

Constructing Carbon Abatement Cost Curves

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Abstract

Companies across industries face increasing pressure to assess the costs of decarbonizing their operations. This paper develops a generic model for constructing abatement cost curves in connection with carbon dioxide emissions. The resulting abatement cost curves provide a planning tool for companies seeking to project their decarbonization pathways and to determine optimal abatement levels in response to environmental regulations such as carbon pricing. We calibrate our model in the context of European cement producers that are required to obtain emission permits under the European Emissions Trading System. We find that a price of €85 per ton of carbon dioxide, as observed on average in 2023, incentivizes firms to reduce their annual direct emissions by about one-third relative to the status quo. Yet, this incentive increases sharply when prices rise above the benchmark of €100 per ton of carbon dioxide.

Keywords: life-cycle costing, capacity investments, marginal abatement cost, carbon emissions, industrial decarbonization

JEL Codes: M41, M48, Q54, Q56

1 Introduction

Amid growing calls to slow the pace of climate change, companies worldwide have pledged to reduce their carbon emissions over time and achieve a position of net-zero emissions by 2050 (Net Zero Tracker, 2025). While these pledges vary substantially in scope and specificity, companies face the challenge of assessing the costs of technological and operational changes required to meet their abatement targets. Aside from voluntary carbon reduction pledges by individual companies, many jurisdictions have adopted regulations such as charges on carbon emissions or tax credits for the adoption of low-carbon products and production technologies.¹ Companies will then need to assess to what extent any abatement costs are effectively counterbalanced by reduced emission charges or the implicit revenues associated with tax credits.

This paper develops a generic model for abatement cost curves pertaining to carbon dioxide (CO₂) and other greenhouse gas emissions. To that end, companies are assumed to have access to elementary abatement levers that will result in emission reductions relative to some status quo level. These elementary levers reflect a range of potential measures such as energy efficiency, process improvements, input material substitutions, and possibly the deployment of carbon capture and sequestration technology. For alternative emission reduction targets, the *Total Abatement Cost* (TAC) is given by the life-cycle expenditures of the combined lever that is minimal among all combinations of elementary levers that result in future emissions not exceeding the target level. Our life-cycle cost metric comprises all upfront investment expenditures and subsequent changes in fixed and variable operating costs associated with the optimal combined lever.²

In microeconomics, the cost associated with a given output target is usually derived as the expenditure-minimizing input bundle chosen from a continuum of alternatives. The optimal input bundle then satisfies the usual first-order conditions; that is, the technical rate of substitution between any two inputs must be equal to the ratio of their input prices (Mas-Colell et al., 1995). As a consequence, the resulting cost curves are typically continuous and even smooth. In contrast, our framework of a finite number of elementary and combined levers entails a combinatorial optimization problem where the resulting cost curve is a step function that is increasing in the abatement target.

The *Marginal Abatement Cost* (MAC) curves emerging in our framework are struc-

¹As part of the Corporate Sustainability Reporting Directive (CSRD), publicly listed companies in the European Union are required to disclose the abatement targets they have adopted and to describe the quantitative contributions of different measures they expect to implement (European Union, 2023).

²Thus, our abatement cost concept is consistent with the notion of life-cycle costing as advocated for in accounting textbooks, such as Horngren et al. (2015) and Atkinson et al. (2020).

turally different from the classical marginal abatement cost curves popularized by the consulting firm McKinsey (2007) and studied in numerous contexts.³ As shown in Figure 1, a common assumption underlying classical marginal abatement cost curves is that the abatement impact of elementary levers is separable. 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. In many industries, however, elementary levers exhibit interactions when implemented together at one plant (McKittrick, 1999).⁴ For instance, the abatement effects of alternative raw materials used in the production of cement depend heavily on whether the plant in question also installs a carbon capture facility for flue gases. The MAC curves emerging in our framework are generally not monotonically increasing in the level of abatement because the joint costs and emission levels corresponding to different combined levers are not separable between the constituent elementary levers⁵

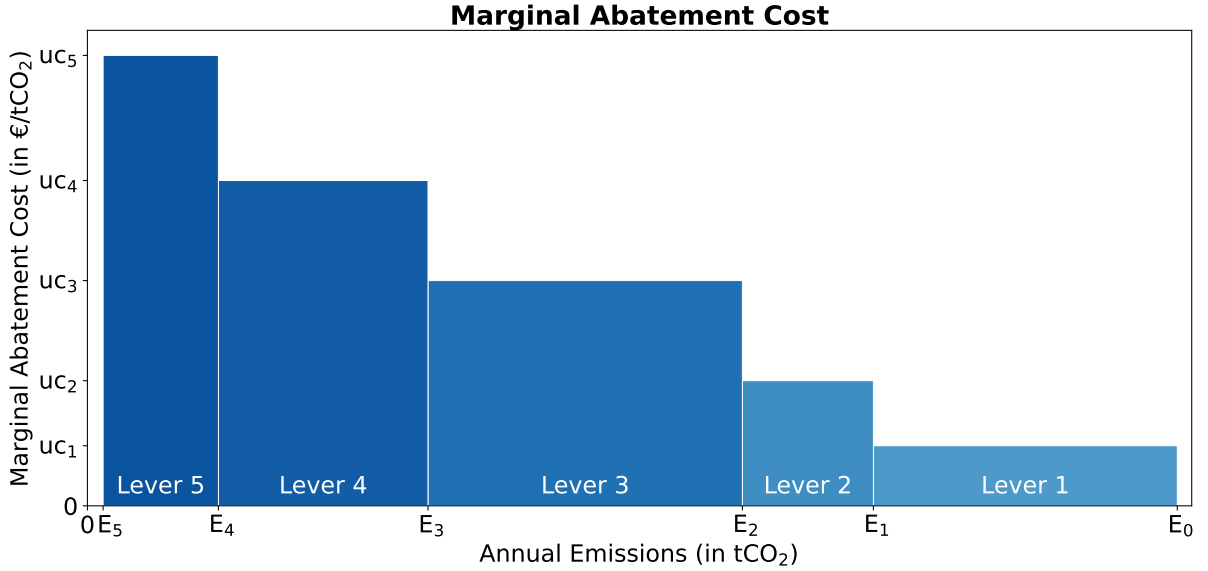


Figure 1. Classical marginal abatement cost curve. This figure illustrates the curve resulting from ordering different elementary levers i by their unit cost uc_i . The curve always increases in the level of abatement, i.e., the difference between the status quo emissions E_0 and the remaining emissions E_i after implementing levers 1 to i .

Industries such as steel, cement, and chemicals deliver products that are essential to a modern economy. Yet, they significantly contribute to global annual carbon emissions

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

⁴To 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).

⁵The marginal abatement cost curves invoked in the environmental economics literature are typically smooth and monotonically increasing (Stavins, 2019; Grubb et al., 2014). These specifications reflect a continuum of potential abatement levers as well as the lack of any interaction effects among the levers.

and are often characterized as hard to decarbonize (Davis et al., 2018).⁶ Our model of abatement cost curves can be used to project the cost of alternative decarbonization targets for these industries. In particular, we calibrate our model in the context of European cement plants. Portland cement production is considered hard to decarbonize because the heating of limestone involves significant process emissions that cannot be avoided by phasing out the burning of fossil fuels. Our numerical analysis examines nine elementary levers that are considered to be technologically ready for deployment at cement plants around the world. Since these elementary levers can essentially be freely combined, there are potentially up to $2^9 = 512$ combined levers. Our estimates for the cost and abatement effects of these nine elementary levers are based on recent industry data (ECRA, 2022).

We find that among the potential 512 combined levers, only 18 are cost-efficient insofar as they are not dominated by another combined lever that delivers lower emissions without an increase in cost. We then proceed to examine the incentives for European cement producers to adopt combined levers that are optimal in response to alternative carbon prices that have prevailed and may emerge in the future under the European Emissions Trading System (EU ETS). It turns out that for a wide range of alternative carbon prices, only nine of the 18 cost-efficient combined levers emerge as potentially optimal. This finding reinforces the structural difference between our and the classical abatement cost model: if our marginal abatement cost curve were monotonically increasing, all 18 cost-efficient levers would emerge as optimal at some carbon price.

Our calculations further show that if cement producers were to expect carbon prices under the EU ETS to continue at their 2023 average value of €85 per ton of CO₂ in future years, they would be incentivized to abate annual direct CO₂ 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 CO₂, while €141 per ton would provide incentives sufficient for near-full decarbonization.

In addition to charging firms for their CO₂ emissions, some countries have recently embraced so-called *carbon contracts for difference*. Accordingly, governments sign bilateral contracts with firms that specify annual lump-sum payments in exchange for the direct emissions of particular plants not exceeding the contractually specified limit. Our

⁶Among these industries, cement alone is responsible for about 8% of global annual CO₂ emissions (Fennell et al., 2021).

abatement cost model allows analysts to gauge the minimum lump-sum payment required for firms to agree to such contracts. This payment reflects the life-cycle incremental cost of abating annual emissions from a base level to some target level. In the context of the cement industry, we find that if the prevailing carbon price were to be €85 per ton of CO₂, European reference plants 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 CO₂ per year. This amounts to about €33 per ton for the additional emissions abated.

A common concern about increasing emission charges is their impact on the production cost 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 from the prevailing carbon price increasing from p to p^+ , possibly in response to regulators issuing fewer permits under a cap-and-trade system.⁷ 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 CO₂, the life-cycle cost of producing one ton of cement would increase by about €16, 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.⁸

Our findings on the cost of decarbonizing cement production are shown to be robust to various sensitivity tests. These robustness findings partly reflect that for most of the nine elementary levers we consider, there are effective substitutes. Further, our model relies on an embedded optimization algorithm that is flexible in identifying alternative cost-efficient combined levers. Our results are also consistent with the recent surge in market activity for those levers that we identify as economically viable at recent carbon prices for EU firms. For example, Heidelberg Materials (2023a), HOLCIM (2023), and CEMEX (2023), three globally leading cement producers, have all begun to implement the process improvements and input substitutions we identify as “low-hanging fruit.”

Beyond cement production, our abatement cost concept is applicable in other emission-intensive industries such as power generation, transportation, or the production of primary goods such as steel and chemicals. As we discuss in Section 5, elementary levers applicable in these settings typically involve capital investments and exhibit interactions when deployed at the same plant or asset. For instance, energy efficiency upgrades re-

⁷Our metric of life-cycle product costs draws on the concept of levelized product costs (Reichelstein and Rohlfing-Bastian, 2015) and the literature on full cost pricing (see, for instance, Banker and Hughes (1994); Balakrishnan and Sivaramakrishnan (2002); Göx (2002)).

