# Pollution Permits and the Evolution of Market Structure

Meredith Fowlie, Mar Reguant, and Stephen P. Ryan[*]

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## Abstract

We explore the long run dynamic implications of subjecting an imperfectly competitive industry to market-based pollution regulation. We are particularly interested in understanding how emissions permit allocation design choices can influence the evolution of industry structure in an oligopolistic market with capacity constraints. Using two decades of panel data on the US Portland cement industry, we estimate a fully dynamic model of firms' strategic entry, exit, production, and investment decisions. We then use the model to simulate counterfactual outcomes under three allocation regimes: auctioning, grandfathering, and output-based updating. This paper summarizes some proof of concept simulations under fairly stylized assumptions regarding product market structure and permit market design. We find that the dynamic evolution of market structure can vary significantly across the policy scenarios we consider. This has potentially important implications for the overall costs of achieving desired emissions reductions and the distribution of those costs. Future work will explore these implications in more applied policy settings.

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[*] UC Berkeley and NBER, MIT, and MIT and NBER.

# 1 Introduction

With the passage of the 1990 Amendments to the Clean Air Act, Congress gave the United States Environmental Protection Agency (EPA) a mandate to implement market-based strategies for the control of regulated emissions. Specifically, Title IV of the Amendments encourages the EPA to transition from prescriptive, "command and control" emissions regulations to more decentralized, market-based mechanisms, such as emissions trading programs.[1] So called "cap-and-trade" programs have since become the favored approach to regulating industrial emissions.

To implement a cap-and-trade program, the regulator must first set a limit on the total quantity of permitted emissions, usually some percentage of historic emissions. Then, a corresponding number of emissions rights or allowances must be distributed. To remain in compliance, a regulated source must hold sufficient allowances to offset its uncontrolled emissions. If a firm's emissions exceed (fall below) the number of allowances it has been allocated, it can buy (sell) allowances in the open market. How permits are initially allocated can thus have significant implications for who ultimately bears the cost of achieving the mandated emissions reductions. Allocation mechanisms can also influence the path of industry evolution by distorting firm behavior. In this paper, we focus our attention on the second issue and examine the long run dynamic implications of permit allocation design in an imperfectly competitive industry.[2]

Economists have long concerned themselves with the efficiency and distributional implications of the permit allocation design choice. Seminal work by Coase (1960) and Montgomery (1972) gave rise to the classic result that a cap-and-trade program's societal costs are independent of how permits are initially allocated. Subsequent papers have drawn attention to policy-relevant cases in which this principle fails to hold. In particular, several authors have demonstrated that the

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[1] The CAAA legislation authorized the use of "economic incentive regulation" for the control of acid rain, the development of cleaner burning gasoline, the reduction of toxic air emissions, and for states to use in controlling carbon monoxide and urban ozone.

[2] A majority of emissions regulated under existing and planned cap-and-trade program come from industries that can likely be classified as imperfectly competitive. Emissions from restructured electricity markets represent the majority of emissions currently targeted by existing cap-and-trade programs in the United States and Europe. Numerous studies provide empirical evidence of the exercise of market power in these industries, such as Borenstein et al. (2002); Joskow and Kahn (2002); Wolfram (1999); Puller (2007); Sweeting (2007); Bushnell et al. (2008). Other emissions intensive industries being targeted by regional emissions trading programs, such as cement and refining, are also highly concentrated.

initial allocation of emissions permits can affect firms' compliance and trading decisions if permit or product markets are imperfectly competitive.

To date, this literature has focused primarily on the static, short-run implications of initial permit allocations.[3] However, policy makers are increasingly concerned with more long-run, dynamic impacts of permit allocation design choices. In particular, there are concerns about adverse impacts on entry, exit, and capital investment going forward in the event that mandatory emissions caps are not accompanied by a free allocation of allowances to industry.

In the literature, the effects of market based environmental regulation - and emissions trading programs in particular- on the long run evolution of market structure has received surprisingly little theoretical or empirical attention. In a recent survey, Millimet et al. (2009) note:

> "Perhaps the most striking gap in the literature on environmental regulation is its inability to connect to this rich literature on dynamic industry models in order to understand the long-term impacts of environmental regulation on industries and firms."

This paper begins to fill that gap, and in so doing, provides rich insights into the long-run efficiency implications of the permit allocation design decision.

