# Assessing the Costs of Industrial Decarbonization

**Gunther Glenk***
Business School, University of Mannheim
CEEPR, Massachusetts Institute of Technology
glenk@uni-mannheim.de

**Rebecca Meier**
Business School, University of Mannheim
rebecca.meier@uni-mannheim.de

**Stefan Reichelstein***
Business School, University of Mannheim
Leibniz Centre for European Economic Research (ZEW)
Graduate School of Business, Stanford University
reichelstein@uni-mannheim.de

August 2024

*We thank Wolfgang Dienemann, Jon Glover, Nicola Kimm, Teresa Landaverde, Patrick Liebmann, Peter Lukas, Eric Trusiewicz, colleagues at Harvard University, Stanford University, and the University of Mannheim, seminar participants at the 2022 Decarbonization Forum, the 2023 Mannheim Energy Conference, and the 2024 Columbia Management Accounting Conference for helpful suggestions and discussions. Particular thanks to Anton Kelnhofer for his contributions at the early stages of this project. We acknowledge valuable research assistance from Abirami Kumar and Thimo Merke. Financial support for this study was provided by the German Research Foundation (DFG Project-ID 403041268, TRR 266), the Joachim Hertz Foundation, and the Konrad Adenauer Foundation.

**Abstract**
Companies in various industries are under growing pressure to assess the costs of decarbonizing their operations. This paper develops a generic abatement cost concept to identify the cost-efficient combination of technological and operational changes firms would need to implement to drastically reduce greenhouse gas emissions from current production processes. The abatement cost curves resulting from our framework further serve as a decision tool for managers to determine the optimal abatement levels in the presence of environmental regulations, such as carbon pricing. We calibrate our model in the context of European cement producers that must obtain emission permits under the European Emission Trading System (EU ETS). We find that a price of €85 per ton of carbon dioxide ($CO_2$), as observed on average in 2023 under the EU ETS, incentivizes firms to reduce their annual direct emissions by about one-third relative to the status quo. Yet, this willingness to abate emissions increases sharply if carbon prices were to rise above the €100 per ton of $CO_2$ benchmark.

**Keywords:** marginal abatement cost, carbon emissions, industrial decarbonization, cement production

**JEL Codes:** M1, O33, Q42, Q52, Q54, Q55, Q58

# 1 Introduction

Amid growing calls to slow the pace of climate change, companies around the world have adopted the goal of reducing their greenhouse gas emissions to net zero by 2050 (Net Zero Tracker, 2023). While there is substantial variation in the scope and specificity of these pledges, most companies will soon need to assess the costs of implementing technological and operational changes so as to meet their self-selected abatement targets. Beyond their own targets, industrial companies in many countries also face increasingly stringent environmental regulations, such as rising carbon emission charges. These companies will also need to assess how the resulting abatement costs relate to any offsetting gains associated with avoided emission charges.

This paper first develops a generic abatement cost framework for firms to identify cost-efficient pathways towards their emission reduction targets. Our model presumes that firms can implement a variety of elementary levers that abate carbon dioxide ($CO_2$) emissions at a representative plant relative to the status quo emissions. These elementary levers include investments in process improvements, input material substitutions, and possibly the deployment of carbon capture and sequestration technology. For alternative emission reduction targets, our *Total Abatement Cost* (TAC) curve identifies the life-cycle cost associated with the cost-minimizing combination of elementary levers that results in future plant emissions not exceeding the target level.

We then apply our abatement cost model to Portland cement production.[1] Industries such as steel, cement, and chemicals deliver products that are essential to a modern economy. Yet, they significantly contribute to global annual greenhouse gas emissions and are frequently characterized as hard to decarbonize (Davis et al., 2018).[2] Our numerical analysis considers nine elementary levers that are becoming technologically ready for deployment at cement plants around the world. Since most of these elementary levers can be freely combined, there are potentially up to $2^9 = 512$ combined levers. Yet, for the TAC curve we obtain only 18 combined levers are cost-efficient insofar as they are not dominated by some other combined lever that achieves lower emissions at lower cost.

[1] Our model is calibrated to European reference plants based on new industry data provided by the European Cement Research Association (ECRA, 2022).

[2] Among these industries, cement alone is responsible for about 8% of global annual $CO_2$ emissions (Fennell et al., 2021). Portland cement production is considered hard to decarbonize because the heating of limestone involves significant process emissions that will not be avoided by phasing out the burning of fossil fuels.

The Total Abatement Cost curves emerging from our model framework give rise to *Marginal Abatement Cost* (MAC) curves that are structurally different from the classical marginal abatement cost curves popularized by McKinsey (2007). As illustrated in Figure 1, a common assumption underlying marginal abatement cost curves examined in economics textbooks and numerous studies is that the abatement impact of elementary levers is separable.[3] This allows different levers to be ordered according to their unit costs, resulting in a curve that is always increasing in the level of abatement.

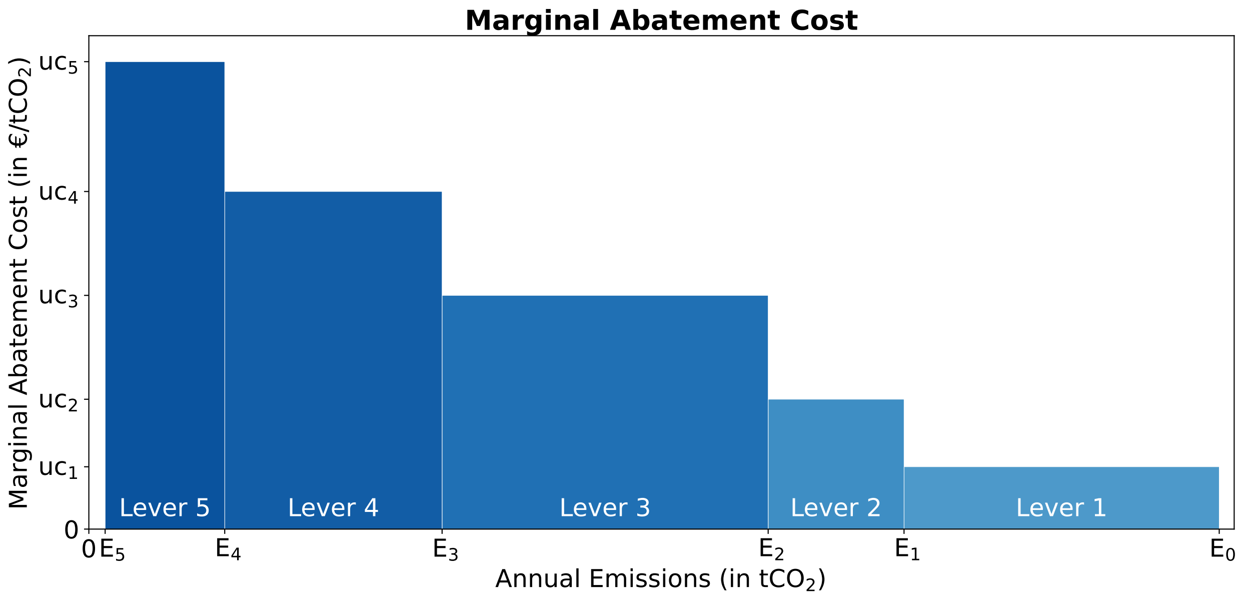


**Figure 1. Classical marginal abatement cost curve.** This figure illustrates the marginal abatement cost curve resulting from ordering different elementary levers $i$ by their unit cost $uc_i$.

In many industrial contexts, however, elementary levers exhibit interactions when implemented together at a particular plant (McKitrick, 1999). For instance, the abatement effects of alternative raw materials for Portland cement production vary depending on whether the use of these materials is combined with carbon capture installations.[4] As a consequence, our MAC curves are generally not monotonically increasing in the level of abatement, precisely because the joint costs and emission levels corresponding to different combined levers are

[3] See, for instance, Stavins (2019); Grubb et al. (2014); Kuosmanen and Zhou (2021); Harmsen et al. (2019); Beaumont and Tinch (2004).

[4] To circumvent this issue, some studies have estimated marginal abatement cost curves based on firms' emission responses to different carbon prices, while others have numerically identified optimal combinations of abatement levers in response to emission charges without constructing marginal abatement cost curves (Kesicki and Strachan, 2011).

not separable across the constituent elementary levers.

Our analysis proceeds to examine the incentives for European cement producers to adopt combined levers that are optimal in response to alternative carbon prices that might prevail under the European Emission Trading System (EU ETS). We find that, for a wide range of alternative carbon prices, only nine of the 18 cost-efficient combined levers emerge as potentially optimal.[5] If carbon prices under the EU ETS were also to continue at their 2023 average value of €85 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. 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.

In addition to charging producers for their $CO_2$ emissions, some countries have recently embraced so-called *carbon contracts for difference*. Accordingly, governments sign bilateral contracts with companies that specify annual lump-sum payments in exchange for the direct emissions of particular plants not exceeding the contractually specified limit. Our abatement cost model allows analysts to gauge the minimum lump-sum payment required for firms to agree to such contracts. In the context of the cement industry, we find that if the prevailing carbon price were to be €85 per ton of $CO_2$, European reference plans would require an annual lump-sum payment of about €12 million to reduce their emissions from about 550,000 tons to about 185,000 tons of $CO_2$ per year. This amounts to about €33 per ton for the additional emissions abated.

A common concern about high charges for carbon emissions is their impact on the production costs of essential commodities such as steel, aluminum, and cement. Our abatement cost model allows analysts to estimate the increase in the life-cycle production cost that results as a consequence of the prevailing carbon price increasing from $p$ to $p^+$, possibly in response to regulators issuing fewer permits under a cap-and-trade system.[6] In the context of European cement producers, we find that if the carbon price under the EU ETS were to increase from €85 to €141 per ton of $CO_2$, the life-cycle cost of producing one ton of

[5] If the MAC curve identified in our calculations had been monotonically increasing, all 18 cost-efficient levers would have emerged as optimal at some carbon price.

[6] Our measure of life-cycle product cost draws on the concept of levelized product cost, which includes both capacity-related capital expenditures and operating expenditures required to produce goods and services (Reichelstein and Rohlfing-Bastian, 2015).

cement would increase by about €15, or about 12% of the average selling price of a ton of cement in 2023. This surprisingly small cost increase reflects a firm's ability to avoid higher emission charges by pulling additional abatement levers, specifically carbon capture and sequestration.[7]

Our findings on the cost of decarbonizing Portland cement production emerge as robust to various sensitivity tests. This robustness result is partly a consequence of the fact that within the set of the nine elementary levers we consider, most have effective substitutes. Further, our model framework relies on an embedded optimization algorithm that always identifies the cost-efficient combined lever from the set of available elementary levers. Our results are also consistent with the recent surge in early market activity for low-carbon cement products. For example, Heidelberg Materials (2023a), HOLCIM (2023), and CEMEX (2023), three globally leading cement producers, have all begun implementing process improvement and input substitution levers in their production plants worldwide. Over the coming decade, Heidelberg Materials and HOLCIM also plan to install carbon capture equipment at their cement plants, primarily in Europe but also in North America.

Our paper relates to several branches of the emerging literature on decarbonization. One branch has empirically examined the drivers of firms' voluntary abatement efforts and the strategies companies pursue to reduce emissions. These drivers include self-disciplining initiatives such as management targets (Ioannou et al., 2016), executive compensation (Cohen et al., 2023), and governance changes (Dyck et al., 2023), yet they also include external sources of pressure, such as shareholder engagement (Desai et al., 2023; Azar et al., 2021; Dyck et al., 2019) and mandatory disclosure regulation (Downar et al., 2021; Tomar, 2023; Christensen et al., 2021). So far, most firms have made only limited progress toward their long-term emission targets, mainly through energy efficiency improvements (Achilles et al., 2024) or by reducing their direct emissions through divestiture from polluting assets (Berg et al., 2023). Our analysis takes a more granular micro-economic approach by identifying cost-efficient combinations of multiple levers. Our approach thereby provides analysts with a tool for examining the economic credibility of firms' voluntary carbon pledges.

A second branch of the decarbonization literature has studied the cost and adoption of low-carbon technologies in response to emission regulations. For example, Drake et al. (2016) and Drake (2018) have examined the effect of different carbon pricing mechanisms on

[7] In contrast, Fennell et al. (2022) estimate that comprehensive decarbonization would double the full cost of cement production.

a firm's decision to invest in a low-carbon production technology. Islegen and Reichelstein (2011) have estimated the costs associated with the adoption of carbon capture technologies at fossil fuel power plants in the United States. Many studies have also examined the cost-efficient mix of sustainable power generation and storage technologies to meet a given electricity demand (see, for instance, Peng et al. (2024); Kaps et al. (2023); Kök et al. (2020)). Our findings complement these studies with a generic combinatorial model for identifying the optimal combined abatement measures a firm can implement in response to emission charges. Conversely, our analysis identifies the price incentives required for firms to adopt particular abatement technologies.

Our study also contributes to the large literature on the effectiveness of carbon pricing mechanisms. Most recently, Bai and Ru (2024) have analyzed the effect of emission trading systems on corporate emissions and renewable energy use. Martinsson et al. (2024) have studied the effect of the Swedish $CO_2$ tax on firm emissions, while Colmer et al. (2024) have examined the effect of the EU ETS on firm-level emissions in the EU and beyond. More specifically, Fowlie et al. (2016) and Ryan (2012) have examined the economic and environmental implications of market-based $CO_2$ regulations in the U.S. cement industry. Similarly, Armitage et al. (2024) seek to document the effectiveness of climate policy on investments in low-carbon cement production. To these studies, our analysis adds a range of estimates for the $CO_2$ price elasticity of abatement among European cement producers.

The remainder of the paper proceeds as follows. Sections 2 and 3 develop the generic framework for abatement cost curves, including several formal claims. Section 4 analyzes the application of our model to European cement manufacturers. Section 5 provides concluding remarks. The Appendix contains formal proofs, a detailed description of abatement levers for Portland cement production, an algorithm for operationalizing our generic model in the context of cement production, and several sensitivity tests.