⁸In contrast, Fennell et al. (2022) estimate that comprehensive decarbonization would double the full cost of cement production.

duce fuel consumption and thereby diminish the abatement effect of low-emission fuel substitutes. Data on the cost and operational parameters of common emission-reducing technologies, such as solar photovoltaic, lithium-ion batteries, and electric vehicles, are monitored by organizations like BloombergNEF and the International Energy Agency. Industry-specific data are becoming increasingly available in review articles and technology reports (e.g., Rissman et al. (2020); Agora Industry et al. (2022)). Beyond these sources, firms frequently develop their own assessments regarding the cost and abatement effects of elementary levers applicable to them (e.g., Lu et al. (2022)).

Our paper relates to several branches of the emerging literature on the costs of corporate decarbonization. One branch has empirically examined the drivers of firms' voluntary abatement efforts and the strategies firms 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). 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., 2024). Our analysis takes a cost accounting approach by identifying cost-efficient combinations of abatement levers. The resulting cost curves allow external analysts to gauge the credibility of firms' voluntary carbon pledges.

Another branch of the decarbonization literature has studied the cost and adoption of low-carbon production technologies in response to emission regulations. For example, Drake et al. (2016) and Drake (2018) have examined the effect of carbon pricing mechanisms on 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, 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 carbon price required for firms to adopt particular abatement technologies.⁹

⁹Our study also relates to the sizable 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. Colmer et al. (2025) have examined the effect of the EU ETS on firm-

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 discusses the applicability of our model in industries other than cement production, while Section 6 provides concluding remarks. The Appendix contains formal proofs, a detailed description of abatement levers for Portland cement production, an algorithm for operationalizing our model in the context of cement production, and several sensitivity tests.

2 Abatement Cost Curves

Our model considers a firm that produces a fixed quantity q of a single product each year.¹⁰ The underlying production process causes emissions that impose external costs on the natural environment. For concreteness, the following discussion will focus on CO₂ emissions, even though the abatement cost concept developed in this section is generic.¹¹ Suppose that, for the production facility in question, the status quo entails E_0 metric tons of direct (Scope 1) CO₂ emissions each year in order to produce q units of output.

To abate emissions, the firm can implement combinations of m different measures, referred to as *elementary levers*. These levers may involve input substitutions, changes in product design, or structural changes in the production process. The adoption of levers is binary in our model, with $v_i = 1$ indicating that elementary lever i is implemented, and $v_i = 0$ otherwise.¹² We refer to a combination of elementary levers as a *combined lever*, denoted by the m -dimensional vector $\vec{v} = (v_1, \dots, v_m)$. Accordingly, $\vec{v}_0 = (0, \dots, 0)$ 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 .

level emissions in the EU, while Fowlie et al. (2016) and Ryan (2012) have studied the economic and environmental implications of market-based CO₂ regulations in the U.S. cement industry. Similarly, Armitage et al. (2024) analyze the effectiveness of climate policies on investments in low-carbon cement production. To these studies, we add a range of estimates for the CO₂ price elasticity of abatement.

¹⁰Our model can readily incorporate variable production volumes and product prices that depend on production volumes and abatement levels. The firm would then seek to maximize the discounted cash flows rather than minimize the discounted expenditures associated with alternative abatement measures.

¹¹Other greenhouse gases could be converted to CO₂ equivalents in accordance with commonly accepted conversion factors.

¹²To extend our model to settings where the i -th lever can be implemented on a finite scale from 1 to k , one could introduce k different levers, corresponding to the different scale levels. Furthermore, the cost minimization problem stated in (2) would be stated subject to the additional constraint that adoption of any of these k elementary levers is mutually exclusive.

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.¹³

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

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

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.

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

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

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.

¹³Our model can be adapted to account for a shorter remaining life of the existing plant by adjusting $I(\vec{v})$ to reflect that a combined lever will still have residual value at date T (see Appendix A5).

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 $E_u \rightarrow E$, it follows that:

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

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.¹⁴ 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 $E_- = E_n < \dots < E_i < \dots < E_1$. By construction, $TAC(E_i|E_0) > TAC(E_{i-1}|E_0)$ for $2 \leq i \leq n$. 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

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

as the set of *cost-efficient emission thresholds*.¹⁵ Since the cardinality of $\mathbf{E}$ (i.e., n) may be substantially smaller than the number of possible combined levers (i.e., 2^m),

¹⁴This corresponds to the growing empirical literature on “win-win” solutions that reduce corporate pollution without decreasing corporate financial performance (Ambec et al., 2013).

¹⁵If E_0 is not a stepping point of the $TAC(\cdot|E_0)$ function, then E_0 is not cost-efficient insofar as the firm can achieve lower emissions without incurring an abatement cost.

the complexity of the economic optimization problem may be significantly reduced by restricting attention to the emission thresholds in $\mathbf{E}$.¹⁶

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 $1 \leq i \leq n$:

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

where $A(r, T) \equiv \sum_{t=1}^T (1+r)^{-t}$ denotes the annuity value of \$1.0 paid over T years at the discount rate r . Including the annuity value in the denominator ensures that the life-cycle cost of reducing annual emissions, $TAC(E_i|E_{i-1})$, is divided by the corresponding life-cycle emission reduction.

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.¹⁷ As 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. The resulting $TAC(\cdot)$ curve may then not be convex, resulting in corresponding $MAC(\cdot)$ curves that are not monotonically increasing in the abatement level, i.e., the index i .

Appendix A5 develops two extensions of our base model. First, in contrast to the formulation above, firms may be uncertain about the cost and abatement effects of different levers. Such uncertainty may reflect various factors, including technological progress, the

¹⁶In 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 $n = 18$.

¹⁷See, for instance, Stavins (2019); Grubb et al. (2014); Kuosmanen and Zhou (2021); Harmsen et al. (2019); Beaumont and Tinch (2004)

availability of input factors, fluctuations in energy and raw material prices, and variation in the charges imposed on carbon emissions. To introduce uncertainty into our model, the variables $w_t(\vec{v})$, $F_t(\vec{v})$, and $I(\vec{v})$ can be reinterpreted as the respective expected value of the underlying random variables. For a risk-neutral decision-maker, the effective $TAC(\cdot)$ function in equation (2) then becomes the expected total abatement cost of reducing annual emissions from E_0 to E . If the uncertain cost components $w_t(\cdot)$, $F_t(\cdot)$, and $I(\cdot)$ are calculated based on uncertain per-unit cost primitives of the constituent elementary levers, as they are in our cement application, Appendix A5 demonstrates that the expected total abatement cost will be minimized by the same combined lever that minimizes the deterministic $TAC(\cdot)$ when the costs of different levers assume their expected values for sure.

For a second extension of our base model, we consider the possibility that firms do not adopt an entire combined lever at the initial point in time. Instead, they may prefer to stagger the adoption of elementary levers over time, especially if more expensive levers become economical only once carbon prices reach a sufficiently high level at some future date. Appendix A5 constructs abatement cost curves for settings with two (or more) dates at which irreversible investments can be undertaken. Under certain conditions, the total abatement cost curves emerging from such a staggered adoption setting are again right-continuous step-functions, where the stepping points correspond to the sequential achievement of the stepping points of the $TAC(\cdot | E_0)$ function in equation (2). Finally, Section 4.3 quantifies the value of decision flexibility arising from the possibility of staggered adoption in the context of Portland cement production.

3 Abatement Responses 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 CO₂ 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 choose the emission level E to minimize the *Comprehensive Abatement Cost* (CAC) given by:

$$CAC(E, p | E_0) \equiv TAC(E | E_0) - p \cdot (E_0 - E) \cdot A(r, T). \quad (4)$$

Relative to the status quo, the firm now trades off the additional cost of higher abate-

ment levels against lower emission charges. For any given p , the abatement levels that minimize $CAC(E, p|E_0)$ are 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 $CAC(E, p|E_0)$ for any given p .¹⁸

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.¹⁹ 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 classical 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:

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

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 $j \in \{0, 1, \dots, n\}$ such that $j > i$, and

(ii) $IAC(E_i|E_j) < p$ for any $j \in \{0, 1, \dots, n\}$ such that $j < i$.²⁰

¹⁸Allowing for $E^*(\cdot)$ to be a correspondence, part (i) of Claim 1 can be extended to any selection from the 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 $3 \leq j \leq 4$.

¹⁹The proofs for all claims are relegated to Appendix A1.

²⁰We note in passing that the corollary recovers the necessary first-order conditions stated in Claim 1, since $IAC(E_i|E_{i-1}) = MAC(E_i)$.

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 regulatory bodies and individual firms in hard-to-abate industries where firms commit to reducing their emissions to a specified target level, say E^+ . If the prevailing carbon price is expected to be p in the foreseeable future and the 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 abatement 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:*

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

The lump-sum payment in (6) is based on the implicit assumption that the government has the entire bargaining power in offering such contracts. While the firm is merely indifferent between 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 expected 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.²¹ 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 expected increase in the levelized product cost (LPC) of the firm’s sales product.²²

²¹A rapidly growing literature has analyzed the credibility and ambition of corporate net-zero pledges; see, for instance, Bolton and Kacperczyk (2025); Comello et al. (2022); Hale et al. (2022).

²²Levelized 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, Reichelstein and Rohlfling-Bastian (2015) argue that the LPC should be viewed as the long-run marginal product cost because, in a competitive market equilibrium, the expected market price must be equal to the LPC.

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

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

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 CO₂ from p to p^+ . We denote the product cost increase by $\Delta LPC(p^+|p)$.

Corollary to Claim 2.

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

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 classical concept of marginal abatement cost curves in settings where producers face emission charges. 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.²³ 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,

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

denotes the change in emissions that results 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:

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

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:

$$uc_i \equiv \frac{DE(\vec{v}_{-i}, v_i = 1) - DE(\vec{v}_{-i}, v_i = 0)}{[E(\vec{v}_{-i}, v_i = 0) - E(\vec{v}_{-i}, v_i = 1)] \cdot A(r, T)}, \quad (11)$$

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 .*

²³In 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 emissions level 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 1 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 $\mathbf{E}^*$, but not on the full domain $\mathbf{E}$. We demonstrate this formally as a Corollary to Claim 4 in Appendix A1.

4 Model Application: Portland Cement Production

We calibrate our model to European reference plants for Portland cement production. The cement industry delivers products that are essential to a modern economy, yet it also accounts for about 8% of global annual CO₂ emissions (Fennell et al., 2021). Portland cement production is often characterized as particularly hard to decarbonize because a major share of its emissions are intrinsic process emissions that cannot be avoided by phasing out the burning of fossil fuels. Nonetheless, major cement producers have recently embraced net-zero emission goals by the year 2050. The achievement of these goals will require the adoption of abatement levers that drastically reduce the emissions associated with current production processes.

4.1 Abatement Levers for Portland Cement Production

Portland cement production 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 CO₂. 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 CO₂ 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).