We extend the Markov-perfect Nash equilibrium (Maskin and Tirole, 1988; Ericson and Pakes, 1995) dynamic oligopoly model developed in Ryan (2009) to an analysis of the relationships between permit allocation design choices and the evolution of industry structure. In this model, firms are differentiated both by their productive capacity and their emissions intensities. They make optimal entry, exit, and investment decisions in order to maximize their expected stream of profits conditional on the strategies of their rivals. Firms are assumed to compete in quantities in each period, subject to their capacity constraint. To convert this theoretical framework into an estimable empirical model, we make explicit assumptions about the structural errors which allow us to estimate the cost structure of the industry, including the distribution of sunk entry costs and capacity adjustment costs.

We estimate the model using detailed, plant-level data from an industry that is increasingly

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[3] A noteworthy exception is Montero and Liski. (2009). These authors investigate market dynamics in a scenario where the number of permits allocated decreases over time. Strategic firms can bank permits for future use; they must decide how to sell and consume their endowment of permits over time.

attracting the attention of environmental policy makers: the domestic Portland cement industry. This industry is the third largest source of industrial emissions currently regulated under cap-and-trade programs.[4] Perhaps more importantly, cement production currently accounts for 5 percent of global carbon dioxide emissions. Over half of these emissions derive from a chemical reaction that is essential to the cement production process. Consequently, the industry is particularly concerned about how the introduction of a binding emissions cap will affect entry, exit, and capital replacement decisions going forward.

With parameter estimates in hand, we simulate the cement industry response to the introduction of a cap-and-trade program. The basic intuition underlying these counterfactual simulations is quite simple. In the benchmark scenario in which emissions are unconstrained, firms invest at the level where marginal costs equal expected marginal benefits subject to covering their fixed costs. The expected benefits are a function of the period payoffs, as firms with larger capacities are able to compete over a larger segment of the market. With the introduction of the permit system, firms face a different payoff structure. We consider the three most commonly observed permit allocation regimes: auctioning, grandfathering, and a periodic updating of free allowance allocations contingent upon lagged production decisions. Production and investment incentives conferred by these different permit allocation regimes alter the period payoffs in different ways, which in turn has implications for the marginal benefits of investment and the dynamics in equilibrium.

In this working paper, we present results from a proof of concept exercise that considers a range of stylized policy scenarios that differ along two dimensions: the elasticity of permit supply in the permit market and the initial structure of the product market. We find the long-run dynamic implications of the permit allocation design choice to be significant in this industry. More specifically, we find that rates of entry, exit, and investment in new capacity differs significantly across the policy scenarios we consider. Differences in industry structure beget differences in the cost effectiveness of emissions abatement, producer profits, and consumer surplus. A more static analysis that takes industry structure as fixed would miss these first order implications. Future work, will extend the model to consider the exercise of market power in the permit market, the role of imports (and

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[4] United States v. St. Mary's Cement settlement, September 8, 2008. US EPA.

associated implications for emissions leakage), and the distribution of costs and benefits associated with different policy designs across regional markets with different structural characteristics.

With this paper, we hope to make three contributions. First, we believe this to be the first analysis of the implications of the permit permit allocation design choices for the U.S. cement industry. This industry has an important role to play in efforts to reduce industrial $CO_2$ emissions. The proposed use of permit allocation design to mitigate the adverse impacts of stringent emissions limits on trade exposed, emissions intensive industry is increasingly controversial. Our results will help to inform this important policy discussion.

Second, we hope to make a more general contribution to the burgeoning literature that considers the long-term impacts of environmental regulation on industries and firms. By their very nature, long-run policy impacts are very difficult to identify empirically. During the time it takes for these impacts to manifest, a host of other potentially confounding factors and processes change and evolve. The conventional approach to analyzing these long run relationships has been to use highly stylized analytical models, or large, deterministic, optimization-based simulation models to carry out counterfactual simulations. Our paper is unique in its detailed representation of industry dynamics and its use of state-of-the-art econometric modeling tools. We will argue that this approach confers important advantages, particularly in an analysis of the cement industry where important structural parameters are difficult to observe directly.

Finally, the paper makes an important methodological contribution in its application of parametric value function methods to a dynamic game. We make use of interpolation techniques to compute the equilibrium of the counterfactual simulations. This allows us to treat the capacity of the firms as a continuous state.