# 2 Model Framework: Abatement Cost Curves

Our model considers a firm that produces a fixed quantity $q$ of a single product each year. The underlying production process causes emissions that impose external costs on the natural environment. For concreteness, the following discussion will focus on carbon dioxide ($CO_2$) emissions, even though the abatement cost concept developed in this section is generic. Suppose that, for the production facility in question, the status quo entails $E_0$ metric tons of direct (Scope 1) $CO_2$ emissions each year in order to produce $q$ units of output.

To abate carbon emissions, the firm can implement a combination of $m$ different measures, referred to as *elementary levers*. These levers may involve input substitutions, changes in the product design, or structural changes in the production process. The adoption of levers is binary in our model, with $v_i \in \{0, 1\}$ indicating whether elementary lever $i$ is implemented.[8] We refer to a combination of elementary levers as a *combined lever*, denoted by the $m$-dimensional vector $\vec{v} = (v_1, \ldots, v_m)$. Accordingly, $\vec{v}_0 = (0, \ldots, 0)$ reflects the status quo, which results in $E_0$ units of emissions per year. The set of technologically feasible combined levers is denoted by $V_f$. Since technological constraints may render some combinations of elementary levers infeasible, the cardinality of $V_f$ is at most $2^m$.

Let $E(\vec{v})$ denote the annual emissions associated with the production of $q$ units of output if combined lever $\vec{v}$ is pulled. By definition, $E(\vec{v}_0) = E_0$. A combined lever $\vec{v}$ may require upfront investment $I(\vec{v})$ to upgrade equipment or build auxiliary production facilities. Our analysis considers the capital expenditures for the plant in its existing form as sunk costs. Thus, $I(\vec{v}_0) = 0$. The existing plant is assumed to have a remaining useful life of $T$ years, and all combined levers are assumed to have the same useful life.[9]

Combined levers may also result in modified operating expenses, both fixed and variable, for the $T$ years of operation. Fixed operating costs are given by $F_t(\vec{v})$ for year $t$. Examples of changes herein include modified maintenance, labor, and insurance expenditures. Variable operating costs are given by $w_t(\vec{v})$. Changes herein may result from modified prices or quantities of consumable inputs, product components, transportation services, or variable maintenance expenses. Fixed and variable operating costs corresponding to a particular combined lever may be lower than in the status quo if the combined lever reduces both emissions and operating costs.

We denote the applicable cost of capital by $r$, interpreting it as a fixed weighted average cost of capital. The discounted value of all cash expenditures, including upfront investment and future operating costs, resulting from the implementation of the combined lever $\vec{v}$ will

[8]Our model could also consider different capacity sizes at which some levers might be implemented, for example, by adjusting $v_i$ to reflect the fraction of the technological peak capacity of lever $i$.

[9]Our model is readily adapted to account for a shorter remaining life of the existing plant, for example, by adjusting $I(\vec{v})$ to reflect that a combined lever may still have residual value at date $T$.

be denoted by $DE(\vec{v})$. Formally:

$$DE(\vec{v}) \equiv \sum_{t=1}^{T} \big[w_t(\vec{v}) \cdot q + F_t(\vec{v})\big] \cdot \big(1+r\big)^{-t} + I(\vec{v}). \tag{1}$$

Firms seeking to reduce their annual emissions can choose $E$ on the interval of $[E_-, E_0]$, where $E_- \equiv \min_{\vec{v}\in V_f} E(\vec{v})$ denotes the minimal level of emissions attainable with some combined lever in the feasible set $V_f$. Let $V_f(E)$ denote all combined levers in $V_f$ that result in the plant's future annual emissions $E(\vec{v})$ not exceeding $E$. For any target level, $E$, the firm seeks to identify the combined lever $\vec{v} \in V_f(E)$ that minimizes the associated discounted expenditures. We initially restrict attention to settings where the firm makes a single irreversible investment in a combined lever.

The *Total Abatement Cost* (TAC) of reducing annual emissions from $E_0$ to $E$ is then defined as:

$$TAC(E|E_0) \equiv \min_{\vec{v}\in V_f(E)} \{DE(\vec{v})\} - \min_{\vec{v}\in V_f(E_0)} \{DE(\vec{v})\}. \tag{2}$$

Given annual emissions of $E_0$ in the status quo, $TAC(E|E_0)$ reflects the minimal payment that a firm would require for its investments and increased operating costs to produce the same output with no more than $E$ units of emissions per year for the next $T$ years. By construction, $TAC(E_0|E_0) = 0$.

**Lemma 1.** *The total abatement cost function, $TAC(\cdot|E_0)$, has the following properties:*

*(i) $TAC(\cdot|E_0) \geq 0$ on the interval $[E_-, E_0]$.*

*(ii) $TAC(\cdot|E_0)$ is weakly decreasing in $E$.*

*(iii) $TAC(\cdot|E_0)$ is a right-continuous step-function with at most $n \leq 2^m$ steps.*

The first property in Lemma 1 follows directly from the definition. The second property follows from the observation that $V_f(E_2) \subset V_f(E_1)$ if $E_2 < E_1$. $TAC(\cdot|E_0)$ must then be a step function on the interval $[E_-, E_0]$, since it can assume at most finitely many values corresponding to the finite set of feasible levers in $V_f$. To see that $TAC(\cdot|E_0)$ is a right-continuous function, we note that for any given $E$ and any sequence $\{E_u\}$, such that $E_u > E$ and $E_u \to E$, it follows that:

$$\lim_{u\to\infty} TAC(E_u|E_0) = TAC(E|E_0).$$

The $TAC(\cdot|E_0)$ function may or may not have a stepping point at $E_0$. Suppose that some combined levers result in lower emissions, say $E_1 < E_0$, relative to the status quo without increasing discounted expenditures. Then $E_0$ is not a stepping point of the total abatement cost curve, since $TAC(E_1|E_0) = TAC(E_0|E_0) = 0$. On the other hand, if for any $E < E_0$, $\min_{\vec{v}\in V_f(E)} \{DE(\vec{v})\} > DE(\vec{v}_0)$, then the firm incurs a cost for any targeted level of emissions below $E_0$. In that case, $E_0$ will be a stepping point and $TAC(E_1|E_0) > TAC(E_0|E_0) = 0$.

Aside from $E_0$, we denote the stepping points of the $TAC(\cdot|E_0)$ function by $E_- = E_n < \ldots < E_i < \ldots < E_1$. By construction, $TAC(E_i|E_0) > TAC(E_{i-1}|E_0)$ for $1 \leq i \leq n$. Since $TAC(E|E_0) = TAC(E_i|E_0)$ for any $E$ with $E_i < E < E_{i-1}$, there is no loss of generality in presuming that the firm will always select either $E_0$ or one of the stepping points $E_i$, with $1 \leq i \leq n$. Accordingly, we refer to

$$\mathbf{E} \equiv \{E_n, E_{n-1}, \ldots, E_1, E_0\}.$$

as the set of *cost-efficient emission thresholds.*[10] Since the cardinality of $\mathbf{E}$ (that is, $n$) may be substantially smaller than the number of possible combined levers (that is, $2^m$), the complexity of the economic optimization problem may be significantly reduced by restricting attention to the thresholds in $\mathbf{E}$.[11]

On the domain of cost-efficient thresholds, $\mathbf{E}$, we define the *Marginal Abatement Cost* (MAC) curve corresponding to the total abatement cost curve as the difference quotient associated with reducing annual emissions from $E_{i-1}$ to $E_i$ over the $T$ period planning horizon. Formally, for $1 \leq i \leq n$:

$$MAC(E_i) \equiv \frac{TAC(E_i|E_0) - TAC(E_{i-1}|E_0)}{(E_{i-1} - E_i) \cdot A(r,T)} \equiv \frac{TAC(E_i|E_{i-1})}{(E_{i-1} - E_i) \cdot A(r,T)}, \tag{3}$$

where $A(r,T) \equiv \sum_t^T (1+r)^{-t}$ denotes the annuity value of \$1 paid over $T$ years at the discount rate $r$.

The $MAC(\cdot)$ curve defined in equation (3) is conceptually related to the classical marginal abatement cost curve examined in economics textbooks and numerous earlier studies.[12] As

[10] If $E_0$ is not a stepping point of the $TAC(\cdot|E_0)$ function, then $E_0$ is not cost-efficient in so far as that the firm can achieve lower emissions without incurring an abatement cost.

[11] In our application of Portland cement plants, there will be $m = 9$ elementary levers and thus $2^9 = 512$ potential combined levers, yet the number of cost-efficient thresholds turns out to be $n = 18$.

[12] See, for instance, Stavins (2019); Grubb et al. (2014); Kuosmanen and Zhou (2021); Harmsen et al. (2019); Beaumont and Tinch (2004)

noted in the Introduction, these marginal abatement cost curves are constructed by calculating the unit cost and abatement increment for each elementary lever and reordering the elementary levers according to their unit cost. Conceptually, such a construction requires separability in the cost and abatement effects of the elementary levers. Subject to proper relabeling of all levers, the resulting marginal abatement cost curves will then always be increasing in the aggregate abatement level.

In contrast, the $MAC(\cdot)$ curve in equation (3) is constructed from the total abatement cost curve as the difference quotient associated with reducing annual emissions from one cost-efficient emission threshold to the next. The elementary levers that implement emission threshold $E_{i-1}$ may not carry over to the set of elementary levers that efficiently implement the next lowest cost-efficient threshold $E_i$. Importantly, our construction does not require separability in the cost and abatement effects of the elementary levers. However, the resulting $TAC(\cdot)$ curve may not be convex, and thus the corresponding $MAC(\cdot)$ curve may not be monotonically increasing in the abatement level, i.e., the index $i$.

# 3 Optimal Abatement in Response to Emission Charges

We now embed our abatement cost concept in a decision context where the firm faces charges for its carbon emissions. Such charges may reflect a tax or market prices for emission permits under a cap-and-trade system, such as the European Union Emissions Trading System (EU ETS) for $CO_2$ emissions. Incentives for emission abatement then arise from the avoided expenditures for emission charges. Specifically, if the firm expects the prevailing charge to be $p$ per unit of emissions in the future, the objective is to minimize:

$$Z(E, p|E_0) = TAC(E|E_0) - p \cdot (E_0 - E) \cdot A(r, T). \tag{4}$$

Relative to the status quo, the firm now trades off the additional cost of higher abatement levels against lower emission charges. For any given $p$, the abatement levels that minimize $Z(E, p|E_0)$ is denoted by $E^*(p)$. While $E^*(\cdot)$ may be multi-valued, i.e., a correspondence, for some values of $p$, the following analytical results presume that $E^*(\cdot)$ is single-valued. The following result is readily adapted to settings where multiple abatement levels minimize $Z(\cdot, p|E_0)$ for any given $p$.[13]

[13] Allowing for $E^*(\cdot)$ to be a correspondence, part (i) of Claim 1 can be extended to any selection from the

**Claim 1.** *(i) $E^*(\cdot)$ is a decreasing step function in $p$.*

*(ii) If $E^*(p) = E_i$ for $1 \leq i \leq n-1$, then $MAC(E_{i+1}) > p > MAC(E_i)$.*

*(iii) If $E^*(p) = E_0$, then $p < MAC(E_1)$, while $E^*(p) = E_n$ implies $p > MAC(E_n)$.*

The inequalities $MAC(E_{i+1}) > p > MAC(E_i)$ are the discrete analog of the standard first-order condition equating marginal revenue and marginal cost.[14] In order for the emissions level $E_i$ to be optimal, the unit revenue from avoided emission charges, $p$, must be above the marginal cost of reducing emissions from $E_{i-1}$ to $E_i$, but this unit revenue must not exceed the marginal cost of reducing emissions from $E_i$ to $E_{i+1}$. These inequalities would be necessary and sufficient for $E^*(p) = E_i$ to be optimal, provided the $MAC(\cdot)$ curve was monotonically increasing in $i$, the very monotonicity condition that traditional marginal abatement cost curves satisfy due to the maintained assumption that there are no interaction effects between the elementary levers.

To state conditions that are both necessary and sufficient for $E^*(p)$ to be cost-minimizing for a given carbon price $p$, we define the *Incremental Abatement Cost (IAC)* of abating emissions from some base level $E_i$ to some target level $E_j$ for $j > i$ on the domain $\mathbf{E}$ as:

$$IAC(E_j|E_i) \equiv \frac{TAC(E_j|E_i)}{(E_i - E_j) \cdot A(r,T)}. \tag{5}$$

**Corollary to Claim 1.** *Suppose $E^*(p)$ is single-valued for a given $p$. Then $E^*(p) = E_i$ if and only if:*

*(i) $IAC(E_j|E_i) > p$ for any $j \in \{0, 1..., n\}$ such that $j > i$, and*

*(ii) $IAC(E_i|E_j) < p$ for any $j \in \{0, 1..., n\}$ such that $j < i$.*[15]

The construct of incremental abatement cost $IAC(\cdot|\cdot)$ is of direct use in the context of so-called *carbon contracts for difference*. Such contracts are bilateral agreements between governments and individual firms in hard-to-abate industries in which firms commit to reducing their emissions to a specified target level, say $E^+$. If the prevailing carbon price is

correspondence. Specifically, suppose $p_2 > p_1$ and both $E^1 \in E^*(p_1)$ and $E^2 \in E^*(p_1)$, while $E^3 \in E^*(p_2)$ and $E^4 \in E^*(p_2)$. Then $E^i \geq E^j$ for all $1 \leq i \leq 2$ and $3 \leq j \leq 4$.

[14]The proofs of all claims are relegated to the Appendix.

[15]We note in passing that the corollary recovers the necessary first-order conditions stated in Claim 1, since $IAC(E_i|E_{i-1}) = MAC(E_i)$.

expected to be $p$ in the foreseeable future and the corresponding best abatement response is $E^*(p)$, then, given the prevailing carbon price of $p$, the lump-sum contract payment must, at a minimum, make the firm indifferent between emitting $E^*(p)$ annually and implementing additional decarbonization levers that would limit annual emissions to $E^+$ tons of $CO_2$.