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 supplementary cementitious materials (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.²⁴

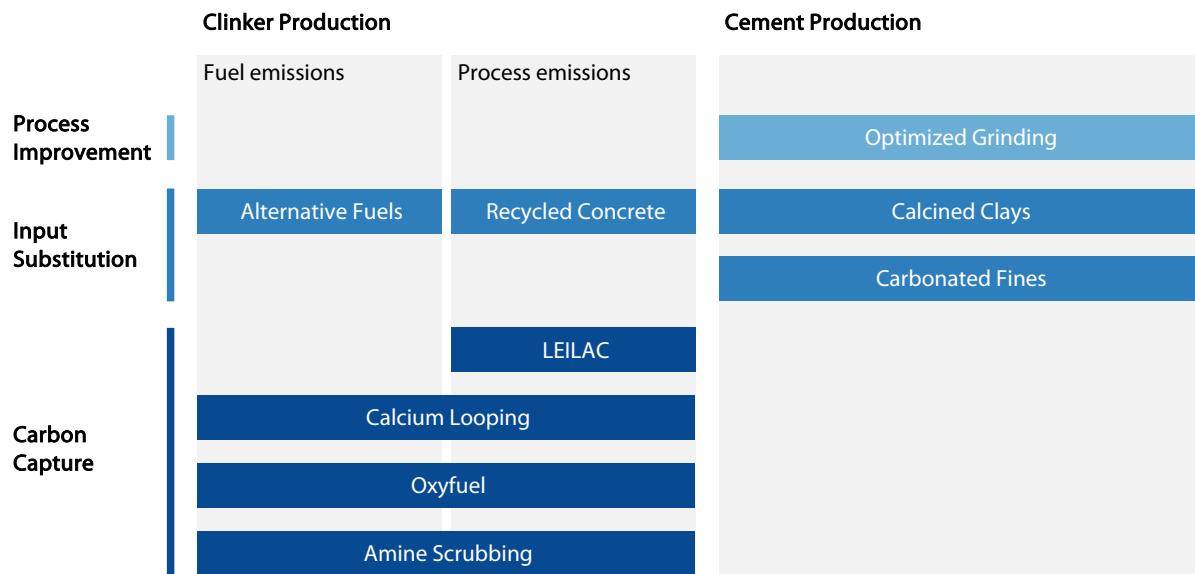


Figure 2. Elementary abatement levers. This figure illustrates the nine elementary abatement levers considered in our analysis.

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) when heating the kiln. *Recycled Concrete* specifies the replacement of limestone with fines made from demolished concrete, which emit no CO₂ 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

²⁴See, for instance, Griffiths et al. (2023); Napp et al. (2014); Rissman et al. (2020); ECRA (2022); Dunant et al. (2024).

technologies that capture both the fuel- and process-related emissions. Details about the technological characteristics and limitations of these elementary levers are provided in Appendix A2.

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 Appendix A3. 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 reference plants have 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 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 CO₂. Our calculations set these off-take charges at €80 per ton. Following the lead of cement industry experts, we set the weighted average cost of capital at 7.0% and the useful life of capital investments at 30 years.

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.

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 $E_1 = 790,400$ tCO₂ 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 tCO₂ annually or 0.3% of the status quo emissions.

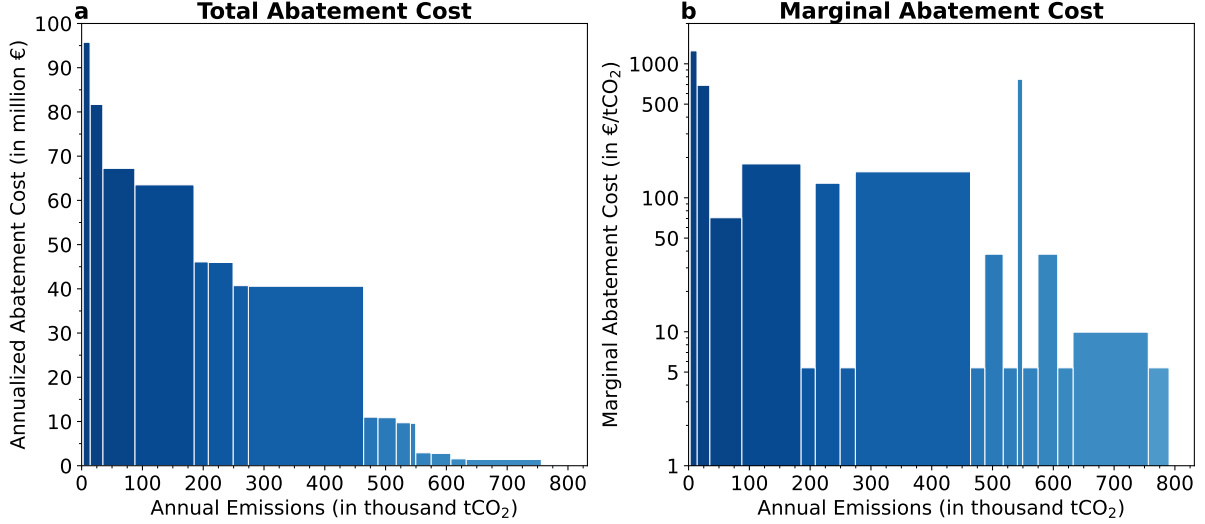


Figure 3. Abatement cost curves for Portland cement. This figure shows (a) the annualized total abatement cost and (b) the marginal abatement cost for the cost-efficient emission thresholds.

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 (BusinessAnalytics, 2024). The annual revenue of a representative plant would, therefore, be $\text{€}120/\text{t} \cdot 1,381,215\text{t} = \text{€}165,745,800$. 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/tCO₂. 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/tCO₂ and €1,249/tCO₂, respectively. These sharp cost increases reflect the installation of a

second carbon capture technology for achieving the two lowest thresholds.²⁵ The spike at $E_7 = 540,800$ tCO₂ 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.

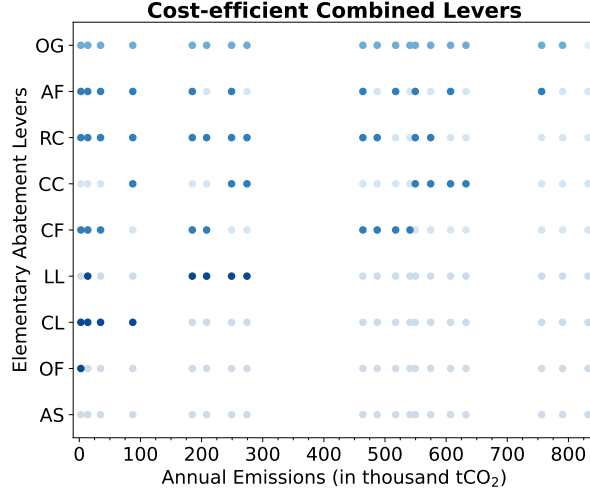


Figure 4. Cost-efficient combined levers. This figure shows the combined levers corresponding to the cost-efficient emission thresholds. Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), Carbonated Fines (CF), LEILAC (LL), Calcium Looping (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 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 $E_2 = 756,184$ tCO₂ (91% of the status quo emissions). There, firms would adopt the elementary levers Optimized Grinding (OG) and Alternative Fuels (AF). For a target of $E_{11} = 274,253$ tCO₂ (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 not be put to use, as other carbon capture technologies

²⁵Our 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 Appendix A4, examine the possibility that firms could instead operate the first adopted carbon capture technology at a higher abatement efficiency in connection with higher variable operating costs.

dominate this alternative in terms of cost and abatement potential.²⁶

For the different elementary levers, the cost estimates in Table 1 are set to the arithmetic mean of the corresponding upper and lower bounds reported in ECRA (2022). These bounds suggest that there is some uncertainty about the costs of the elementary levers, where the underlying probability distributions have yet to be observed. Appendix A5 demonstrates that, irrespective of the probability distributions, the total abatement cost curve in Figure 3a can be interpreted as the expected total abatement cost derived from a model with underlying cost uncertainty, provided that the expected value of each cost component (variable, fixed, and upfront investment) of all elementary levers is equal to the arithmetic mean of its upper and lower bounds.

To further examine potential variation in the cost and abatement effects of elementary levers, 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 CO₂, (iii) the possibility of operating carbon capture technologies at higher capture rates with increased variable operating costs, (iv) improvements in the cost and capture rates of carbon capture technologies, and (v) small simultaneous deviations in the assumed abatement effect of all elementary levers. As detailed in Appendix A4, our analysis delivers a fairly robust assessment of the costs of decarbonizing Portland cement production. 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.

Overall, our results on the cost of decarbonizing cement production are generally 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 that our calculations are based on more recent 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 al-

²⁶In 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.

gorithm that selects for each abatement target the unique cost-efficient combined lever.

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 5a 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/tCO₂, 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.

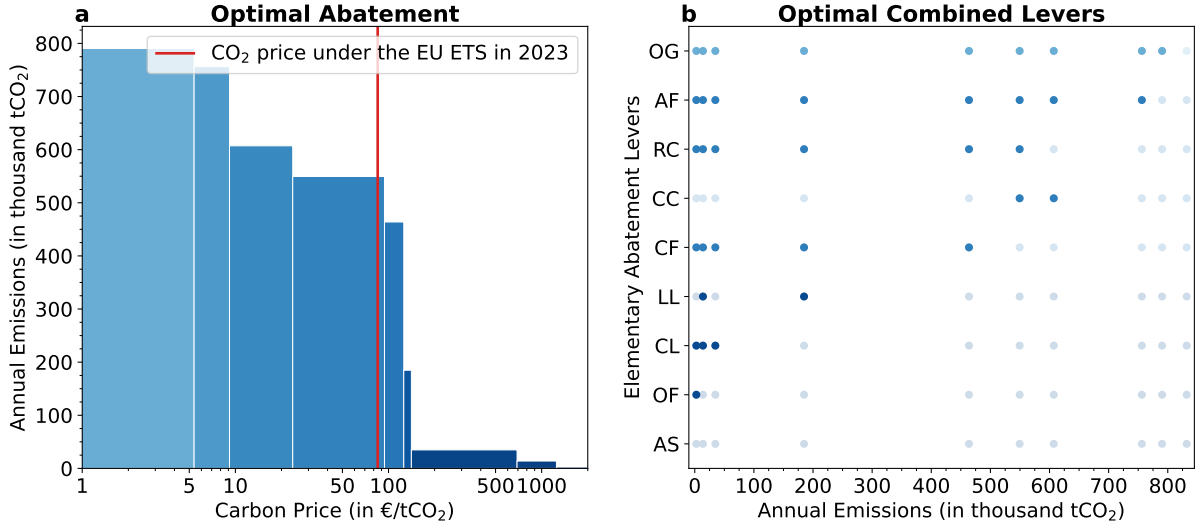


Figure 5. Optimal abatement for Portland Cement. This figure shows the (a) optimal abatement at different CO₂ prices and (b) optimal combined levers. Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), Carbonated Fines (CF), LEILAC (LL), Calcium 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/tCO₂ in 2023. If firms expect this price to persist, they will be incentivized to reduce annual emissions to 549,503 tCO₂ (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/tCO₂, 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 tCO₂ (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/tCO₂, 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/tCO₂.²⁷

