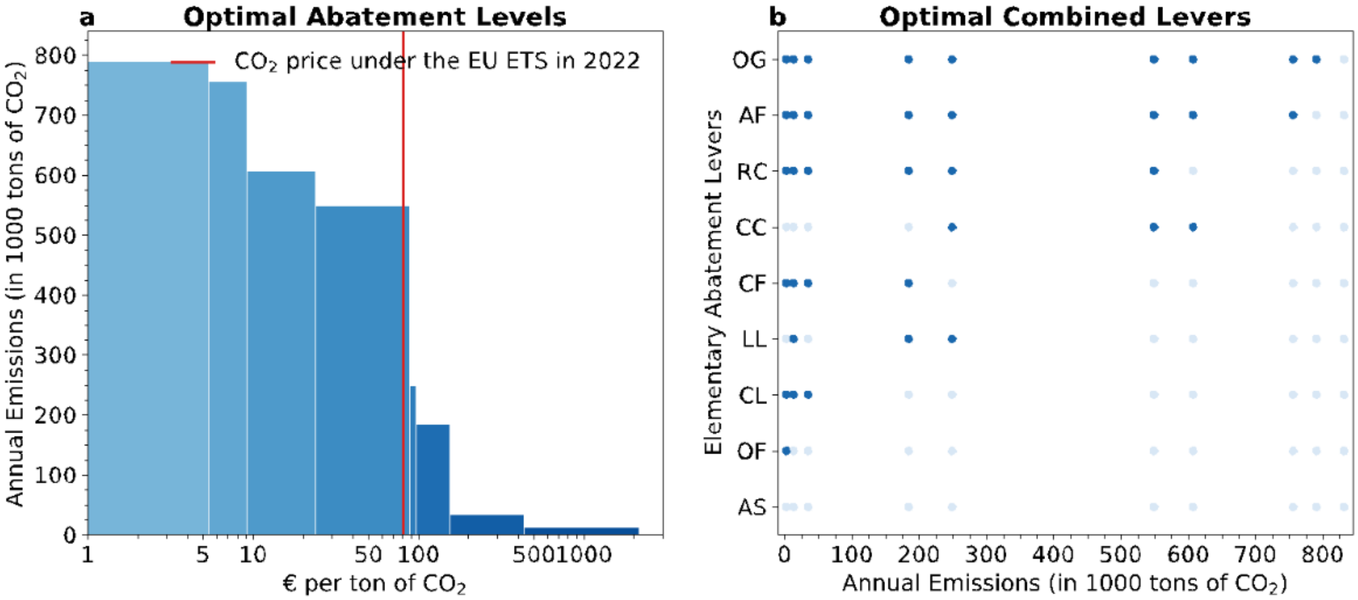

Figure 2: Optimal abatement for Portland Cement. *This figure shows (a) the optimal abatement at different CO2 prices and (b) the optimal combined levers. Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), LEILAC (LL), Calcium Looping (CL), Oxyfuel (OF), and Amine Scrubbing (AS). Dots highlighted in dark blue indicate the elementary levers that will be implemented at different emission thresholds.*

differences partly reflect that our calculations are based on new industry data showing advances in the cost and emission profiles of different abatement technologies. In addition, our abatement cost calculations rely on an embedded optimization algorithm that selects for each abatement target the unique cost-efficient combination of elementary levers from a large set of technologically feasible combinations.

Current climate policy discussions have yet to reach a consensus on how far carbon pricing regulations or subsidies for decarbonization efforts need to be expanded in order to ensure a timely transition to a net-zero economy. In this regard, our analysis quantifies the sensitivity of the abatement cost of representative European Portland cement plants to different carbon prices. For instance, we find that a 55% increase in the market price of EU ETS emissions allowances relative to the 2022 average of €81/tCO_2 could reduce the annual demand for emission permits from representative Portland cement plants from approximately 550,000 to 180,000 permits. If carbon capture technologies were also to improve in cost and capture rates by 20-30% over the coming decade, as developers anticipate, then a 55% increase in the prevailing carbon price would even suffice to reduce the annual demand to approximately 23,000 permits.