**Claim 2.** *Given an emissions charge of p, the annual lump-sum payment under a carbon contract for difference that obligates the firm to reduce its emissions to $E^+$ is given by:*

$$CCD(E^+|p) = [IAC(E^+|E^*(p)) - p] \cdot [E^*(p) - E^+]. \tag{6}$$

We note that the lump-sum payment in (6) is based on the implicit assumption that the government has the entire bargaining power in proposing such contracts. In contrast, the firm is merely indifferent about accepting and rejecting the contract. We also note that the "price premium" $[IAC(E^+)|E^*(p)) - p]$ under the annual payment is bounded above by $(p^+ - p)$, where $p^+$ denotes the carbon price that would have induced the firm to reduce its emissions to $E^+$ without such a contract, that is, $E^*(p^+) = E^+$. This follows directly from a revealed preference argument: if it were the case that $IAC(E^*(p^+)|E^*(p)) > p^+$, the firm could achieve a lower cost by choosing $E^*(p)$ rather than $E^+$ in response to the carbon price of $p^+$.

The preceding characterization is also relevant in connection with firms' voluntary pledges to reduce their carbon emissions to some target level by a certain date. These commitments are frequently made even though current regulations and policy support do not provide a clear business case for reducing emissions in accordance with the pledge.[16] At the same time, there is a general perception that some customer segments exhibit a higher willingness to pay for the products of companies that voluntarily pledge to lower their emissions. While the exact increase in the willingness to pay for "greener" products will be industry- and company-specific, our abatement cost framework allows us to project the increase in the levelized product cost (LPC) of the firm's sales product.[17]

Suppose again that the firm anticipates a carbon price of $p$ that would incentivize emissions in the amount $E^*(p)$, yet the firm also pledges to achieve some target level $E^+ < E^*(p)$.

[16] A rapidly growing literature has analyzed the credibility and ambition of corporate net-zero pledges; see, for instance, Bolton and Kacperczyk (2023); Comello et al. (2022); Hale et al. (2022).

[17] Levelized cost measures have been studied extensively in the energy literature (see, for example, Joskow (2011); Jansen et al. (2020); Glenk and Reichelstein (2022)). In a generic model framework, Reichelstein and Rohlfing-Bastian (2015) argue that the LPC should be interpreted as the long-run marginal product cost because, in a competitive market equilibrium, the expected market price must be equal to the LPC.

Given our characterization of the annual lump-sum payment under a carbon contract for difference in Claim 2, the change in levelized product cost amounts to:

$$\Delta LPC(E^+|p) = \frac{CCD(E^+|p)}{q}. \tag{7}$$

Holding production and sales volume constant, the expression in (7) can be interpreted as a "green premium," that is, the increase in the product price required for the firm to recover the incremental cost associated with fulfilling the voluntary carbon pledge. As such, the expression in (7) can be viewed as an indicator of both the ambition and the credibility of a firm's voluntary carbon pledge.

In the ongoing discussion about regulating carbon emissions, a common concern is that if deep decarbonization is driven by means of high emission charges, producers will face large increases in their product costs. Our abatement cost framework allows us to quantify the increase in the levelized product cost that results from increasing the charge for $CO_2$ from $p$ to $p^+$. We denote the corresponding product cost increase by $\Delta LPC(p^+|p)$.

**Corollary to Claim 2.**

$$\Delta LPC(p^+|p) = \frac{CCD(E^*(p^+)|p) + E^*(p^+) \cdot (p^+ - p)}{q}. \tag{8}$$

Direct comparison of (7) and (8) confirms that reducing emissions to $E^+$ tons annually will increase the LPC by a larger amount if the reduction results from an increase in the charge for emissions rather than from a voluntary pledge. The difference corresponds exactly to the additional emission charges for the remaining emissions (i.e., $E^*(p^+) \cdot (p^+ - p)$) the firm bears as a consequence of the higher emissions charge.

In closing this section, we link our model framework more tightly to the traditional framework of marginal abatement cost curves. To that end, we first note that as the set of potential emission charges increases from $p = 0$ to large values of $p$, the collection of cost-efficient emission thresholds that are optimal for different $p$ values comprises a subset of $\mathbf{E}$. We denote this subset by:

$$\mathbf{E}^* \equiv \{E_i \in \mathbf{E} \mid E_i = E^*(p) \text{ for some } p \geq 0\}.$$

**Claim 3.** *On the domain $\mathbf{E}^*$, the total abatement cost function, $TAC(\cdot|E_0)$, is a decreasing and convex step function.*

Claim 3 shows that one obtains a "convexification" of the original $TAC(\cdot)$ curve by eliminating from the domain $\mathbf{E}$ any cost-efficient thresholds, $E_i$, that do not emerge as optimal regardless of the prevailing price on emissions, $p$. Put differently, if abatement cost curves are viewed as a tool for identifying cost-minimizing abatement responses to alternative levels of emission charges, one can effectively restrict attention to a subset of the cost-efficient thresholds, i.e., the domain $\mathbf{E}^*$, such that the resulting $TAC(\cdot)$ curve exhibits increasing marginal costs on this restricted domain.[18] On the domain $\mathbf{E}^*$, the necessary first-order conditions for optimality stated in Claim 1 then also become sufficient.

To further integrate our model framework with classical marginal abatement cost curves, we formalize the notion of separability in the cost and abatement effects of the elementary levers. Specifically,

$$E(\vec{v}_{-i}, v_i = 0) - E(\vec{v}_{-i}, v_i = 1) \tag{9}$$

denotes the change in emissions that result from pulling elementary lever $v_i$, while holding all other elementary levers constant. Here, $\vec{v}_{-i}$ denotes the $(m-1)$-dimensional vector obtained by omitting the i-th component $v_i$ from $\vec{v}$. Thus, $(\vec{v}_{-i}, v_i) \equiv \vec{v}$. Similarly, the unilateral change in abatement cost associated with pulling elementary lever $i$ is denoted by:

$$DE(\vec{v}_{-i}, v_i = 1) - DE(\vec{v}_{-i}, v_i = 0). \tag{10}$$

The total abatement cost curve, $TAC(\cdot|E_0)$, is then said to be *separable* in the cost and abatement effects of all elementary levers if the differences in equations (9) and (10) are both invariant to $\vec{v}_{-i}$, that is, both of these differences assume the same values for all $\vec{v}_{-i}$. We denote the unit cost of these elementary levers by:

$$uc_i \equiv \frac{DE(\vec{v}_{-i}, v_i = 1) - DE(\vec{v}_{-i}, v_i = 0)}{E(\vec{v}_{-i}, v_i = 0) - E(\vec{v}_{-i}, v_i = 1)},$$

and, for simplicity, assume they are all strictly positive.

**Claim 4.** *Suppose the cost and abatement effects of the elementary levers are separable. On the domain* $\mathbf{E}^*$*, each step of the marginal abatement cost curve* $MAC(\cdot)$ *can then be uniquely identified with one of the elementary levers* $i$*, where* $1 \leq i \leq m$*. The corresponding marginal cost values are given by* $uc_i$*.*

[18] In the context of the cement industry, we find below that moving from $\mathbf{E}$ to the restricted domain $\mathbf{E}^*$ reduces the number of effective candidates for an optimal level of carbon emissions from eighteen to nine.

Given separability in the cost and abatement effects of elementary levers, a classical marginal abatement cost curve emerges on the restricted domain $\mathbf{E}^*$. Further, Claim 2 implies that the unit cost, $uc_i$, associated with different levers is ascending in the abatement levels.

We emphasize that the result in Claim 4 is valid only on the restricted domain $\mathbf{E}^*$. This is most easily seen when there are two elementary levers. On the domain $\mathbf{E}^*$, the marginal abatement cost curve then has two steps, which, in case $uc_1 < uc_2$ amounts to first pulling lever 1. On the domain $\mathbf{E}$, however, the $MAC(\cdot)$ curve will entail three steps, provided

$$E(\vec{v}_{-1}, v_1 = 0) - E(\vec{v}_{-1}, v_1 = 1) < E(\vec{v}_{-2}, v_2 = 0) - E(\vec{v}_{-2}, v_2 = 1).$$

The first of these steps results from pulling lever 1 and reduces emissions from $E_0$ to $E_1$, with $E_0 - E_1 = E(\vec{v}_{-1}, v_1 = 0) - E(\vec{v}_{-1}, v_1 = 1)$. Thereafter, lever 2 is pulled on its own, reducing emissions to $E_2$, with $E_0 - E_2 = E(\vec{v}_{-2}, v_2 = 0) - E(\vec{v}_{-2}, v_2 = 1)$. Finally, levers 1 and 2 are both pulled for maximum decarbonization, resulting in emission level $E_-$, with $E_0 - E_- = E(\vec{v}_{-1}, v_1 = 0) - E(\vec{v}_{-1}, v_1 = 1) + E(\vec{v}_{-2}, v_2 = 0) - E(\vec{v}_{-2}, v_2 = 1)$. This example thus shows that on the larger domain $\mathbf{E}$, the $MAC(\cdot)$ curve has three steps, and these cannot be identified uniquely with the two elementary levers.

# 4 Model Application: Portland Cement Production

## 4.1 Decarbonization Levers

Our model is calibrated to European reference plants for Portland cement production. The production process begins with the extraction of limestone that is subsequently crushed into small pieces, and then mixed with components such as gypsum, shale, clay, or sand. This mixture is finely ground, dried to a powder, and heated in a rotating kiln to about 1,400°C. The heating process converts the mixture to clinker by separating calcium carbonate into calcium oxide (clinker) and $CO_2$. Cooled clinker is then blended with gypsum and other additives, such as fly ash or slag, before being finely ground into cement (Fennell et al., 2021; Schneider et al., 2011). Almost all direct (Scope 1) $CO_2$ emissions of cement production stem from the conversion of limestone to clinker, where roughly two-thirds are process emissions resulting from the chemical separation of limestone. The remaining third are emissions caused by burning fossil fuels, frequently coal, for heating the kiln (Fennell et al., 2022;

Schorcht et al., 2013).

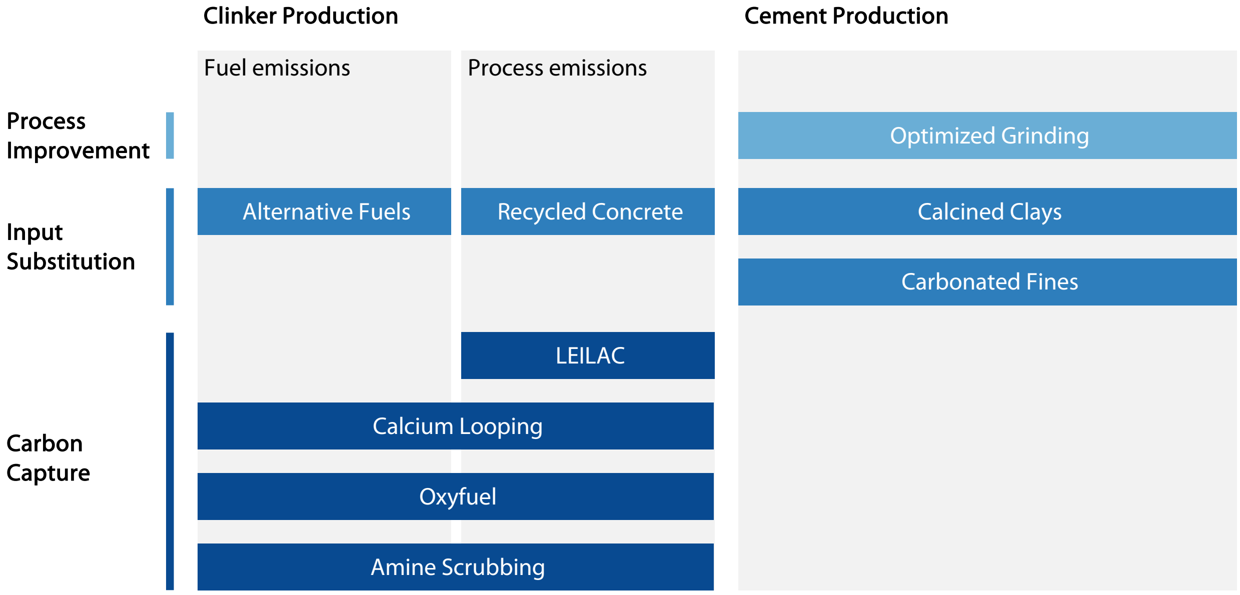


**Figure 2. Elementary abatement levers.** This figure illustrates the nine elementary abatement levers considered in our analysis.

Our analysis focuses on nine elementary levers shown in Figure 2. These are grouped into three categories: process improvements, input substitutions, and carbon capture and sequestration technologies. All levers have been successfully demonstrated in recent pilot projects and are expected to become available to representative cement plants around the world soon. We exclude energy efficiency measures, such as thermal insulation and waste heat recovery, and conventional SCMs, such as fly ash and slag, because many cement producers already apply them (Obrist et al., 2021; Zuberi and Patel, 2017). The supply of conventional SCMs is also expected to diminish with the phase-out of coal power plants and conventional steel production (Juenger et al., 2019). Our analysis omits a number of prospective technologies that are still in earlier stages of development, such as electric or hydrogen-fueled kilns or electric recycling of Portland cement. The state of these advanced abatement levers for cement production is discussed in recent articles.[19]

Pulling the elementary levers affects the cement production process in different ways. *Optimized Grinding* refers to grinding clinker more finely. That improves the adhesion properties of cement in concrete and enables the replacement of clinker with limestone. *Alternative Fuels* refer to the replacement of fossil fuels with alternative materials (biomass)

[19]See, for instance, Griffiths et al. (2023); Napp et al. (2014); Rissman et al. (2020); ECRA (2022); Dunant et al. (2024).

when heating the kiln. *Recycled Concrete* specifies the replacement of limestone with fines made from demolished concrete, which emit no $CO_2$ when heated in the kiln. *Calcined Clays* and *Carbonated Fines* are SCMs that reduce the amount of clinker required per ton of cement. *LEILAC* (Low Emissions Intensity Lime and Cement) is an alternative kiln design for heating the limestone mixture indirectly and capturing process emissions. *Calcium Looping*, *Oxyfuel*, and *Amine Scrubbing* are tail-end carbon capture technologies that capture both the fuel- and process-related emissions. Details about the technological characteristics and limitations of these elementary levers are provided in the Appendix.

It is readily seen that the abatement effects of the elementary levers shown in Figure 2 are not separable. For instance, the emission reductions associated with installing a LEILAC kiln depend on the mix of limestone and recycled concrete loaded into the kiln. Similarly, the abatement effect of Calcium Looping depends on whether clinker is produced in a traditional or a LEILAC kiln. In principle, there are $2^9 = 512$ combinations of elementary levers, each with its own joint cost and emission profile. Yet, our calculations preclude the simultaneous use of calcined clays and carbonated fines, as industry experts remain concerned about potential structural issues for the resulting cementitious material (Zajac et al., 2020).