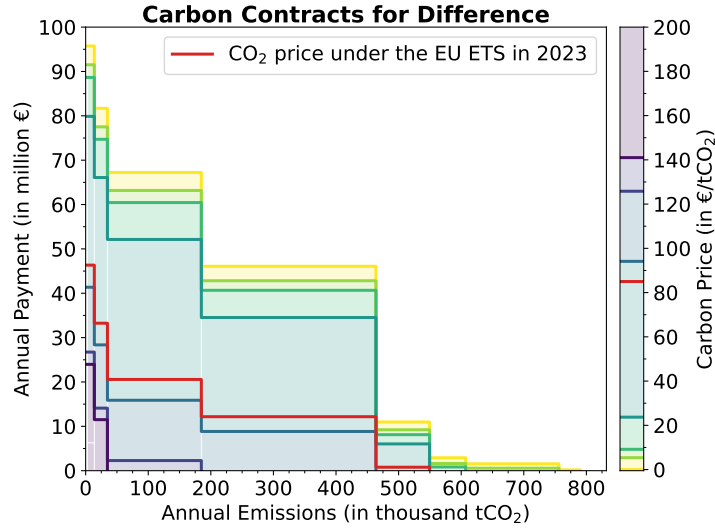


Figure 6. Carbon contracts for difference. Given a prevailing carbon price of p , this figure shows the annual payment, $CCD(E^+|p)$, cement manufacturers would need to receive in order to be willing to reduce their annual emissions from $E^*(p)$ to some target level E^+ .

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

²⁷This 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.

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/tCO₂ for the eight optimal abatement levels below $E^*(0) = 790,400$ tCO₂ on the domain $\mathbf{E}^*$.

To further illustrate our findings on carbon contracts for difference, suppose that the prevailing carbon price is again €85/tCO₂ and, therefore, absent any contractual agreement, the optimal abatement response of representative cement plants would be to emit $E^*(85) = 549,503$ tCO₂ (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 $E^+ = 34,787$ tCO₂ (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/tCO₂ additionally abated.²⁸ This payment may seem too small in light of our finding in Figure 5a that a carbon price of €141/tCO₂ would be required to incentivize firms to reduce their emissions to $E^+ = 34,787$ tCO₂. 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/tCO₂ and a corresponding best response of annual emissions of $E^*(85) = 549,503$ tCO₂. 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.²⁹

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,

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

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 $E^*(p)$. This cost increment can be interpreted as the “green premium,” the firm would need to obtain on the product price to recover the incremental cost associated with achieving its voluntary carbon pledge. To illustrate our findings on the product cost implications of voluntary carbon pledges, suppose that firms again anticipate a prevailing carbon price

²⁸Specifically: $40 \approx \frac{20,570,619}{549,503 - 34,787}$.

²⁹As observed in Section 3, $(p^+ - p) \cdot (E^*(p) - E^*(p^+))$ constitutes an upper bound on $CCD(E^*(p^+)|p)$. For the example of $p = €85/\text{tCO}_2$, $p^+ = €141/\text{tCO}_2$, $E^*(p) = 549,503$ tCO₂, and $E^*(p^+) = 34,787$ tCO₂, 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 $E^*(p^+)$.

of €85/tCO₂ and therefore reduce their annual emissions to $E^*(85) = 549,503$ tCO₂ (66% of the status quo emissions). The red line in Figure 7 shows that if firms pledge to substantially cut emissions to $E^+ = 34,787$ tCO₂ (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.

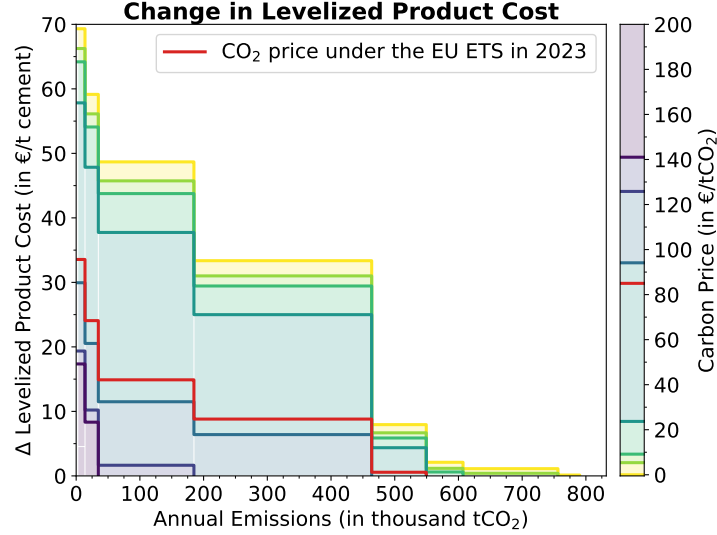


Figure 7. Impact of voluntary carbon pledges on levelized product cost. This figure shows the change in the levelized product cost of Portland cement, $\Delta LPC(E^+|p)$, associated with the pledge to reduce emissions from $E^*(p)$ to some target E^+ .

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 is bound to increase sharply.³⁰ 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 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.

To illustrate our findings emerging from Figure 8, suppose that the prevailing carbon price increases from €85/tCO₂ to €141/tCO₂ and therefore, the optimal response of a representative cement plant is to reduce its annual emissions from $E^*(85) = 549,503$ tCO₂ (66% of the status quo emissions) to $E^*(141) = 34,787$ tCO₂ (4% of the status quo

³⁰To 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).

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/tCO₂.

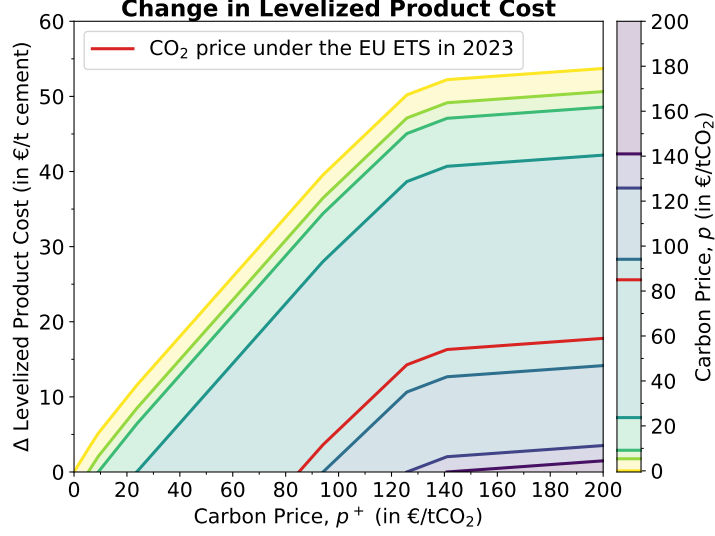


Figure 8. Impact of higher carbon prices on levelized product cost. This figure shows the change in the levelized product cost of Portland cement, $\Delta LPC(p^+|p)$, that results if the prevailing carbon price increases from p to p^+ .

Figure 8 has immediate policy implications for the ongoing discussion about tightening the overall emissions cap under the EU ETS. For baseline carbon prices, p , up to €94/tCO₂, 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/tCO₂ added to p^+ , provided $p^+ \leq$ €126/tCO₂. 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/tCO₂, firms will first adopt the carbon capture technology LEILAC. $\Delta LPC(\cdot|p)$ then increases at a constant rate of about €0.13 per ton of cement whenever p^+ increases by €1/tCO₂. More comprehensive carbon capture technologies will be adopted once $p^+ \geq$ 141/tCO₂, 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^+ .

In closing this section, we examine a setting where cement producers can stagger the adoption of elementary levers over time. In accordance with the model extension described in Appendix A5, suppose cement producers can implement one combined lever

at the start of the planning horizon and a second combined lever halfway through (i.e., after 15 years). Suppose further that firms expect a carbon price of p for the first 15 years and $p^\circ \geq p$ thereafter. Table 2 shows the optimal emission levels and combined levers for a range of carbon prices (see the Supplementary Data for details). For each p , the first row shows the optimal outcomes under a constant price, corresponding to the single-investment results in Figure 5. As one might expect, we find that when firms expect carbon prices to rise, they are incentivized to delay costly investments. Importantly, if p° is sufficiently large relative to p , firms are also incentivized not to adopt certain elementary levers early on and maintain higher initial emissions. This approach avoids unfavorable path dependencies in connection with the adoption of more comprehensive elementary levers later. Conversely, if firms expect carbon prices to rise only moderately, they are incentivized to adopt a set of elementary levers early without adopting any further levers.

Table 2. Staggered Adoption of Elementary Levers.

Carbon Price €/tCO ₂	Annual Emissions tCO ₂	Combined Lever Elementary Levers
24 → 24	549,503 → 549,503	OG, AF, RC, CC → OG, AF, RC, CC
24 → 126	549,503 → 249,041	OG, AF, RC, CC → OG, AF, RC, CC, LL
24 → 141	549,503 → 87,463	OG, AF, RC, CC → OG, AF, RC, CC, CL
24 → 187	756,184 → 34,787	OG, AF → OG, AF, RC, CF, CL
85 → 85	549,503 → 549,503	OG, AF, RC, CC → OG, AF, RC, CC
85 → 119	463,824 → 463,824	OG, AF, RC, CF → OG, AF, RC, CF
85 → 126	463,824 → 184,824	OG, AF, RC, CF → OG, AF, RC, CF, LL
85 → 141	463,824 → 34,787	OG, AF, RC, CF → OG, AF, RC, CF, CL
94 → 94	463,824 → 463,824	OG, AF, RC, CF → OG, AF, RC, CF
94 → 126	463,824 → 184,824	OG, AF, RC, CF → OG, AF, RC, CF, LL
94 → 141	463,824 → 34,787	OG, AF, RC, CF → OG, AF, RC, CF, CL
126 → 126	184,824 → 184,824	OG, AF, RC, CF, LL → OG, AF, RC, CF, LL
126 → 141	463,824 → 34,787	OG, AF, RC, CF → OG, AF, RC, CF, CL

Abbreviations are Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Calcined Clays (CC), Carbonated Fines (CF), LEILAC (LL), Calcium Looping (CL), Oxyfuel (OF), and Amine Scrubbing (AS).