In Germany and other countries, governments seek to accelerate corporate decarbonization efforts by providing targeted subsidies to companies in the form of *carbon contracts for difference*. Such contracts set a fixed carbon price for a given period of time, reducing the risk of price volatility for firms and allowing governments to contractually require firms to reduce their emissions beyond the levels incentivized by current carbon prices. Our model lends itself to estimating the minimum subsidy required for cement manufacturers to reduce their annual emissions to a target below what the prevailing carbon price incentivizes. Suppose that the prevailing carbon price is €81/tCO_2 and, therefore, absent any further inducement, the optimal abatement response of representative cement plants is to reduce current emissions by 34%. For firms to be willing to enter into a contractual agreement that sets the maximum annual emissions of representative plants at 22% of the status quo emissions, we find that the annual subsidy would need to be about €14 million per plant, or €37/tCO_2 additionally abated.

The Intergovernmental Panel on Climate Change and other research organizations have published a variety of forecasts for the amount of CO_2 that is likely to be emitted in 2050. Such residual emissions would then have to be compensated by carbon removals in order to achieve a net-zero position. Our findings on the optimal abatement of companies suggest that unless carbon prices reach a range of several hundred Euro per ton of CO_2 emitted, cement producers would continue to emit at least about 4% of their current emissions. Of course, such projections must be qualified by the observation that they are based on current manufacturing and abatement technologies.

ABOUT THE AUTHORS

Gunther Glenk is an Assistant Professor of Business at the University of Mannheim and a Climate Fellow at Harvard Business School.

Anton Kelnhofer is a Consultant at Bain & Company and a former doctoral candidate at the Technical University of Munich.

Rebecca Meier is a Manager at Kearney. She obtained her doctorate at the University of Mannheim.

Stefan Reichelstein is the William R. Timken Professor of Accounting, Emeritus at Stanford Business School, and the director of the Mannheim Institute for Sustainable Energy Studies at the University of Mannheim.

REFERENCES

1. Davis, S. J. et al. Net-zero Emissions Energy Systems. *Science* 9793 (2018).
2. Habert, G. et al. Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries. *Nature Reviews Earth and Environment* 1, 559–573 (2020).
3. IEA. Technology Roadmap - Low-Carbon Transition in the Cement Industry (2018). URL https://bit.ly/3J7kMe8.
4. ECRA. State of the Art Cement Manufacturing: Current Technologies and their Future Development (2022). URL http://bit.ly/3m5TKdE.
5. McKinsey. A Cost Curve for Greenhouse Gas Reduction (2007). URL http://bit.ly/3kpYxWA.
6. Harmsen, J. H. et al. Long-term Marginal Abatement Cost Curves of Non-CO2 Greenhouse Gases. *Environmental Science and Policy* 99, 136–149 (2019).
7. Jiang, H. D., Dong, K. Y., Zhang, K. & Liang, Q. M. The Hotspots, Reference Routes, and Research Trends of Marginal Abatement Costs: A Systematic Review. *Journal of Cleaner Production* 252, 119809 (2020).
8. Huang, S. K., Kuo, L. & Chou, K. L. The Applicability of Marginal Abatement Cost Approach: A Comprehensive Review. *Journal of Cleaner Production* 127, 59–71 (2016).
9. Obrist, M. D., Kannan, R., Schmidt, T. J. & Kober, T. Decarbonization Pathways of the Swiss Cement Industry Towards Net Zero Emissions. *Journal of Cleaner Production* 288, 125413 (2021).
10. Dinga, C. D. & Wen, Z. China's Green Deal: Can China's Cement Industry Achieve Carbon Neutral Emissions by 2060? *Renewable and Sustainable Energy Reviews* 155, 111931 (2022).
11. Fennell, P., Driver, J., Bataille, C. & Davis, S. J. Going Net Zero for Cement and Steel. *Nature* 603, 574–577 (2022).