To operationalize the model in Section 2, we provide closed-form expressions for the variables $E(\vec{v})$, $w_t(\vec{v})$, $F_t(\vec{v})$, and $I(\vec{v})$ in the Appendix. Based on data inputs for the changes in the cost and operational parameters associated with each elementary lever, these expressions capture the interaction effects between the elementary levers. For example, the abatement effect of the LEILAC technology interacts multiplicatively with that of Recycled Concrete, yet this effect is additive to that of Alternative Fuels. This is because LEILAC captures process-related emissions but not those related to fuel combustion. The abatement effects of these three elementary levers, in turn, interact multiplicatively with those of Optimized Grinding, Calcined Clays, and Carbonated Fines. The latter three reduce the amount of clinker required per ton of cement, while the others reduce the emissions associated with clinker production.

Regarding scale, we assume that a reference cement plant has an annual production capacity of 1.0 million tons of clinker, resulting in $q = 1,381,215$ tons of cementitious material and status quo emissions of $E_0 = 832,000$ tons of $CO_2$. Cost and operational parameters for all elementary levers were taken from a recent report by the European Cement Research Academy (ECRA, 2022). This report provides a current and comprehensive assessment of technologies for reducing the $CO_2$ emissions of Portland cement production. The assessment has been conducted based on industry data provided and reviewed by members and project partners of the Global Cement and Concrete Association. For additional validation, we cross-checked all input parameters with information obtained from expert interviews, technical reports, and peer-reviewed academic articles (see Supplementary Data for details).

**Table 1. Main changes in cost and operational parameters.**

| in 2020€ | **Abatement** % | **Investment** € | **Fixed Cost** €/year | **Variable Cost** €/ton of clinker |
|---|---|---|---|---|
| **Process Improvement** | | | | |
| Optimized Grinding | 5.0% clinker replacement | 5,000,000 | 0 | -0.03 |
| **Input Substitution** | | | | |
| Alternative Fuels | 15.0% increase in biomass | 5,000,000 | 0 | -0.21 |
| Recycled Concrete | 16.0% limestone replacement | 5,000,000 | 2,240,000 | -0.69 |
| Calcined Clays[1] | 25.0% clinker replacement | 45,454,546 | 3,750,000 | -5.80 |
| Carbonated Fines[2] | 30.0% clinker replacement | 75,000,000 | 4,035,326 | 16.55 |
| **Carbon Capture** | | | | |
| LEILAC | 57.3% capture rate | 150,937,500 | 0 | 7.50 |
| Calcium Looping | 92.5% capture rate | 282,187,500 | 3,855,000 | 7.15 |
| Oxyfuel | 92.5% capture rate | 203,437,500 | 595,000 | 22.91 |
| Amine Scrubbing | 92.5% capture rate | 155,859,375 | 23,881,500 | 25.12 |

1: For an annual production volume of 165,000 tons; 2: For an annual production volume of 300,000 tons.

Table 1 shows for each elementary lever the main changes in operational parameters and operating cash flows relative to the status quo (see Supplementary Data for details). All levers require upfront investment to retrofit the manufacturing units in place or build an additional production or recycling facility onsite. Most levers also require incremental fixed costs to cover increased labor, insurance, and maintenance costs for the added production or processing facilities. Exceptions are Optimized Grinding, Alternative Fuels, and LEILAC, where existing machinery is upgraded. Changes in variable costs are negative for levers entailing cost savings relative to the status quo. The variable costs of carbon capture technologies reported in the table do not include charges for transportation and storage of the captured $CO_2$. Our calculations set these off-take charges at €80 per ton. Finally, we set the applicable cost of capital at 7.0% and the useful life of capital investments at 30 years.

## 4.2 Portland Cement Abatement Cost Curves

Figure 3a shows the annualized total abatement cost for the cost-efficient emission thresholds identified in our analysis. We depict the total abatement cost in annualized form, that is, $TAC(E|E_0) \cdot A(r,T)^{-1}$, since our metric of interest is the reduction in emissions each year. While there are potentially up to 512 different combined levers to choose from, our analysis identifies only $n = 18$ of them as cost-efficient in the sense that the firm cannot achieve lower emissions without incurring a higher cost. $E_0$ turns out not to be a stepping point, since $TAC(E_1|E_0) = TAC(E_0|E_0) = 0$. This equality reflects that the elementary lever Optimized Grinding lowers the status quo emissions by 5% to $E_1 = 790,400$ $tCO_2$ per year, yet also decreases total discounted expenditures because the savings in variable costs more than compensate for the investment expenditure. At all other stepping points, the abatement cost curve is positive and strictly increasing. The most ambitious emission level at $E_{18}$ amounts to 2,609 $tCO_2$ annually or 0.3% of the status quo emissions.

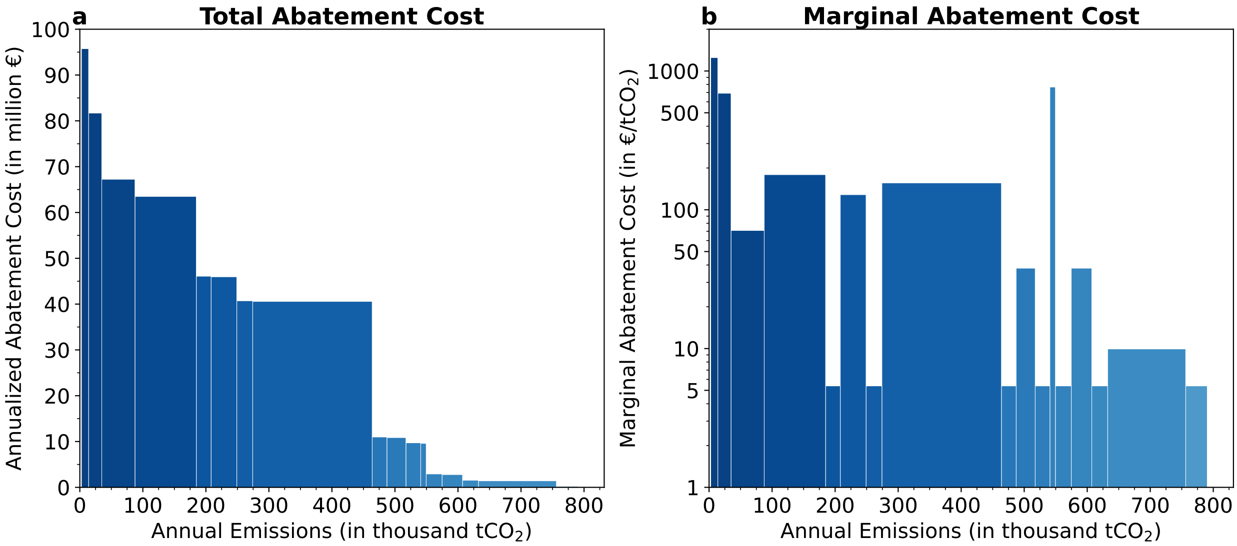


**Figure 3. Abatement cost curves for Portland cement.** This figure shows (**a**) the annualized total abatement cost and (**b**) the marginal abatement cost for the cost-efficient emission thresholds.

Figure 3a also predicts that the total abatement costs increase sharply as firms choose more ambitious emission targets. These increases can be significant relative to the overall revenue that can be obtained from a typical cement plant. To calibrate, the European market price for cement in 2023 was, on average, about €120 per ton (BusinessAnalytiq, 2024). The annual revenue of a representative plant would, therefore, be €120/t · 1,381,215t

= €165,745,800. Holding the price of the sales product constant, Figure 3a suggests that a two-thirds reduction in annual emissions would result in an annualized abatement cost of about one-quarter of the plant's annual revenue.

Figure 3b shows the corresponding marginal abatement cost curve. This curve is far from increasing monotonically in the level of abatement. Several emission thresholds entail MAC values of about €5/$tCO_2$. This reflects that, depending on the abatement target, it is sometimes cost-efficient to include the elementary lever Alternative Fuels. The slightly varying width of the corresponding bars reflects the interaction in the abatement effects of the elementary lever Alternative Fuels with the other adopted elementary levers. For the lowest two emission thresholds, we obtain MAC values of €691/$tCO_2$ and €1,249/$tCO_2$, respectively. These sharp cost increases reflect the installation of a second carbon capture technology for achieving the two lowest thresholds.[20] The spike at $E_7 = 540,800$ $tCO_2$ per year reflects a denominator effect, as the change in the total abatement cost associated with reducing annual emissions from $E_6$ to $E_7$ is divided by a small reduction in emissions.

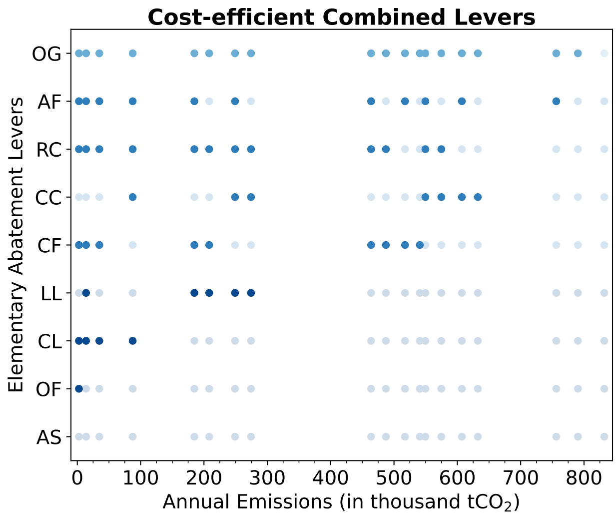


**Figure 4. Cost-efficient combined levers.** This figure shows the combined levers corresponding to the cost-efficient emission thresholds. Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), LEILAC (LL), Calcium Looping (CL), Oxyfuel (OF), and Amine Scrubbing (AS). Dots highlighted in darker colors indicate the elementary levers that will be implemented at the emission thresholds.

The combinations of elementary levers that correspond to the cost-efficient emissions

[20]Our base calculations shown in Figure 3 examine the scenario that firms could adopt more than one carbon capture technology at a particular plant. Our sensitivity calculations shown in the Appendix examine the possibility that firms could instead operate the first adopted carbon capture technology at higher abatement efficiency in connection with higher variable operating costs.

thresholds are shown in Figure 4. Dots highlighted in darker colors indicate the elementary levers that will be implemented at the emission thresholds. The lowest positive abatement cost occurs at $E_2 = 756,184$ $tCO_2$ (91% of the status quo emissions). There, firms would adopt the elementary levers Optimized Grinding (OG) and Alternative Fuels (AF). For a target of $E_{11} = 274,253$ $tCO_2$ (33% of the status quo emissions), firms would adopt the lowest-cost carbon capture technology, LEILAC (LL), together with the elementary levers Optimized Grinding (OG), Recycled Concrete (RC), and Calcined Clays (CC). For more ambitious targets, our analysis predicts that firms would install the carbon capture technology Calcium Looping (CL) alone or in combination with LEILAC (LL). The cost information underlying our calculations suggests that the elementary lever Amine Scrubbing (AS) would never be put to use, as other carbon capture technologies dominate this alternative in terms of cost and abatement potential.[21]

To examine potential variation across cement plants, we test the sensitivity of our cost estimates to various changes in input parameters. In particular, we explore the consequences of (i) individual elementary levers being unavailable, (ii) different costs for transporting and storing captured $CO_2$, (iii) the possibility of operating carbon capture technologies at higher capture rates with increased variable operating costs, and (iv) improvements in the cost and capture rates of carbon capture technologies. As detailed in the Appendix, our analysis delivers a fairly robust assessment of the costs of decarbonizing cement. Specifically, our finding that the annualized total abatement cost of reducing annual emissions by one-third would amount to approximately €10 million emerges in most variations examined in our sensitivity analysis. Furthermore, in most of the variations we consider, the more substantial abatement levels corresponding to approximately 75% and 95% of the status quo emissions would result in an annualized total abatement cost in the range of €50 and €70 million, respectively.

Our results on the cost of decarbonizing cement production are generally also more favorable than those reported in earlier studies (see, for instance, Obrist et al. (2021); Zuberi and Patel (2017); Huang and Wu (2021); Strunge et al. (2022)). These differences partly reflect

[21] In contrast, Heidelberg Materials (2024) recently equipped the first cement plant with an industrial-scale carbon capture unit using Amine Scrubbing technology. If Amine Scrubbing had to be installed, possibly because both Calcium Looping and Oxyfuel were unavailable, our calculations suggest that the annualized total abatement cost at $E_{15}$ to $E_{17}$ would be respectively 31–22% higher than the corresponding values in Figure 3a. $E_{18}$ would no longer be achievable as it would require the combination of Amine Scrubbing with either Calcium Looping or Oxyfuel.

that our calculations are based on new industry data showing advances in the cost and emission profiles of different abatement technologies. Our more favorable results also reflect that our calculations rely on an embedded optimization algorithm that selects for each abatement target the unique cost-efficient combined lever from a large set of elementary levers.

## 4.3 Optimal Abatement under Carbon Pricing

Figure 5a shows the optimal abatement levels of European reference plants for Portland cement production for different carbon prices. We find that the optimal abatement response to any carbon price always selects one of nine different combined levers, that is $|\mathbf{E}^*| = 9$. In accordance with Claim 3, we find that the non-convexity of the $TAC(\cdot|E_0)$ curve, effectively eliminates half of the 18 cost-efficient combined levers in Figure 4, as these will never emerge as optimal regardless of the prevailing carbon price. A striking feature of the optimal response curve $E^*(\cdot)$ displayed in Figure 5 is its inverted S-shape, once the full range of alternative carbon prices is displayed on a logarithmic scale. For prices in the range of €90–140/t$CO_2$, the $E^*(\cdot)$ curve exhibits a high price elasticity of abatement. Thus, for prices in that range, a 1% increase in $p$ is predicted to trigger a relatively large abatement effect.