To illustrate our findings from Table 2, suppose that the prevailing carbon price is initially at €24/tCO₂ and increases later to €125/tCO₂ (or €141/tCO₂). The optimal response of representative cement plants is to reduce annual emissions first to 549,503 tCO₂ by adopting the elementary levers Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC) and Calcined Clays (CC) and later to 249,041 tCO₂ by adding the lever LEILAC (LL) (or 87,463 tCO₂ by adding the lever Calcium Looping (CL)). These lower emission thresholds are not optimal in the single-investment case, yet

they emerge here because the elementary lever Calcined Clays (CC) has been adopted at the outset. In contrast, if the prevailing carbon price instead increases from €24/tCO₂ to €187/tCO₂, the optimal response is to reduce annual emissions initially to only 756,184 tCO₂ by adopting the elementary levers Optimized Grinding (OG) and Alternative fuels (AF) and then leap to 34,787 tCO₂ by adding the levers Recycled Concrete (RC), Carbonated Fines (CF), and Calcium Looping (CL). This abatement response avoids the path dependency associated with the lever Calcined Clays (CC).

To highlight two more examples, suppose that the prevailing carbon price is expected to be €85/tCO₂ for the entire planning horizon. Like for a price of €24/tCO₂, the optimal abatement response is then to reduce annual emissions to 549,503 tCO₂ by adopting a combined lever that includes Calcined Clays (CC). Yet, if the carbon price is expected to rise later to at least €119/tCO₂, firms are incentivized to skip Calcined Clays (CC) and instead adopt Carbonated Fines (CF) to reduce annual emissions to 463,824 tCO₂. Similarly, if the carbon price is expected to remain at €126/tCO₂ for the entire planning horizon, the optimal emissions response amounts to 184,824 tCO₂ by adopting the combined lever Optimized Grinding (OG), Alternative Fuels (AF), Recycled Concrete (RC), Carbonated Fines (CF), and LEILAC (LL). Yet, if carbon prices are expected to rise later to at least €141/tCO₂, firms are incentivized to reduce emissions initially to only 463,824 tCO₂ and later to 34,787 tCO₂, omitting LEILAC (LL) and instead adopting Calcium Looping (CL).

To capture the value of staggered abatement, suppose firms expect a carbon price of p for the first 15 years and $p^\circ \geq p$ thereafter, yet they can only choose one emission level in response to this price trajectory. As formalized in Appendix A5, the value of staggered abatement is then given by the difference between the minimized comprehensive abatement cost when the firm can only choose one emission level and the minimized comprehensive abatement cost with staggered adoption. Clearly, this option value is equal to zero whenever firms are indifferent between single and staggered adoption of elementary levers, for instance, when $p = p^\circ$ and therefore the optimal abatement response is to pick one emission level for the entire planning horizon. Alternatively, the option value is positive whenever the optimal emission levels in either or both periods differ from the optimal emission level in the one-shot investment case. For example, if the prevailing carbon price rises from €24/tCO₂ initially to €141/tCO₂ (or €187/tCO₂) later, the annualized value of staggered abatement for representative cement plants amounts to €1.21 million (or €6.83 million; see the Supplementary Data for details). This value reflects the flexibility gained by delaying the investment in costly combined levers and

avoiding unfavorable path dependencies.

Overall, our findings are corroborated by the recent emergence of low-carbon cement products.³¹ 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 CO₂ emissions to approximately 560 tCO₂ 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.

5 Model Applicability in Other Industries

This section argues that our abatement cost model is applicable in emission-intensive industries other than cement. Power generation, for instance, emits about 23% of global annual greenhouse gas emissions (Dhakal et al., 2022), mainly from coal-fired steam turbines and natural gas (combined-cycle) turbines. Common levers for emission reduction include efficiency upgrades and operational changes at existing turbines, such as heat recovery, flexible load-following, and high-temperature operation. They also include the deployment of renewable energy sources (e.g., solar photovoltaic, wind turbines, and hydro-power) and complementary storage technologies (e.g., pumped hydro-power and lithium-ion batteries). Like in the cement industry, select power producers are piloting carbon capture and storage technology at coal- and gas-fired plants (Davis et al., 2018).

Transportation accounts for about 15% of global annual emissions (Dhakal et al., 2022), largely from burning kerosene in airplanes, heavy fuel oil in ships, and diesel or gasoline in road vehicles. Common abatement levers include energy efficiency improvements (e.g., winglets on airplanes and propeller upgrades for ships) and low-emission fuel blends (e.g., biofuels, ethanol, and synthetic fuels) for existing vehicles. Yet, they also include the adoption of new vehicles with advanced aerodynamics and propulsion systems, such as wind-assist systems for ships and (hybrid-)electric drivetrains for airplanes, ships, and road vehicles (Davis et al., 2018).

Industrial manufacturing generates about 24% of global annual emissions (Dhakal et al., 2022), primarily due to the production of primary goods, including iron, steel, cement, and chemicals. Iron and steel production causes direct emissions mainly due to the use of coal for heat generation and the chemical reduction of iron ore in blast

³¹See, for instance, Research and Markets (2022); George (2022); Heidelberg Materials (2023b).

furnaces. Widely discussed levers for emission reduction include using alternative fuels, including hydrogen and natural gas, the recycling of scrap steel, carbon capture and storage technologies, and the deployment of electric arc furnaces (Rissman et al., 2020). In refineries and chemical plants, direct emissions stem largely from the combustion of oil and natural gas in order to produce heat and organic base molecules, such as ethane, naphtha, and hydrogen. Emerging abatement levers include novel catalysts to reduce the energy intensity of chemical transformations, replacing fossil fuels with biological feedstock (e.g., biomass and biogas), the shift to electrolytic hydrogen production, the electrification of process heat and steam generation (e.g., high-temperature heat pumps), and retrofitting facilities with carbon capture and storage technologies (Rissman et al., 2020). Glass and ceramics production generates direct emissions mainly from the firing of high-temperature furnaces with natural gas, alongside some process emissions from the chemical decomposition of carbonates, such as soda ash and calcium carbonate. Applicable abatement levers include waste heat recovery, the use of alternative fuels (e.g., biogas and hydrogen) in existing furnaces, the electrification of furnaces, and the installation of carbon capture and storage technologies (Rissman et al., 2020).

A common feature of the preceding examples is that many elementary levers require capital investments. The deployment of different elementary levers also often entails interactions in terms of the resulting abatement effect. Similar to our observations for cement production, energy efficiency upgrades, for instance, result in lower fuel use and thereby reduce the abatement effect of switching to low-emission fuels in a multiplicative manner. In the opposite direction, there may be synergies across different elementary levers. For instance, the installation of solar photovoltaic panels may replace conventional power generation and thereby increase the abatement effect of adopting electric vehicles.

Reports on system prices and the operational performance of key climate technologies, such as solar photovoltaic systems, wind turbines, lithium-ion batteries, electrolytic hydrogen, and electric vehicles, are regularly published by BloombergNEF, the International Energy Agency, and similar organizations. Industry-specific information on applicable abatement technologies is becoming increasingly available in review articles in academic journals and technology reports from research institutions and industry associations. For example, Rissman et al. (2020) and Agora Industry et al. (2022, 2024) provide data on the cost and operational parameters of elementary levers for iron and steel production. In addition to such data sources, our discussions with industry representatives have shown that companies often develop their own assessments regarding the cost and operational performance of the abatement levers applicable at their production sites.

6 Concluding Remarks

Ongoing debates about climate change have yet to reach a consensus on how far carbon pricing regulations or subsidies for decarbonization investments must be expanded to ensure a timely transition to a net-zero economy. This paper has introduced a generic abatement cost concept for identifying cost-efficient pathways for corporate decarbonization. We calibrate our model 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 CO₂, 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 increment in carbon prices is estimated to increase the levelized product cost of cement by about €16 per ton of cement, or 12% of the average European market price for cement in 2023.

The Intergovernmental Panel on Climate Change and other research organizations have issued a variety of forecasts for the amount of CO₂ 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 euros per ton of CO₂ 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.

A promising extension of our work is to model the adoption of elementary levers as a stochastic, dynamic decision problem. Abatement technologies such as carbon capture solutions are expected to improve in cost and capture rates as cumulative deployment drives learning effects. But these learning effects are viewed as uncertain. Further, carbon prices under the EU ETS are volatile and expected to rise with the declining cap on emission permits. Extending our model to a stochastic dynamic program would allow firms to assess the option value of waiting for the realization of particular market or technology improvements before adopting some abatement levers. This option value, in turn, may affect which elementary levers are cost-efficient at the initial stage.

Moving further afield, our cost analysis can be extended to quantify the impact of alternative accounting rules for CO₂ emissions.³² For instance, the use of biomass as an alternative fuel in combination with carbon capture and sequestration technology could

³²See, for instance, Kaplan and Ramanna (2021); Reichelstein (2024); Glenk (2024).

potentially result in cement production that removes more CO₂ from the atmosphere than it emits. Finally, future research along this line of inquiry could apply our model to other industries such as steel, glass, and chemicals. Like cement, these industries are essential to economic development, yet they are also significant contributors to annual global emissions, and their decarbonization is frequently viewed as prohibitively expensive.

Appendix

A1 Proofs

Claim 1

Part (i): The function $E^*(\cdot)$ is weakly decreasing in p because the function $CAC(E, p|E_0)$ exhibits decreasing differences, that is, $\frac{\partial}{\partial p}CAC(E, p|E_0) = -E$ 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 $\{E_- = E_n, \dots, E_i, \dots, E_0\}$.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 $CAC(E_{i-1}, p|E_0) < CAC(E_i, p|E_0)$, which would contradict that $E^*(p) = E_i$. Further, it cannot be that $p = MAC(E_i)$, because in that case $CAC(E_{i-1}, p|E_0) = CAC(E_i, p|E_0)$, 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 $CAC(E_0, p|E_0) < CAC(E_1, p|E_0)$ and therefore $p < MAC(E_1)$. A parallel argument shows that $p > MAC(E_{m-1})$ if E_m is the unique value minimizing $CAC(\cdot, p|E_0)$. $\square$

Corollary to Claim 1

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

¹As 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 $CAC(E_j, p|E_0) > CAC(E_i, p|E_0)$ for all $E_j, j \neq i$, and therefore E_i is the unique emission level minimizing $CAC(\cdot, p|E_0)$. $\square$

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. $\square$

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:

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

$\square$

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

$$uc_i \equiv \frac{DE(\vec{v}_{-i}, v_i = 1) - DE(\vec{v}_{-i}, v_i = 0)}{[E(\vec{v}_{-i}, v_i = 0) - E(\vec{v}_{-i}, v_i = 1)] \cdot A(r, T)}$$

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 $CAC(\cdot, p | E_0)$ 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 $1 \leq i \leq m$, say $u(2)$, and selecting $E_{u(2)}$ such that:

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

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

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:

$$DE(\vec{v}) + p \cdot E(\vec{v}) \tag{A12}$$

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 (A12), 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. $\square$

Corollary to Claim 4. *Claim 4 is valid only on the restricted domain $\mathbf{E}^*$, but not on the full domain $\mathbf{E}$.*

Proof: Suppose 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 emission reductions, resulting in emission level E_- , with $E_0 - E_- = E(\vec{v}_{-1}, v_1 = 0) - E(\vec{v}_{-1}, v_1 = 1) + E(\vec{v}_{-2}, v_2 = 0) - E(\vec{v}_{-2}, v_2 = 1)$. Thus, on the full domain $\mathbf{E}$, the $MAC(\cdot)$ curve has three steps, and these cannot be identified uniquely with the two elementary levers. $\square$

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 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 refuse-derived 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 CO₂ 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 CO₂ 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 CO₂ from flue gas. Oxyfuel technology burns fuels in the presence of pure oxygen instead of ambient air to produce

flue gas with a high CO₂ concentration. Calcium Looping separates CO₂ from the flue gases by taking advantage of the reversibility of splitting calcium carbonate into calcium oxide and CO₂. Specifically, calcium oxide first reacts with CO₂ in the flue gas to form calcium carbonate. The calcium carbonate is then heated to separate into the initial components, where the CO₂ is captured, and the calcium oxide is looped back into the process. Amine Scrubbing, Calcium Looping, and Oxyfuel can currently capture 90–95% of the CO₂ 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 and 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 CO₂ intensity due to the heat required for the calcination process. Given our focus on direct emissions, the accounted CO₂ 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 CO₂ emissions. Also, the CO₂ 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, $\vec{v} = (v_1, \dots, v_{11})$, where $v_1, v_2 = 1$ and $v_i \in \{0, 1\}$ for $i \in \{3, \dots, 11\}$. Accordingly, the status quo is described by $\vec{v}_0 = (1, 1, 0, \dots, 0)$. 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 CO₂ intensity of clinker production. To capture that intensity, let $\vec{\beta} = (0, 0, \beta_3, \dots, \beta_8, 0, 0, 0)$, where $\beta_i \in [0, 1]$ for $i \in \{3, \dots, 8\}$ gives the relative reduction of the CO₂ 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 η , which quantifies the tons of clinker required per ton of cement in the status quo. Let $\vec{\alpha} = (0, \dots, 0, \alpha_9, \alpha_{10}, \alpha_{11})$, where α_9 , α_{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 $\vec{i} = (0, i_2(\vec{v}), i_3, \dots, i_{11})$ denote the vector of CO₂ intensities of production processes and elementary levers measured in tons of CO₂ per ton of clinker. Here, $i_3, \dots, i_{11}$ are the direct input parameters, while the carbon intensity of clinker production, $i_2(\vec{v})$, is given by:

$$i_2(\vec{v}) \equiv i_2 \cdot [(1 - \beta_3 \cdot v_3) \cdot (1 - \beta_4 \cdot v_4) - \beta_5 \cdot v_5] \cdot \prod_{i=6}^{11} (1 - \beta_i \cdot v_i). \quad (\text{A13})$$

Equation (A13) 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 CO₂ intensity of cement for the combined lever $\vec{v}$ is given by:

$$i(\vec{v}) \equiv \vec{i}'(\vec{v} \circ \vec{s}_1). \quad (\text{A14})$$

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

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

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

$$E(\vec{v}) \equiv i(\vec{v}) \cdot q. \quad (\text{A15})$$

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

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

Turning to variable operating costs, $w_t(\vec{v})$, let $\vec{w}_t = (w_{1,t}, w_{2,t}(\vec{v}), w_{3,t}, \dots, w_{11,t})$ 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:

$$w_{2,t}(\vec{v}) \equiv w_{2,t} + w_{2,t}^{CO_2} \cdot i_2^{cap}(\vec{v}), \quad (A16)$$

where $w_{2,t}^{CO_2}$ refers to the cost per ton of captured CO₂ 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 CO₂ captured per ton of clinker produced. The variable cost per ton of cement resulting from a combined lever $\vec{v}$ then becomes:

$$w_t(\vec{v}) \equiv \vec{w}'_t(\vec{v} \circ \vec{s}_1). \quad (A17)$$

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:

$$F_t(\vec{v}) \equiv \vec{F}'_t(\vec{v} \circ \vec{s}_2) \text{ and } I(\vec{v}) \equiv \vec{I}'(\vec{v} \circ \vec{s}_2), \quad (A18)$$

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

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

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/tCO₂ but €193,657/tCO₂. 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.

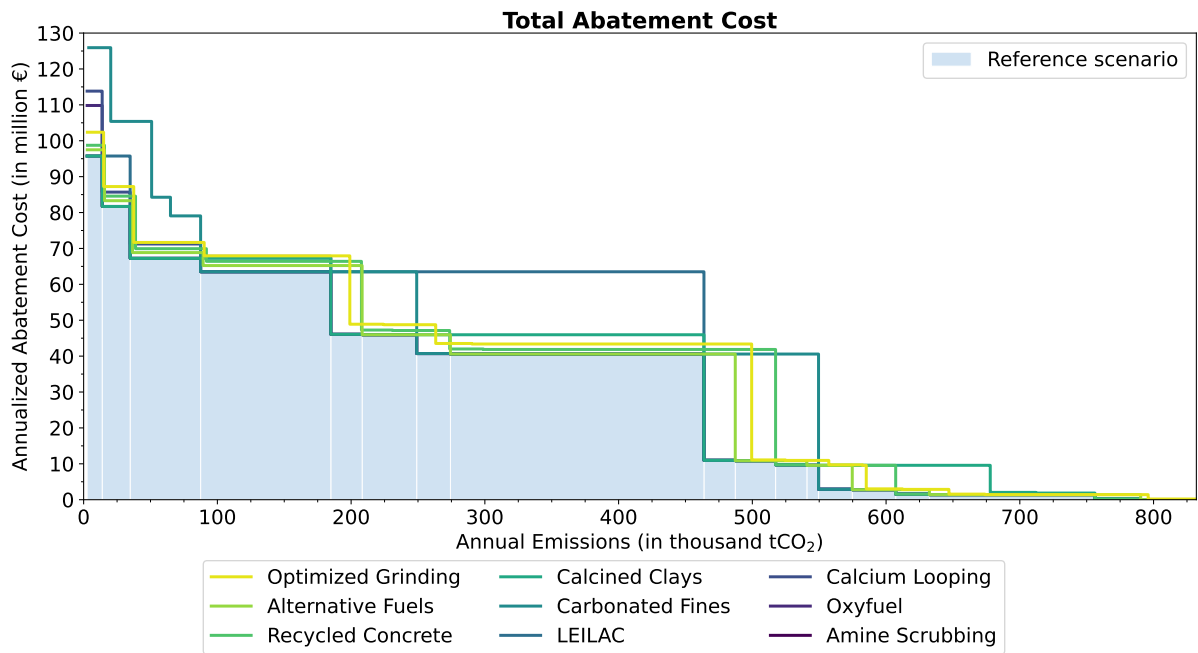


Figure A1. Cost-efficient abatement for Portland cement. This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming a particular elementary lever is unavailable. The cost-efficient combined levers corresponding to the total abatement costs are provided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

Cost of Transporting and Storing CO₂

Our analysis has assumed a cost of €80 per ton of captured CO₂ 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 CO₂ 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 CO₂ 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 CO₂ sequestration because the cost of CO₂ 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 CO₂ sequestration affect all carbon capture technologies in the same way.

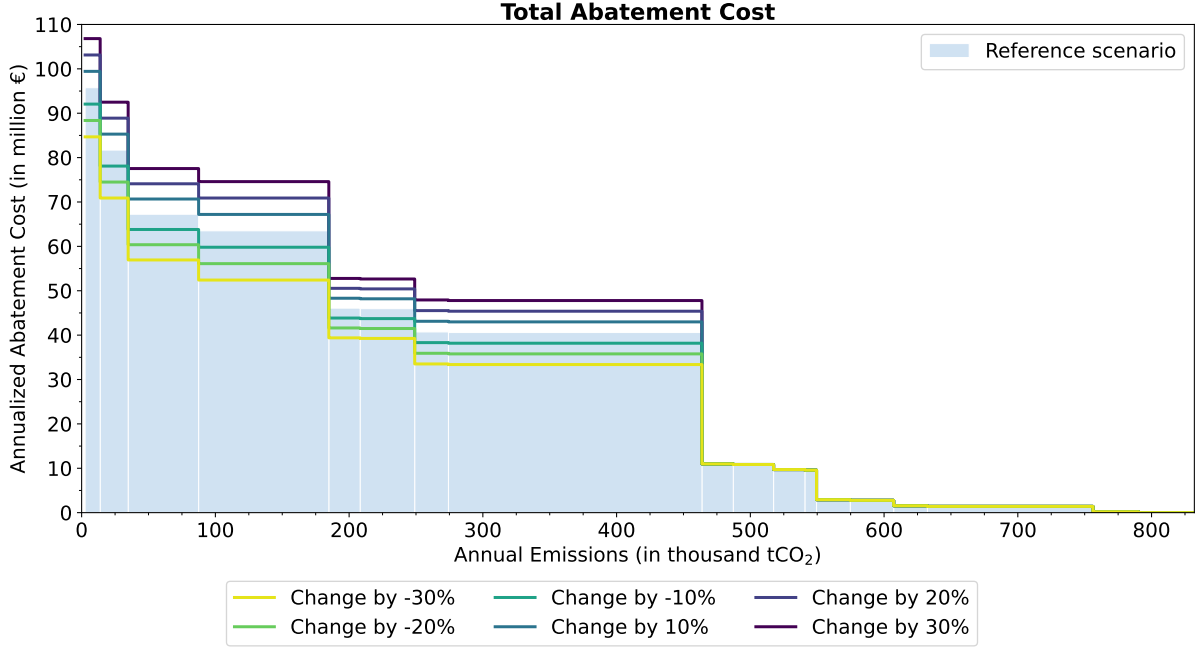


Figure A2. Cost-efficient abatement for Portland cement. This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming changes in the costs of transporting and storing captured CO₂. The cost-efficient combined levers corresponding to the abatement costs are 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.