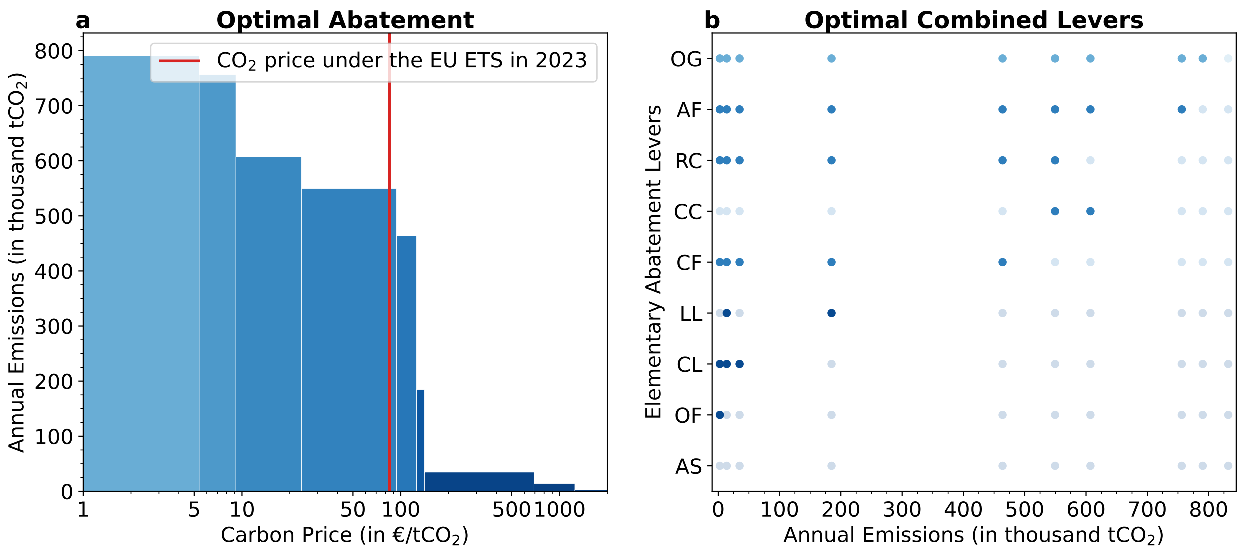


**Figure 5. Optimal abatement for Portland Cement.** This figure shows the (**a**) optimal abatement at different $CO_2$ prices and (**b**) optimal combined levers. Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), LEILAC (LL), Calcium Looping (CL), Oxyfuel (OF), and Amine Scrubbing (AS). Dots highlighted in darker colors indicate the elementary levers that will be implemented at the emission thresholds.

Emission allowances under the EU ETS traded at an average of €85/t$CO_2$ in 2023. If firms expect this price to persist, they will be incentivized to reduce annual emissions to 549,503 t$CO_2$ (66% of the status quo emissions). The corresponding combined lever shown in Figure 5b comprises Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), and Calcined Clays (CC). Alternatively, if carbon prices reach at least €126/t$CO_2$, then firms are incentivized to adopt Carbonated Fines (CF) instead of Calcined Clays (CC) and also adopt the carbon capture technology LEILAC (LL), resulting in annual emissions of 184,824 t$CO_2$ (22% of the status quo emissions). As Figure 5a shows, however, there is only a relatively narrow window of carbon prices, where LEILAC emerges as part of an optimal combined lever. Once the expected carbon charges reach €141/t$CO_2$, it becomes advantageous for firms to leapfrog to the more comprehensive carbon capture technology Calcium Looping (CL), which leaves only 4% of the status quo emissions. Finally, our calculations predict that near-complete decarbonization, resulting in 0.3% of the status quo emissions, would require the addition of Oxyfuel (OF) and a carbon price of at least €1,249/t$CO_2$.[22]

In Germany and other countries, governments seek to accelerate corporate decarbonization by providing targeted subsidies to companies in the form of *carbon contracts for difference*. Figure 6 shows the annual payment, $CCD(E^+|p)$, cement manufacturers would need to receive in order to be willing to reduce their annual emissions from $E^*(p)$ to some target level $E^+$, given a prevailing carbon price of $p$. Each colored line shows a particular carbon price, where each line (except for the red one) corresponds to one of the carbon prices associated with an optimal abatement level in Figure 5a. The steps of a line show the optimal abatement levels below the one associated with the prevailing carbon price that could be chosen as an emission target. The yellow line thus shows the annual payment at a prevailing carbon price of €0/t$CO_2$ for the eight optimal abatement levels below $E^*(0) =$ 790,400 t$CO_2$ on the domain $\mathbf{E}^*$.

To further illustrate our findings on carbon contracts for difference, suppose that the prevailing carbon price is again €85/t$CO_2$ and, therefore, absent any contractual agreement, the optimal abatement response of representative cement plants would be to emit $E^*(85) =$ 549,503 t$CO_2$ (66% of the status quo emissions) annually. For firms to be willing to enter into a contractual agreement that sets the maximum annual emissions at $E^+ =$ 34,787

[22]This price reflects an upper bound if manufacturers can instead add a second unit of the first carbon capture technology (Calcium Looping), potentially at lower capital and operating expenditures than for the first unit.

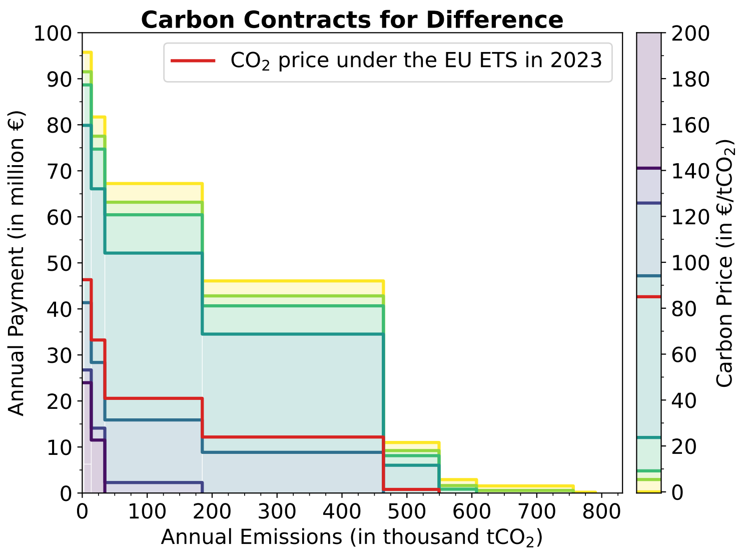


**Figure 6. Carbon contracts for difference.** Given a prevailing carbon price of $p$, this figure shows the annual payment, $CCD(E^{+}|p)$, cement manufacturers would need to receive in order to be willing to reduce their annual emissions from $E^{*}(p)$ to some target level $E^{+}$.

$tCO_2$ (4% of the status quo emissions), we find that the annual payment $CCD(34,787|85)$, represented on the red line in Figure 6, would need to be about €21 million per plant, or about €40/$tCO_2$ additionally abated.[23] This payment may seem too small in light of our finding in Figure 5a that a carbon price of €141/$tCO_2$ would be required to incentivize firms to reduce their emissions to $E^{+} = 34{,}787$ $tCO_2$. The point to recognize is that the carbon contract for difference, as calculated here, amounts to a take-it-leave-it offer that leaves the firm no better off than it would be under a prevailing carbon price of €85/$tCO_2$ and a corresponding best response of annual emissions of $E^{*}(85) = 549{,}503$ $tCO_2$. In practice, firms might be able to negotiate a subsidy payment with the government that effectively shares the available gains from trade and also leaves the firm better off.[24]

Several global cement producers have recently set ambitious decarbonization targets that would substantially reduce emissions relative to current levels. Figure 7 shows the change in the levelized product cost,

$$\Delta LPC(E^{+}|p) = \frac{CCD(E^{+}|p)}{q},$$

[23]Specifically: $40 \approx \frac{20{,}570{,}619}{549{,}503-34{,}787}$.

[24]As observed in Section 3, $(p^{+}-p)\cdot(E^{*}(p)-E^{*}(p^{+}))$ constitutes an upper bound on $CCD(E^{*}(p^{+})|p)$. For the example of $p =$ €85/$tCO_2$, $p^{+} =$ €141/$tCO_2$, $E^{*}(p) = 549{,}503$ $tCO_2$, and $E^{*}(p^{+}) = 34{,}787$ $tCO_2$, the upper bound amounts to about €29 million versus the actual payment of about €21 million. We attribute the "looseness" of this upper bound to the fact that, in this example, $E^{*}(p)$ is much larger than $E^{*}(p^{+})$.

associated with the pledge to reduce annual emissions to some target level $E^+$, even though the prevailing carbon price of $p$ would only induce an optimal response of $E^*(p)$. To illustrate our findings on the product cost implications of voluntary carbon pledges, suppose that firms again anticipate a prevailing carbon price of €85/t$CO_2$ and therefore reduce their annual emissions to $E^*(85) = 549{,}503$ t$CO_2$ (66% of the status quo emissions). The red line in Figure 7 shows that if firms pledge to substantially cut emissions to $E^+ = 34{,}787$ t$CO_2$ (4% of the status quo emissions) and then achieve this pledge, the levelized product cost of cement increases by roughly €15 per ton of cement, or 12% of the average European market price for cement in 2023.

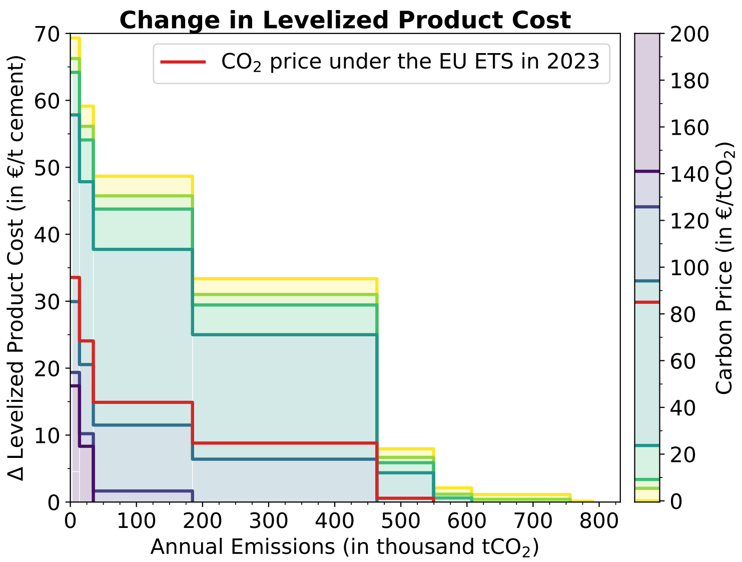


**Figure 7. Impact of voluntary carbon pledges on levelized product cost.** This figure shows the change in the levelized product cost of Portland cement, $\Delta LPC(E^+|p)$, associated with the pledge to reduce emissions from $E^*(p)$ to some target $E^+$.

A widespread policy concern is that if deep decarbonization is to be achieved by means of high carbon prices, the cost of producing essential products like cement would increase sharply.[25] This, in turn, would threaten the affordability of cement as a universal building material. Fennell et al. (2022) estimate that comprehensive decarbonization would double the full cost of cement production. While we lack the requisite data to corroborate such estimates, Figure 8 shows the changes in the levelized product cost, $\Delta LPC(p^+|p)$, if the market price of emission allowances were to increase from $p$ to $p^+$. Each colored line shows

[25]To mitigate this concern, most emission allowances under the EU ETS have been allocated for free. Yet, this free allocation is scheduled to be phased out over the coming decade (European Commission, 2024).

a reference price $p$, with each line (except for the red one) again corresponding to one of the carbon prices associated with an optimal abatement level in Figure 5a.

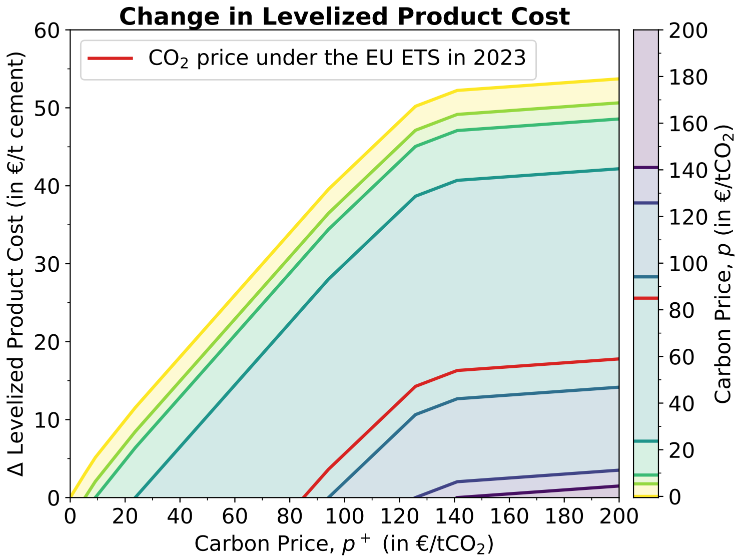


**Figure 8. Impact of higher carbon prices on levelized product cost.** This figure shows the change in the levelized product cost of Portland cement, $\Delta LPC(p^+|p)$, that results if the prevailing carbon price increases from $p$ to $p^+$.

To illustrate our findings emerging from Figure 8, suppose that the prevailing carbon price increases from €85/$tCO_2$ to €141/$tCO_2$ and therefore, the optimal response of a representative cement plant is to reduce its annual emissions from $E^*(85) = 549{,}503$ $tCO_2$ (66% of the status quo emissions) to $E^*(141) = 34{,}787$ $tCO_2$ (4% of the status quo emissions). The corresponding increase in the unit production cost depicted by the red line is then about €16 per ton of cement. Consistent with our analytical characterizations above, the increase in the levelized product cost for a given emissions target, $E^+$, is larger if the target is incentivized by higher carbon prices as opposed to a voluntary pledge, though the actual difference in this particular example is small (i.e., €16 − 15 per ton of cement), because of the high price elasticity of abatement for prices between €90–140/$tCO_2$.

One pattern emerging from Figure 8 that is of immediate policy relevance in the ongoing discussion about tightening the overall emissions cap under the EU ETS is that for baseline carbon prices, $p$, up to €94/$tCO_2$, the levelized product cost, $\Delta LPC(\cdot|p)$, increases at an almost constant rate of about €0.37 per ton of cement for each €1/$tCO_2$ added to $p^+$, provided $p^+ \leq$ €126/$tCO_2$. Consistent with Figure 5, firms will then only adopt combinations of elementary levers that do not include carbon capture technologies. For higher target prices

$p^+ \geq €126/tCO_2$, firms will first adopt the carbon capture technology LEILAC. As a result, $\Delta LPC(\cdot|p)$ increases at a smaller, constant rate of about €0.13 per ton of cement whenever $p^+$ increases by $€1/tCO_2$. More comprehensive carbon capture technologies will be adopted once $p^+ \geq 141/tCO_2$, resulting in an even slower rate of increase for $\Delta LPC(\cdot|p)$. Overall, each of the $\Delta LPC(\cdot|\cdot)$ functions is piecewise linear and concave in $p^+$.

Overall, our findings are corroborated by the recent emergence of low-carbon cement products.[26] Notably, Heidelberg Materials (2023a), HOLCIM (2023) and CEMEX (2023), three leading global cement producers, have begun implementing process improvement and input substitution levers in their production plants worldwide. These efforts have enabled all three companies to reduce the global average net direct $CO_2$ emissions to approximately 560 $tCO_2$ per ton of cementitious material in 2022. Over the coming decade, they plan to further expand the use of these levers in production plants around the world. In addition, Heidelberg Materials and HOLCIM each seek to install more than ten large-scale carbon capture facilities at cement plants, primarily in Europe but also in North America, to further reduce the global average net direct $CO_2$ emissions to about 400 $tCO_2$ per ton of cementitious material by 2030.

# 5 Concluding Remarks

Current climate policy discussions have yet to reach a consensus on how far carbon pricing regulations or subsidies for decarbonization efforts should be expanded to ensure a timely and economical transition to a net-zero economy. This paper has introduced a generic abatement cost concept for identifying cost-efficient pathways for deep industrial decarbonization. We calibrate our model framework with new industry data in the context of European cement plants that must obtain emission permits under the European Emissions Trading System. We find that a price of €85 per ton of $CO_2$, as observed on average in 2023, incentivizes firms to lower their direct emissions by about one-third. Yet, if firms were to expect a price of €141 per ton to prevail in the future, their best response would be to abate their emissions by 96% relative to current levels. This step-up in carbon prices is estimated to increase the levelized product cost of cement by about €16 per ton of cement, or 13% of the average European market price for cement in 2023.

The Intergovernmental Panel on Climate Change and other research organizations have

[26] See, for instance, Research and Markets (2022); George (2022); Heidelberg Materials (2023b).

issued a variety of forecasts for the amount of $CO_2$ that will continue to be emitted in the year 2050 (IPCC, 2023). Such residual emissions would then have to be compensated by carbon removals in order to achieve a net-zero position. Our findings suggest that unless carbon prices were to reach a range of several hundred Euro per ton of $CO_2$ emitted, European cement manufacturers would continue to emit at least 4% of their current emissions. Such projections must, of course, be qualified by their reference to current manufacturing and abatement technologies.

One promising extension of our work is to relax the maintained assumption that firms adopt an entire combined lever at the initial point in time. In particular, if companies expect carbon prices under the European Emissions Trading System to rise or the cost and operational performance of certain abatement technologies to improve over time, it may be beneficial to stagger the adoption of different elementary abatement levers across time periods. Such a staggered adoption would also help companies mitigate the risk of a potentially unfavorable path dependency.

Moving further afield, our cost analysis can be extended to quantify the impact of alternative accounting rules for $CO_2$ emissions.[27] For instance, the use of biomass as an alternative fuel in combination with carbon capture and sequestration technology could potentially result in cement production that removes more $CO_2$ from the atmosphere than it emits. Finally, future research along this line of inquiry could examine the costs of decarbonizing industries such as steel, glass, chemicals, and agriculture. Like cement, these industries are essential to economic development, yet they are also significant contributors to annual global greenhouse gas emissions, and their decarbonization is frequently viewed as prohibitively expensive.

[27] See, for instance, Kaplan and Ramanna (2021); Reichelstein (2024); Glenk (2024).

# Appendix

## A1 Proofs

**Claim 1**

Part (i): The function $E^*(\cdot)$ is weakly decreasing in $p$ because the function $Z(E, p|E_0)$ exhibits decreasing differences, that is, $\frac{\partial}{\partial p}Z(E, p|E_0) = -E$ is a decreasing function in $E$ (Mas-Colell et al., 1995). Since $TAC(\cdot|E_0)$ is a step-function, $E^*(p)$ will, depending on the magnitude of the emissions charge $p$, be one of the $n+1$ stepping points $\{E_- = E_n, \ldots, E_i, \ldots, E_0\}$.[1] Therefore, $E^*(\cdot)$ is a decreasing step-function in $p$.

Part (ii): Suppose $E^*(p) = E_i$ for $1 \leq i \leq n-1$, yet $p < MAC(E_i)$. This would imply:

$$p \cdot (E_i - E_{i-1}) \cdot A(r, T) < TAC(E_i|E_{i-1}),$$

or equivalently:

$$p \cdot (E_i - E_{i-1}) \cdot A(r, T) < TAC(E_i|E_0) - TAC(E_{i-1}|E_0).$$

That, in turn, would imply that $Z(E_{i-1}, p|E_0) < Z(E_i, p|E_0)$, which would contradict that $E^*(p) = E_i$. Further, it cannot be that $p = MAC(E_i)$, because in that case $Z(E_{i-1}, p|E_0) = Z(E_i, p|E_0)$, contradicting that $E^*(p)$ is single-valued. A parallel argument shows that $p < MAC(E_{i+1})$.

Part (iii): If $E^*(p) = E_0$ and this minimizing value is unique, then $Z(E_0, p|E_0) < Z(E_1, p|E_0)$ and therefore $p < MAC(E_1)$. A parallel argument shows that $p > MAC(E_{m-1})$ if $E_m$ is the unique value minimizing $Z(\cdot, p|E_0)$. □

**Corollary to Claim 1**

Suppose $E^*(p) = E_i$, yet $IAC(E_j|E_i) \leq p$ for some $j \in \{0, 1..., n\}$ such that $j > i$. By the arguments provided in Claim 1, it would then follow that $Z(E_j, p|E_0) \leq Z(E_i, p|E_0)$. That would contradict either that $E^*(p) \in E_i$, or that $E^*(p)$ is single valued. Similarly, suppose $IAC(E_i|E_j) > p$ for some $j \in \{0, 1..., n\}$ such that $j < i$. That would imply that $Z(E_j, p|E_0) < Z(E_i, p|E_0)$, yielding a contradiction. Finally, the case $IAC(E_i|E_j) = p$ is again ruled out by the supposed single-valuedness of $E^*(p)$.

[1] As noted in Section 2, $E_0$ may or may not be a stepping point of $TAC(\cdot|E_0)$.

Conversely, if conditions (i) and (ii) of the corollary are met for some $E_i$, then $Z(E_j, p|E_0) > Z(E_i, p|E_0)$ for all $E_j$, $j \neq i$, and therefore $E_i$ is the unique emission level minimizing $Z(\cdot, p|E_0)$. □

**Claim 2**

By construction, the overall lump-sum payment $CCD(E^+|p) \cdot A(r,T)$ is calculated so that the firm is indifferent between accepting and rejecting the carbon contract for difference. Formally,

$$TAC(E^+|E_0) + A(r,T) \cdot p \cdot E^+ - [TAC(E^*(p)|E_0) + A(r,T) \cdot p \cdot E^*(p)] = CCD(E^+|p) \cdot A(r,T).$$

Recalling the definition of $IAC(E_j|E_i)$, the preceding equation can be rewritten as:

$$[IAC(E^+|E^*(p)) - p] \cdot [E^*(p) - E^+] \cdot A(r,T) = CCD(E^+|p) \cdot A(r,T),$$

thereby establishing the claim. □

**Corollary to Claim 2**

If the carbon price increases from $p$ to $p^+$, the firm responds by reducing its emissions from $E^*(p)$ to $E^*(p^+)$. The overall increase in the life-cycle cost of producing q units of output is given by:

$$TAC(E^*(p^+)|E^*(p)) + A(r,T) \cdot p^+ \cdot E^*(p^+) - A(r,T) \cdot p \cdot E^*(p).$$

Recalling again the definition of $IAC(E_j|E_i)$, the increase in the unit cost of production can be expressed as:

$$\Delta LPC(p^+|p) = \frac{[IAC(E^*(p^+)|E^*(p)) - p] \cdot [E^*(p) - E^*(p^+)] + E^*(p^+) \cdot (p^+ - p)}{q}.$$

The result in Claim 2 then yields:

$$\Delta LPC(p^+|p) = \frac{CCD(E^*(p^+|p) + E^*(p^+) \cdot (p^+ - p)}{q}.$$

□

**Claim 3**

To establish that $TAC(\cdot|E_0)$ is convex on the domain $\mathbf{E}^*$, it suffices to show that for any two consecutive points $E_i^*$ and $E_{i+1}^*$ on the domain $\mathbf{E}^*$, we have:

$$\frac{TAC(E_{i+1}^*|E_i^*)}{(E_i^* - E_{i+1}^*) \cdot A(r,T)} \geq \frac{TAC(E_i^*|E_{i-1}^*)}{(E_{i-1}^* - E_i^*) \cdot A(r,T)}.$$

Let $p_i$ and $p_{i+1}$ be unit emission charges at which $E_i^*$ and $E_{i+1}^*$ are optimal, respectively. Thus, $E_i^* \in E^*(p_i)$ and $E_{i+1}^* \in E^*(p_{i+1})$. Since any single-valued selection of $E^*(\cdot)$ is weakly decreasing in $p$ (see arguments in connection with Claim 1), it follows that $p_{i+1} \geq p_i$. Adapting the arguments in the proof of Claim 1, it then follows directly that:

$$p_{i+1} \geq \frac{TAC(E_{i+1}^*|E_i^*)}{(E_i^* - E_{i+1}^*) \cdot A(r,T)} \geq p_i,$$

and furthermore:

$$p_i \geq \frac{TAC(E_i^*|E_{i-1}^*)}{(E_{i-1}^* - E_i^*) \cdot A(r,T)}.$$

□

**Claim 4**

Without loss of generality, suppose that the $m$ values

$$uc_i \equiv \frac{DE(\vec{v}_{-i}, v_i = 1) - DE(\vec{v}_{-i}, v_i = 0)}{E(\vec{v}_{-i}, v_i = 0) - E(\vec{v}_{-i}, v_i = 1)}$$

are all strictly positive. The proof identifies $m+1$ cost-efficient thresholds on the interval $[E_-, E_0]$ and demonstrates that, given separability in the cost and abatement effects of the elementary levers, these thresholds coincide with the set $\mathbf{E}^*$.

If the total abatement cost curve, $TAC(\cdot|E_0)$, is separable in the cost and abatement effects of the elementary levers, then each $uc_i$ is invariant to the choice of the other elementary levers $\vec{v}_{-i}$. Given separability, the boundary value $E_0$ is always in $\mathbf{E}^*$, since $E_0$ minimizes $Z(\cdot, p|E_0)$ if $p = 0$. The next threshold is determined by taking the smallest $uc_i$, for $1 \leq i \leq m$, say $u(1)$, and setting $E_{u(1)}$ such that:[2]

$$E_0 - E_{u(1)} = E(\vec{v}_{-u(1)}, v_{u(1)} = 0) - E(\vec{v}_{-u(1)}, v_{u(1)} = 1).$$

The third of the $m+1$ threshold values is determined by taking the second smallest $uc_i$, for

[2]In case of ties among the $uc_i$, the following constructive proof remains valid for any tie-breaking rule.

$1 \leq i \leq m$, say $u(2)$, and selecting $E_{u(2)}$ such that:

$$E_{u(1)} - E_{u(2)} = E(\vec{v}_{-u(2)}, v_{u(2)} = 0) - E(\vec{v}_{-u(2)}, v_{u(2)} = 1).$$

Applying this selection rule sequentially for all $1 \leq i \leq m$, we obtain $E_{-} = E_{u(m)}$ since $E(\vec{v}) = E_{-}$ if $v_i = 1$ for all $1 \leq i \leq m$. Furthermore, on the domain

$$\{E_{-} = E_{u(m)}, E_{u(m-1)}, \dots, E_{u(1)}, E_0\},$$

we obtain:

$$MAC(E_{u(i)}) = uc_{u(i)}.$$

Suppose now that there exists a threshold $E^*$ such that $E^* \in \mathbf{E}^*$, yet $E^* \notin \{E_{-} = E_{u(m)}, E_{u(m-1)}, \dots, E_{u(1)}, E_0\}$. By definition, there must then exist an emission charge $p$ and a combined lever $\vec{v}^*$ such that $E^* = E(\vec{v}^*)$ and $\vec{v}^*$ minimizes:

$$DE(\vec{v}) + p \cdot E(\vec{v}) \tag{A11}$$

among all $\vec{v} \in V_f$. If $p < uc_1$, it follows directly that $v_i^* = 0$ for all $1 \leq i \leq m$ and $E^* = E_0$.

Next, suppose that $uc_1 \leq p < uc_2$. Since $\vec{v}^*$ minimizes the objective in (A11), we conclude that $v_{u(1)}^* = 1$, while $v_i^* = 0$ for all other $i$. Thus $E^* = E_{u(1)}$ in case $uc_1 \leq p < uc_2$. By proceeding the same way for increasing values of $p$, we conclude that $\mathbf{E}^* = \{E_{-} = E_{u(m)}, E_{u(m-1)}, \dots, E_{u(1)}, E_0\}$, thereby proving the claim. □

# A2 Abatement Levers for Portland Cement

Our analysis considers nine elementary abatement levers. *Optimized Grinding* refers to finer grinding of clinker, thereby increasing the reactivity of the cement as a binding material in concrete. As a result, more low-reactivity limestone can be used in the final cement mix, reducing the amount of clinker required per ton of cement by about 5%. The finer grinding of clinker can be achieved by optimized ball mill settings (Ghalandari and Iranmanesh, 2020; Boehm et al., 2015). *Alternative Fuels* describes the replacement of fossil fuels with alternative materials, particularly biomass for heating the kiln (Aranda Usón et al., 2013; Rahman et al., 2015). Applicable alternatives include dry sewage sludge (85–100% biomass), waste tires (up to 28% biomass), impregnated sawdust (up to 30% biomass), and refusederived fuel (10–60% biomass). Recent demonstration projects suggest that the biomass share of a reference plant with a biomass share of 12% in the status quo can be increased to 27% while maintaining the same burn qualities. Since the use of biomass requires higher heat, the resulting reduction in fuel emissions amounts to about 10%.