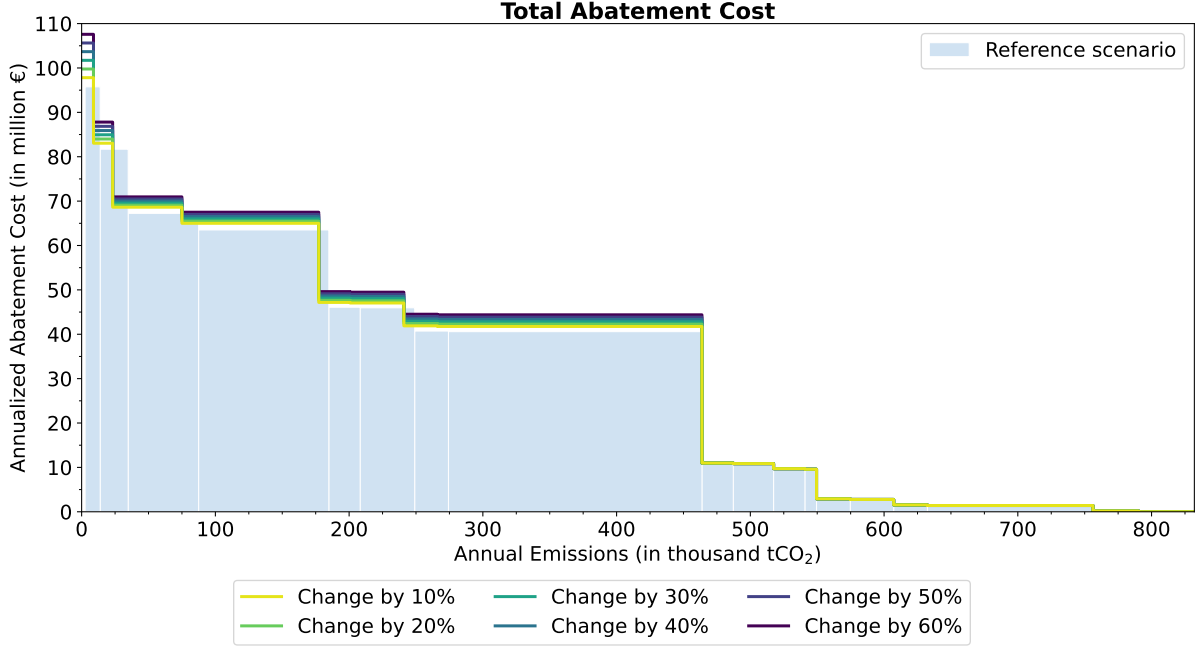


Figure A3. Cost-efficient abatement for Portland cement. This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming deep operation of carbon capture technologies. The cost-efficient combined levers corresponding to the abatement costs are provided in the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

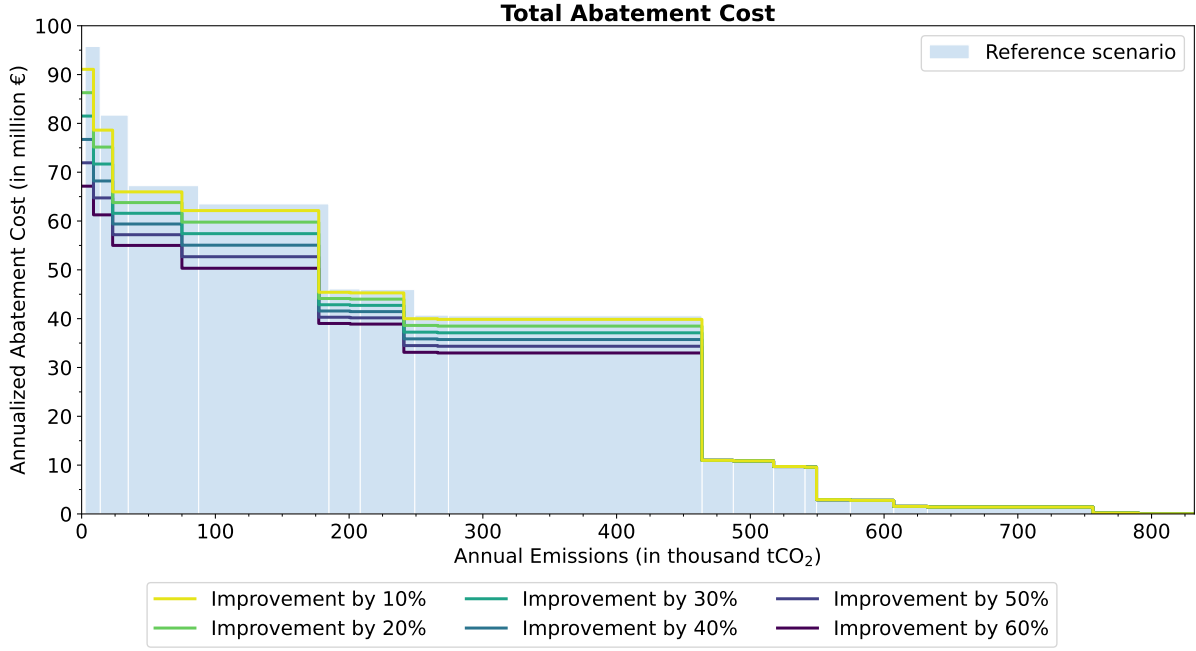


Figure A4. Cost-efficient abatement for Portland cement. This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming improvements in carbon capture technologies. The cost-efficient combined levers corresponding to the abatement costs are provided in the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

Variation in Abatement Effects

Our analysis has relied on point estimates for the abatement effects of elementary levers. Since the interaction in the abatement effect of most elementary levers is non-linear, even small deviations in the point estimates may change the cost-efficient combined levers and the resulting total abatement cost. To examine this possibility, we repeat our calculations 25 times, each time examining a different combination of random variations between -10% and +10% in the abatement effects of each elementary lever. Positive variations entail stronger abatement effects. For carbon capture technologies, improvements in capture rates are again capped at their technical maximum of 95%.

The resulting annualized total abatement cost curves are shown in Figure A5 as semi-transparent blue lines. Darker shades indicate overlapping curves and thus the distribution across scenarios. We find that for most scenarios, the cost-efficient combined levers

are largely the same as in the reference scenario (see the Supplementary Data), and the corresponding cost curves are close to the reference scenario. This reflects that positive and negative variations in the abatement effects of elementary levers implemented together effectively offset each other. Still, some scenarios produce different cost-efficient combined levers. For example, consider the following variations in the abatement effects of elementary levers: Optimized Grinding -6.0%, Alternative Fuels +6.0%, Recycled Concrete -7.0%, Calcined Clays -8.0%, Carbonated Fines -3.0%, LEILAC -7.0%, Calcium Looping -7.0%, Oxyfuel -1.0%, and Amine Scrubbing +8.0%. For this scenario, our analysis identifies $n = 21$ cost-efficient combined levers. Most of these combined levers remain unchanged from the reference scenario, while one includes the elementary lever Amine Scrubbing, which was absent from all the cost-efficient combined levers in the reference scenario.

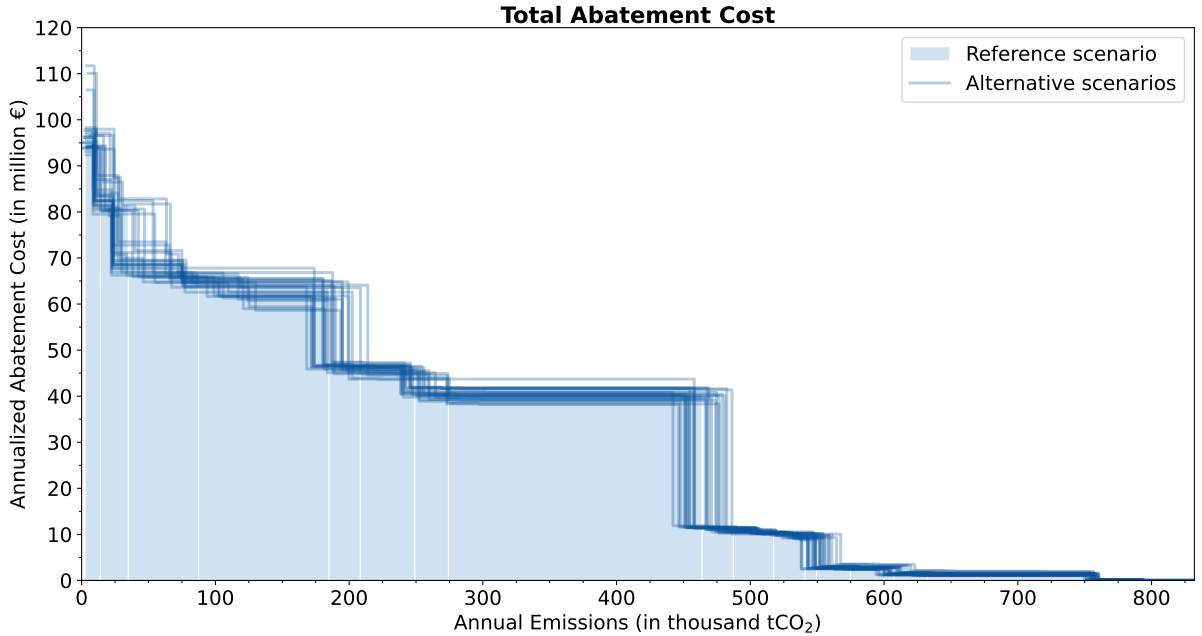


Figure A5. Cost-efficient abatement for Portland cement. This figure shows the annualized total abatement cost for the cost-efficient emission thresholds, assuming small simultaneous deviations in the abatement effects of all elementary levers. The cost-efficient combined levers corresponding to the abatement costs are provided in the Supplementary Data.

A5 Model Extensions

Uncertainty

We first extend our base model to settings where firms are uncertain about the costs of adopting elementary levers. To that end, we introduce a random variable $\tilde{\theta}$ (possibly

multi-dimensional) with cumulative distribution function $F(\theta)$, so that $0 \leq F(\theta) \leq 1$. If the actual state is θ , the fixed and variable operating costs are $F_t(\vec{v}, \theta)$ and $w_t(\vec{v}, \theta)$, while the capital expenditures are $I(\vec{v}, \theta)$.

For any emission target E , a risk-neutral decision-maker then seeks to identify the combined lever $\vec{v} \in V_f(E)$ that minimizes the associated expected discounted expenditures given by:

$$\mathbb{E}[DE(\vec{v}, \tilde{\theta})] \equiv \int \left\{ \sum_{t=1}^T [w_t(\vec{v}, \theta) \cdot q + F_t(\vec{v}, \theta)] \cdot (1+r)^{-t} + I(\vec{v}, \theta) \right\} dF(\theta) \quad (\text{A19})$$

The corresponding expected total abatement cost of reducing annual emissions from E_0 to E is defined as:

$$ETAC(E|E_0) \equiv \min_{\vec{v} \in V_f(E)} \{\mathbb{E}[DE(\vec{v}, \tilde{\theta})]\} - \min_{\vec{v} \in V_f(E_0)} \{\mathbb{E}[DE(\vec{v}, \tilde{\theta})]\}. \quad (\text{A20})$$

In direct analogy to the setting with certainty in costs, $ETAC(E|E_0)$ reflects the minimal payment that a firm would expect to require for its investments and increased operating costs to produce the same output with no more than E tons of annual emissions.