*Recycled Concrete* specifies the replacement of limestone with fines made from recycled demolished concrete, which emit no $CO_2$ when heated in the kiln. Recent demonstration projects and journal articles show that recycled concrete can replace 10–25% of the initial limestone if the resulting cement is to keep the same reactive properties (Cantero et al., 2020, 2021). *Calcined Clays* and *Carbonated Fines* are supplementary cementitious materials (SCMs) that reduce the amount of clinker required per ton of cement. Calcined clays are produced at lower emissions than clinker by heating materials that can be found in natural clay deposits or industry by-products like paper sludge waste or oil sands tailings (GCCA, 2022a). Calcined clays can reduce the amount of clinker traditionally included in cement by about 15–45% (Scrivener et al., 2018; Sharma et al., 2021; Hanein et al., 2022). Carbonated fines are obtained from fine particles and powders of recycled concrete that have been exposed to $CO_2$ gas (Ouyang et al., 2020). They can reduce the amount of clinker by about 30% (Zajac et al., 2020).

*LEILAC* (Low Emissions Intensity Lime and Cement) is an alternative kiln design that heats the limestone mixture indirectly and, therefore, keeps process emissions separate from fuel emissions. LEILAC can currently capture 90–95% of process emissions (56–59% of total direct emissions) (LEILAC, 2020). *Amine Scrubbing*, *Oxyfuel*, and *Calcium Looping* are technologies for capturing process and fuel emissions. Amine Scrubbing is a tail-end technology that uses a chemical solvent to separate $CO_2$ from flue gas. Oxyfuel technology burns fuels in the presence of pure oxygen instead of ambient air to produce flue gas with a high $CO_2$ concentration. Calcium Looping separates $CO_2$ from the flue gases by taking advantage of the reversibility of splitting calcium carbonate into calcium oxide and $CO_2$. Specifically, calcium oxide first reacts with $CO_2$ in the flue gas to form calcium carbonate. The calcium carbonate is then heated to separate into the initial components, where the $CO_2$ is captured, and the calcium oxide looped back into the process. Amine Scrubbing, Calcium Looping, and Oxyfuel can currently capture 90–95% of the $CO_2$ in the flue gases (ECRA, 2022; Rochelle, 2009; IEA, 2018; GCCA, 2022b).

Cost and operational parameters of elementary levers mainly stem from ECRA (2022).

Where parameter ranges were provided, we initially selected point estimates within the ranges based on expert interviews or the arithmetic mean of the highest and lowest values of a particular range. In particular, the upfront investment, fixed operating cost, and variable operating cost of carbon capture technologies were calculated as the arithmetic mean of the ranges in ECRA (2022). Since the report provides investment costs for carbon capture technologies for a cement production plant with an annual production capacity of 2.0 million tons of clinker, we divided the values in the report by an adjustment factor of approximately 1.5 to account for economies of scale. This adjustment factor is based on the fact that the report gives investment costs of €160 per ton of clinker for a reference plant for cement production with an annual capacity of 2.0 million tons of clinker and of €210 per ton of clinker for a plant with a capacity of 1.0 million tons of clinker. Thus, $\frac{2 \cdot 160}{210} \approx 1.5$. Cost information for years before 2020 was adjusted for inflation using an annual average inflation rate of 2%.

Information on the operational cost of the carbon capture technologies is stated in ECRA (2022) without differentiation in fixed and variable components. Therefore, we estimated an allocation of the reported costs based on the additional demand for thermal and electrical energy required by the technologies and the corresponding unit cost for the respective energy medium, as provided in the report. For example, the report provides total operating costs of €49 per ton of clinker for Amine Scrubbing. At the same time, the report specifies for Amine Scrubbing an additional demand for thermal energy of up to 3,500 Mega-joule per ton of clinker and for electrical energy of 80–129 kilowatt-hours per ton of clinker. Multiplying these values with the cost of gas (€4.4 per Giga-joule) and electricity (€93 per Megawatt-hour) given in the report yields a fuel-related variable operating cost of €22.8–27.4 per ton of clinker. The remaining cost of €21.6–26.2 per ton of clinker was considered fixed. One exception to this procedure was LEILAC, as the estimated fuel-related variable operating cost turned out to be higher than the total operating cost. Therefore, we assumed that the total operating cost stated in the report is only comprised of variable components and that changes in fixed operating costs are negligible.

The abatement effects of most levers are calculated conservatively, that is, below their technical upper bounds reported above. For instance, our calculations set the replacement of limestone with recycled concrete at 16% rather than the upper bound of 25% to reflect potential variation across plants. Several levers considered in our analysis replace either fossil fuels, limestone, or clinker with alternatives that entail lower emission intensities. Among the input substitution levers, only calcined clays have a positive $CO_2$ intensity due to the heat required for the calcination process. Given our focus on direct emissions, the accounted $CO_2$ intensity of Alternative Fuels, Recycled Concrete, Optimized Grinding, and Carbonated Fines is zero. For instance, recycled concrete as a raw material input and the direct use of limestone, enabled by Optimized Grinding, entail no additional direct $CO_2$ emissions. Also, the $CO_2$ required for Carbonated Fines is assumed to be sourced externally or from the plant's carbon capture unit.

# A3 Operationalizing the Model

This section operationalizes our model framework in the context of Portland cement production to provide expressions for the variables $E(\vec{v})$, $w_t(\vec{v})$, $F_t(\vec{v})$, and $I(\vec{v})$. To obtain compact expressions, it will be convenient to consider the two main ingredients in Portland cement, SCMs and clinker, and the nine elementary levers in the following order: (1) Conventional SCMs, (2) Conventional Clinker, (3) LEILAC, (4) Recycled Concrete, (5) Alternative Fuels, (6) Amine Scrubbing, (7) Oxyfuel, (8) Calcium Looping, (9) Calcined Clays, (10) Carbonated Fines, and (11) Optimized Grinding. We add (1) Conventional SCMs and (2) Conventional Clinker to $\vec{v}$ and assume that this augmented vector, like all subsequent vectors, maintains the same sequence of entries. Thus, $\vec{v} = (v_1, \ldots, v_{11})$, where $v_1, v_2 = 1$ and $v_i \in \{0, 1\}$ for $i \in \{3, \ldots, 11\}$. Accordingly, the status quo is described by $\vec{v}_0 = (1, 1, 0, \ldots, 0)$. All vectors are considered to be column vectors with $m + 2 = 11$ entries.

Entries (3) LEILAC to (8) Calcium Looping in $\vec{v}$ reduce the $CO_2$ intensity of clinker production. To capture that intensity, let $\vec{\beta} = (0, 0, \beta_3, \ldots, \beta_8, 0, 0, 0)$, where $\beta_i \in [0, 1]$ for $i \in \{3, \ldots, 8\}$ gives the relative reduction of the $CO_2$ intensity of clinker production resulting from implementing lever $i$. For example, our calculations assume a carbon capture rate for (8) Calcium Looping of $\beta_8 = 0.925$ in the reference scenario. Similarly, the elementary levers from (9) Calcined Clays to (11) Optimized Grinding reduce the clinker factor, denoted by $\eta$, which quantifies the tons of clinker required per ton of cement in the status quo. Let $\vec{\alpha} = (0, \ldots, 0, \alpha_9, \alpha_{10}, \alpha_{11})$, where $\alpha_9$, $\alpha_{10}$, and $\alpha_{11} \in [0, 1]$, respectively, give the relative reductions of the clinker factor resulting from implementing the corresponding elementary levers.

To obtain the annual emissions of the reference plant, $E(\vec{v})$, let $\vec{i} = (0, i_2(\vec{v}), i_3, \ldots, i_{11})$

denote the vector of $CO_2$ intensities of production processes and elementary levers measured in tons of $CO_2$ per ton of clinker. Here, $i_3, \ldots, i_{11}$ are the direct input parameters, while the carbon intensity of clinker production, $i_2(\vec{v})$, is given by:

$$i_2(\vec{v}) \equiv i_2 \cdot \big[(1 - \beta_3 \cdot v_3) \cdot (1 - \beta_4 \cdot v_4) - \beta_5 \cdot v_5\big] \cdot \prod_{i=6}^{11}(1 - \beta_i \cdot v_i). \tag{A12}$$

Equation (A12) reflects the interaction in the abatement effects of different elementary levers. For instance, the abatement effects of LEILAC $(1 - \beta_3 \cdot v_3)$ are multiplicative to those of Recycled Concrete $(1 - \beta_4 \cdot v_4)$ and additive to those of Alternative Fuels $(\beta_5 \cdot v_5)$ since LEILAC captures process emissions but not fuel-related emissions. With $\vec{i}'$ denoting the transpose of $\vec{i}$, the $CO_2$ intensity of cement for the combined lever $\vec{v}$ is given by:

$$i(\vec{v}) \equiv \vec{i}'(\vec{v} \circ \vec{s}_1). \tag{A13}$$

Here $\circ$ refers to the (element-wise) vector product, and $\vec{s}_1$ denotes a vector of adjustment factors for production quantities, given by:

$$\vec{s}_1 \equiv \big(1 - \eta, \eta \cdot (1 - \vec{\alpha}'\vec{v}), \ldots, \eta \cdot (1 - \vec{\alpha}'\vec{v}), \eta \cdot \alpha_9, \eta \cdot \alpha_{10}, \eta \cdot \alpha_{11}\big).$$

The annual emissions of the reference plant following from implementing combined lever $\vec{v}$ are then given by:

$$E(\vec{v}) \equiv i(\vec{v}) \cdot q. \tag{A14}$$

To illustrate the preceding derivations, suppose that the reference plant only implements (9) Calcined Clays. Our calculations then simplify to:

$$E\big((1, 1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0)\big) = q \cdot \big(\eta \cdot (1 - \alpha_9) \cdot i_2 + \eta \cdot \alpha_9 \cdot i_9\big).$$

Turning to variable operating costs, $w_t(\vec{v})$, let $\vec{w}_t = (w_{1,t}, w_{2,t}(\vec{v}), w_{3,t}, \ldots, w_{11,t})$ denote the vector of variable operating cost of production processes and elementary levers in year $t$ measured in € per ton of clinker. The variable operating cost of clinker production, $w_{2,t}(\vec{v})$, is thereby given by:

$$w_{2,t}(\vec{v}) \equiv w_{2,t} + w_{2,t}^{CO_2} \cdot i_2^{cap}(\vec{v}), \tag{A15}$$

where $w_{2,t}^{CO_2}$ refers to the cost per ton of captured $CO_2$ for transportation and storage, and

$i_2^{cap}(\vec{v}) \equiv i_2 \cdot (1 - \beta_4 \cdot v_4 - \beta_5 \cdot v_5) - i_2(\vec{v})$ quantifies the tons of $CO_2$ captured per ton of clinker produced. The variable cost per ton of cement resulting from a combined lever $\vec{v}$ then becomes:

$$w_t(\vec{v}) \equiv \vec{w}_t'(\vec{v} \circ \vec{s}_1). \tag{A16}$$

For fixed operating costs and upfront investment, let $\vec{F}_t = (F_{1,t}, \dots, F_{11,t})$ denote the vector of annual fixed operating costs of production processes and elementary levers in year $t$. Similarly, let $\vec{I} = (0, 0, I_1, \dots, I_{11})$ denote the vector of upfront capital expenditures of production processes and elementary levers. The fixed operating cost and upfront investment resulting from implementing the combined lever $\vec{v}$ are then:

$$F_t(\vec{v}) \equiv \vec{F}_t'(\vec{v} \circ \vec{s}_2) \text{ and } I(\vec{v}) \equiv \vec{I}'(\vec{v} \circ \vec{s}_2), \tag{A17}$$

where $\vec{s}_2$ denotes a vector of adjustment factors for production capacity given by:

$$\vec{s}_2 = \big(1, 1, 1 - \vec{\alpha}'\vec{v}, \dots, 1 - \vec{\alpha}'\vec{v}, 1, 1, 1\big).$$

# A4 Sensitivity Analysis

**Availability Restrictions**

Some elementary levers may not be available in some geographic regions. For instance, Alternative Fuels may be unavailable to cement plants due to limited supply from nearby biomass producers or excessive demand from other industrial production processes, such as steel production. Alternatively, Recycled Concrete, Calcined Clays, or Carbonated Fines may be unavailable due to a lack of demolished concrete or natural resources. In addition, the carbon capture technologies considered in our analysis may not reach the technological maturity required for industrial-scale deployment until later than anticipated. Therefore, we repeat our calculations in nine variations, each examining the possibility that a particular elementary lever may be unavailable.

Figure A1 shows the resulting annualized total abatement cost curves as colored lines, while the cost-efficient combined levers corresponding to the cost curves are provided in the Supplementary Data. As one would expect, all of the colored total abatement cost curves lie on or above the reference scenario. Yet, the differences in the colored cost curves relative to the reference scenario are small for most variations. If Optimized Grinding is unavailable, then the annualized total abatement cost at the first emission threshold is no longer €0/t$CO_2$ but €193,657/t$CO_2$. Alternatively, if the lever Carbonated Fines is excluded, then the annualized total abatement cost curve shows higher values for both initial and substantial emission reductions. Finally, if the lever LEILAC is unavailable, it would be cost-efficient for firms to leapfrog to the more comprehensive carbon capture technology Calcium Looping.

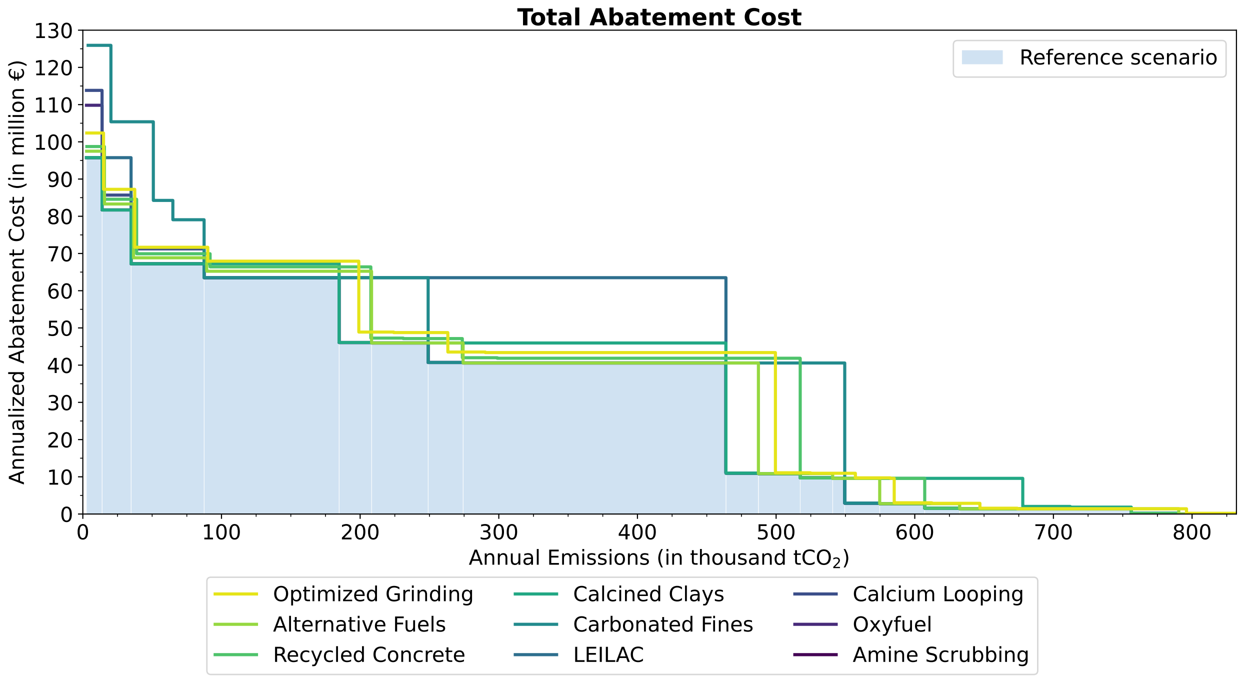


**Figure A1. Cost-efficient abatement for Portland cement.** This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming a particular elementary lever is unavailable. The cost-efficient combined levers corresponding to the total abatement costs are provided in the Supplementary Data.

## Cost of Transporting and Storing $CO_2$

Our analysis has assumed a cost of €80 per ton of captured $CO_2$ for transportation and storage. Yet, this cost can vary substantially depending on the type of infrastructure in place or the distance to storage sites. In this section, we extend our analysis to settings, where the cost of transporting and storing $CO_2$ can vary upward or downward by either 10%, 20%, or 30%.

The resulting annualized total abatement cost curves shown in Figure A2 are higher (lower) for increases (decreases) in the cost of $CO_2$ sequestration, though only for lower emission thresholds that require the deployment of carbon capture technologies. The magnitudes of the relative changes in the annualized total abatement costs are generally less pronounced than the corresponding relative changes in the cost of $CO_2$ sequestration because the cost of $CO_2$ sequestration applies to only a fraction of the total emissions. Furthermore, the shape of the total abatement cost curves and the underlying cost-efficient combined levers remain unchanged, because the changes in the cost of $CO_2$ sequestration affect all carbon capture technologies in the same way.

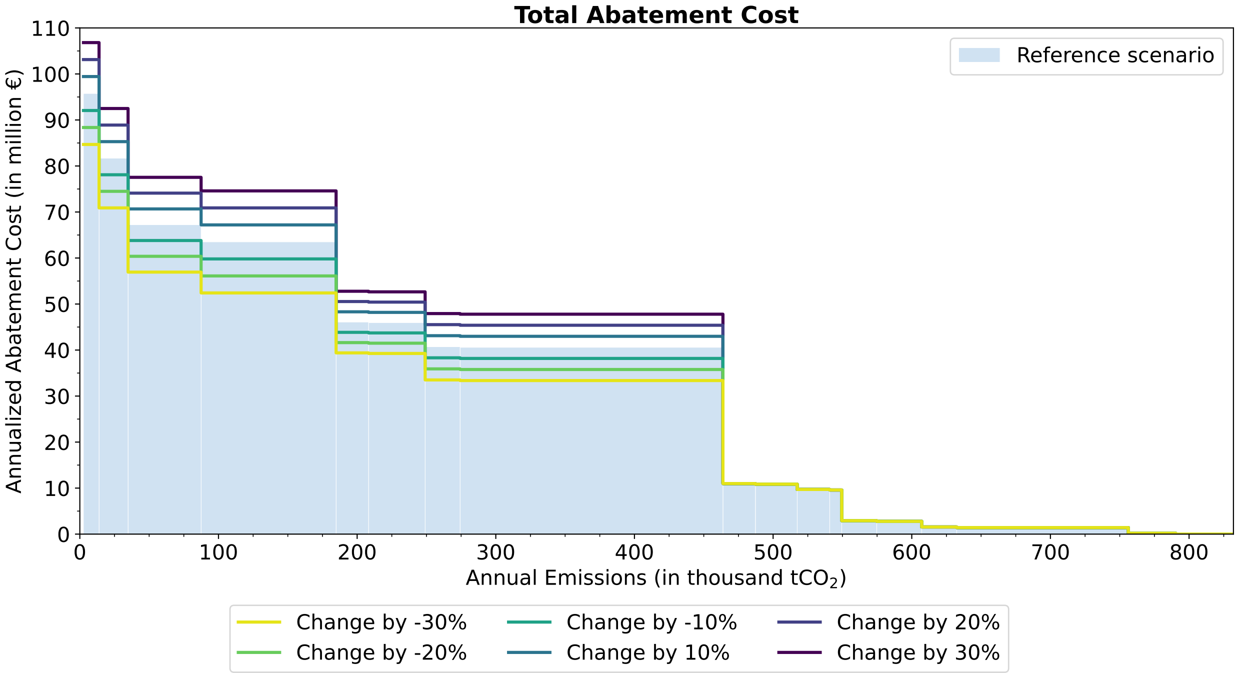


**Figure A2. Cost-efficient abatement for Portland cement.** This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming changes in the costs of transporting and storing captured $CO_2$. The cost-efficient combined levers corresponding to the abatement costs are provided in the Supplementary Data.

## Deep Carbon Capture

Our analysis has assumed that cement manufacturers would implement two carbon capture technologies to achieve near-complete decarbonization. An alternative approach could be to operate one carbon capture technology at a higher capture rate but also with increased variable operating costs. To examine the potential for such an enhanced operation of carbon capture technologies, we repeat our calculations with the capture rates set at the technical maximum value of 95%. In addition, we run several variations where the variable operating costs of carbon capture technologies are higher than in Table 1 by specific values in the range of 10–60%.

The resulting annualized abatement cost curves are shown as colored lines in Figure A3. All of the curves are shifted up and to the left of the reference scenario for emission thresholds that require the deployment of carbon capture technologies. However, the deviations from the reference scenario are relatively small, even for the most pronounced changes in input parameters. Importantly, it is still cost-efficient to combine two carbon capture technologies when cement producers seek to reduce emissions by more than 97%. The cost-efficient combined levers underlying the abatement costs are provided in the Supplementary Data.

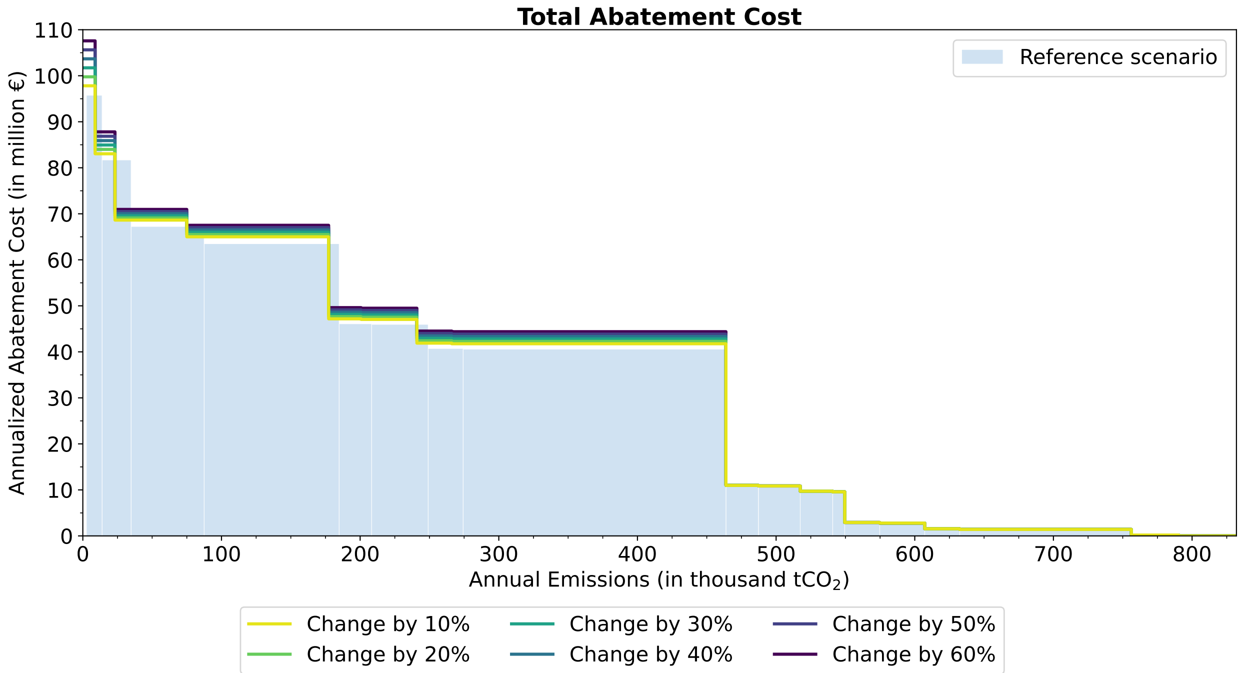


**Figure A3. Cost-efficient abatement for Portland cement.** This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming deep operation of carbon capture technologies. The cost-efficient combined levers corresponding to the abatement costs are provided in the Supplementary Data.

**Advances in Carbon Capture Technologies.**

With industrial decarbonization gaining momentum, carbon capture technologies are expected to improve in cost and capture rates as learning effects materialize with the increasing cumulative deployment of the technologies. Developers of recent demonstration projects, for instance, have estimated that improvements of 20–30% could be achieved within this decade (Kearns et al., 2021). To examine the impact of such advances, we calculate simultaneous improvements in the costs and capture rates of all carbon capture technologies. In particular, we compute several variations where the input parameters of the carbon capture technologies are simultaneously better than in Table 1 by specific values in the range of 10–60%. We again limit the improvements in capture rates to the technical maximum value of 95%.

Figure A4 shows the resulting annualized total abatement cost curves as colored lines. As might be expected, improvements in carbon capture technologies reduce the annualized total abatement costs for emission thresholds that require the deployment of these technologies. Yet, the relative changes from the reference scenario are again relatively small, even for the most pronounced improvements. Moreover, the shape of the total abatement cost curves and the underlying cost-efficient combined levers remain unchanged, because the changes in the costs and capture rates apply equally to all carbon capture technologies.

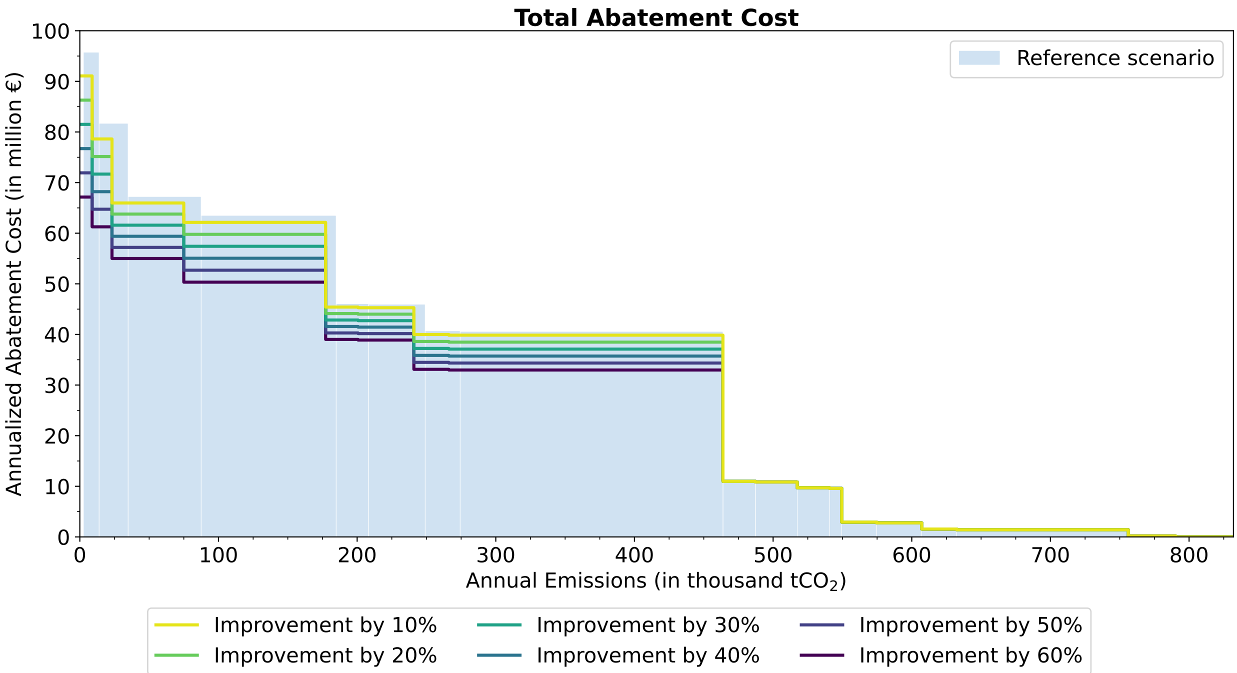


**Figure A4. Cost-efficient abatement for Portland cement.** This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming improvements in carbon capture technologies. The cost-efficient combined levers corresponding to the abatement costs are provided in the Supplementary Data.

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