To identify conditions where the total abatement cost functions in equations (2) and (A20) yield identical values for alternative target levels E , consider a setting where the cost components (variable, fixed, and upfront investment) are given as follows:

$$w_t(\vec{v}, \theta) = \sum_{i=1}^m w_{ti}(\theta) \cdot s_i(\vec{v}), \quad F_t(\vec{v}, \theta) = \sum_{i=1}^m F_{ti}(\theta) \cdot s_i(\vec{v}), \quad I(\vec{v}, \theta) = \sum_{i=1}^m I_i(\theta) \cdot s_i(\vec{v}),$$

with $s_i(\vec{v})$ denoting a capacity adjustment factor that depends on $\vec{v}$. For example, if all cost components are additive across the constituent elementary levers, then $s_i(\vec{v}) = v_i$ for all i . We further denote the expected fixed and variable operating costs of elementary lever i in year t by $\mathbb{E}[F_{ti}(\tilde{\theta})] = \bar{F}_{ti}$ and $\mathbb{E}[w_{ti}(\tilde{\theta})] = \bar{w}_{ti}$, while the expected capital expenditure required for elementary lever i is denoted by $\mathbb{E}[I_i(\tilde{\theta})] = \bar{I}_i$.

The linearity of the discounted expenditures function $DE(\cdot)$ in each of the three cost components $w_t(\cdot)$, $F_t(\cdot)$, and $I(\cdot)$ then yields:

$$\mathbb{E}[DE(\vec{v}, \tilde{\theta})] = \sum_{t=1}^T \left[\sum_{i=1}^m \bar{w}_{ti} \cdot s_i(\vec{v}) \cdot q + \sum_{i=1}^m \bar{F}_{ti} \cdot s_i(\vec{v}) \right] \cdot (1+r)^{-t} + \sum_{i=1}^m \bar{I}_i \cdot s_i(\vec{v}).$$

It then follows immediately that for any emission target E the combined lever $\vec{v} \in V_f(E)$ that minimizes the associated expected discounted expenditures is the same as the one

that minimizes the associated deterministic discounted expenditures when each cost component assumes its expected value for sure. Furthermore, the deterministic and expected total abatement cost functions coincide, regardless of the structure of the probability distribution $F(\cdot)$.

The preceding result has immediate implications for the interpretation of the abatement cost curve we derive in Section 4.2 in the context of Portland cement. There, we base the cost estimates for different elementary levers on the arithmetic mean of the upper and lower bounds of the cost intervals provided by ECRA (2022). Furthermore, the expected fixed and variable costs of each lever are assumed to be constant over time. We denote these by $\bar{w}_i$ and $\bar{F}_i$. The cost curve obtained in Section 4.2 can then be interpreted as an expected total abatement cost curve derived from a model with underlying cost uncertainty, provided each cost component $\bar{w}_i$, $\bar{F}_i$, and $\bar{I}_i$ is equal to the arithmetic mean of its upper and lower bounds for each elementary lever i .

Sequential Lever Adoption

This part develops an extension of our base model that allows for sequential lever adoption over time. Specifically, we assume that the firm can implement combined lever $\vec{v}$ at date $t = 0$ and subsequently expand its initial choice to combined lever $\vec{v}^\circ$ at date $t = t^\circ$. As before, the initial investment decisions are considered irreversible. Therefore the two lever choices must satisfy the constraint $\vec{v}_i^\circ \geq \vec{v}_i$ for all $1 \leq i \leq m$, or, in vector notation, $\vec{v}^\circ \succeq \vec{v}$.

Elementary levers adopted at the later date t° retain a salvage value at the end of the planning horizon, equal to their fair market value. As a share of the initial investment, the fair market value is given by:³

$$s \equiv \frac{(1+r)^T - (1+r)^{T-t^\circ}}{(1+r)^T - 1}. \quad (\text{A21})$$

If some elementary levers improve in cost and operational performance over time, the functional specifications of $w_t(\cdot)$, $F_t(\cdot)$, $I(\cdot)$, and $E(\cdot)$ will capture such technological advances. The discounted value of all cash expenditures, including upfront investment and future operating costs that result from the implementation of the combined levers $\vec{v}$

³Earlier accounting literature has shown that if used assets can be traded in competitive rental markets, a used asset that has a useful life of T periods and was acquired at price $I(\cdot)$ at date t° has a fair market value of $s \cdot I(\cdot)$ at date T (Dutta and Reichelstein, 2021).

and $\vec{v}^\circ$ will be denoted by $DE(\vec{v}, \vec{v}^\circ | \vec{v}^\circ \succeq \vec{v})$. Formally,

$$\begin{aligned}
DE(\vec{v}, \vec{v}^\circ | \vec{v}^\circ \succeq \vec{v}) &\equiv \sum_{t=1}^{t^\circ} [w_t(\vec{v}) \cdot q + F_t(\vec{v})] \cdot (1+r)^{-t} \\
&+ \sum_{t=t^\circ+1}^T [w_t(\vec{v}^\circ) \cdot q + F_t(\vec{v}^\circ)] \cdot (1+r)^{-t} \\
&+ I(\vec{v}) + I(\vec{v}^\circ - \vec{v}) \cdot [(1+r)^{-t^\circ} - s \cdot (1+r)^{-T}].
\end{aligned} \tag{A22}$$

Firms seeking to reduce their annual emissions can now choose the targets E for $t = 0, \dots, t^\circ$ and $E^\circ \leq E$ for $t = t^\circ + 1, \dots, T$. For any target levels E and E° , the firm seeks to identify the combined levers $\vec{v} \in V_f(E)$ and $\vec{v}^\circ \in V_f(E^\circ)$ that minimize the associated discounted expenditures $DE(\vec{v}, \vec{v}^\circ | \vec{v}^\circ \succeq \vec{v})$.

The total abatement cost of reducing annual emissions from E_0 to E for $t = 0, \dots, t^\circ$ and then further to E° for $t = t^\circ + 1, \dots, T$ is then defined as:

$$TAC(E, E^\circ | E_0) \equiv \min_{\substack{\vec{v} \in V_f(E) \\ \vec{v}^\circ \in V_f(E^\circ)}} \{DE(\vec{v}, \vec{v}^\circ | \vec{v}^\circ \succeq \vec{v})\} - \min_{\vec{v} \in V_f(E_0)} \{DE(\vec{v})\}, \tag{A23}$$

Similar to the single-investment case, $TAC(E, E^\circ | E_0)$ denotes the minimum compensation a firm would require to cover its investment and increased operating costs to maintain output while limiting emissions to at most E units per year during the first t° years and to at most E° units per year thereafter. By construction, $TAC(E_0, E_0 | E_0) = 0$.

In direct analogy to the $TAC(\cdot | E_0)$ function, the $TAC(\cdot, \cdot | E_0)$ function is non-negative on the interval $E_- \leq E \leq E^\circ \leq E_0$. In addition, it is weakly decreasing and right-continuous in both E and E° . These stepping points correspond to the sequential achievement of the stepping points of the $TAC(\cdot | E_0)$ function, provided elementary levers exhibit no technological improvements over time.

We embed the two-step abatement model in a decision context where the firm expects an emissions charge of p to prevail until t° and of $p^\circ \geq p$ thereafter. Recalling the annuity value $A(r, T) \equiv \sum_{t=1}^T (1+r)^{-t}$, we define $A^\circ(r, T) = A(r, T) - A(r, t^\circ)$. With sequential decision making, the firm then chooses $\vec{v}$ and $\vec{v}^\circ$ with corresponding emission levels E and E° , respectively, to minimize the comprehensive abatement cost:

$$\begin{aligned}
CAC(E, E^\circ, p, p^\circ | E_0) &\equiv TAC(E, E^\circ | E_0) - p \cdot (E_0 - E) \cdot A(r, t^\circ) \\
&- p^\circ \cdot (E_0 - E^\circ) \cdot A^\circ(r, T).
\end{aligned} \tag{A24}$$

For any given p and p° , the abatement levels that minimize $CAC(E, E^\circ, p, p^\circ | E_0)$ are

denoted by $E^*(p, p^\circ)$ and $E^{\circ*}(p, p^\circ)$. In direct analogy to the single-investment case, $E^*(\cdot, p^\circ)$ is a decreasing step function in p , while $E^{\circ*}(p, \cdot)$ is a decreasing step function in p° . Importantly, $E^*(p, \cdot)$ may not be decreasing in p° . If carbon prices are expected to rise sufficiently fast insofar as p° is sufficiently larger than p , it may be optimal for firms not to adopt certain elementary levers initially but then adopt more costly elementary levers later. Conversely, if carbon prices are expected to rise only moderately, firms may find it optimal to adopt certain elementary levers initially and remain committed to the resulting path dependency. Both patterns can be observed in the context of our Portland cement application.

To capture the flexibility value entailed by staggered lever adoption, we recall the expression for the comprehensive abatement cost in the one-shot decision setting, as introduced in Section 3:

$$CAC(E, \tilde{p}|E_0) \equiv TAC(E|E_0) - \tilde{p} \cdot (E_0 - E) \cdot A(r, T),$$

assuming a generic carbon price $\tilde{p}$. For targets E and E° with $E \geq E^\circ$, the flexibility value of staggered lever adoption is given by:

$$V(p, p^\circ|E_0) \equiv \min_E \{CAC(E, \bar{p}|E_0)\} - \min_{E, E^\circ} \{CAC(E, E^\circ, p, p^\circ|E_0)\}, \quad (\text{A25})$$

where

$$\bar{p} \equiv \frac{p \cdot A(r, t^\circ) + p^\circ \cdot A^\circ(r, T)}{A(r, T)}$$

denotes the properly weighted average of the two prices p and p° .

Clearly, $V(p, p^\circ|E_0) \geq 0$ since the set of feasible abatement responses under staggered abatement contains the set of feasible abatement responses under single abatement as a special case. In particular, $V(p, p^\circ|E_0) = 0$ whenever the firm is indifferent between one-shot and staggered adoption of elementary levers, for instance, when $p = p^\circ$ and the firm picks one emission level for the entire planning horizon. Alternatively, $V(p, p^\circ|E_0) > 0$ if p° is sufficiently larger than p so that the firm's optimal abatement response selects either $E^*(p, p^\circ)$, $E^{\circ*}(p, p^\circ)$, or both different from the optimal response $E^*(\bar{p})$ in the one-shot scenario. Our numerical analysis in Section 4.3 identifies conditions under which $V(p, p^\circ|E_0)$ will indeed be positive for a typical European cement manufacturer.

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