The paper is organized as follows. Section 2 gives an overview of the related literature. Section 3 provides some essential background on the US Portland cement industry. We introduce the model in Section 4. We present the estimation and computational methodology in Section 5. Detailed descriptions of the different pollution permit mechanisms are presented in Section 6. Counterfactual simulation results with and without permit markets are reported in Section 7. We conclude with a discussion of the results and directions for future research in Section 8.

# 2 Background and Related Literature

This paper is germane to two related areas of the literature. The first considers the exercise of market power in permit markets. The second investigates the efficiency implications of alternative approaches to allocating permits to firms in an imperfectly competitive industry.

## 2.1 Allowance allocation when markets are imperfectly competitive

Beginning with the seminal work of Hahn (1984), it has been formally demonstrated that when permit markets are imperfectly competitive, Montgomery's classic result fails to hold: firms' compliance and trading decisions can be affected by how permits are initially allocated. Hahn considers a single firm dominant firm facing a competitive fringe. He demonstrates that if the dominant firm is a net buyer (seller) of permits, the firm will act as a monopolist (monopsonist) and sell (purchase) fewer permits vis a vis the efficient equilibrium outcome.

Subsequent work has extended this simple, static framework in a variety of ways. One branch of the literature maintains the assumption of price taking behavior in the product market, but consider alternative permit market structures.[5] Another line of inquiry releases Hahn's assumption of price taking behavior in the product market and considers the extent to which the exercise of market power in the product market can affect the exercise of market power in the product market (and vice versa). [6]

In another important extension, researchers have moved Hahn's static analysis into a dynamic setting. The primary impetus of these studies has been to understand how the initial allocation of permits can affect firms' strategic banking and borrowing of permits over time.[7] Our study also

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[5] For instance, Westskog (1996) extends Hahn's model to allow for several dominant firms facing a competitive fringe. More recently, Malueg and Yates (2009) analyze a permit market in which all firms are strategic.

[6] Misiolek and Elder (1989) were the first to pick up on this theme, noting that the dominant firm may also have an incentive to manipulate the pollution permit market in order to raise the production costs for the competitive fringe. They demonstrate that this incentive could exacerbate or mitigate the abatement inefficiency identified by Hahn, depending on how permits are initially allocated. von der Fehr (1993) extends this analysis to a symmetric Cournot oligopoly framework. He finds that in a wide range of circumstances, industry profits will be maximized when all permits are concentrated in one firm. When a competitive fringe is added to the permit market (i.e. when the residual supply curve for permits facing the industry is elastic), complete monopolisation may not be possible, but there is still potential for strategic manipulation of the permit market.

[7] For instance, Montero and Liski. (2009) analyze a dynamic permit market characterized by a dominant firm and competitive fringe and a cap that tightens incrementally over time. They find that if the dominant firm's allocation exceeds its efficient level of emissions, it will have an incentive to exercise market power and, consequently, abate

considers strategic permit market interactions in a dynamic setting, however our emphasis is quite different. We analyze long-run entry, exit, and investment decisions under different assumptions about permit market design. We are unaware of any prior work that explores these issues in a setting that accommodates strategic behavior in both product and permit markets.

## 2.2 Implications of the allowance allocation design choice

Traditionally, policy makers have chosen between two general approaches to allocating emissions permits: auctioning and grandfathering. Under an auction regime, emissions permits are sold to the highest bidder. In contrast, "grandfathered" permits are freely distributed to regulated sources based on pre-determined, firm-specific characteristics. More recently, a third design alternative has emerged. Under a "contingent allocation" regime, updating rules established ex ante are used to determine how a firm's permit allocations will be periodically updated over the course of the trading program.

Previous studies that consider the efficiency implications of the permit allocation design decision fall into two general categories. The first consists of theoretical analyses that derive more general results and insights. Among the most relevant to this paper are Fischer (2003) and Neuhoff et al. (2005). Both demonstrate how allocation updating can be used to reduce inefficiencies resulting from the exercise of market power in imperfectly competitive product markets.

The second category includes detailed policy simulations using large-scale linear programming models or other deterministic, optimization-based approaches. Several of these papers consider how strategic cement producers might respond to different emissions permit market designs (see, for example, Demailly and Quirion (2006); Ponssard and Walker (2008); Jensen, 2001; Szaboe et al, 2006; US EPA, 1996).[8]

One limitation of these numerical simulation models is that they must rely on the extant econometric literature to provide "off-the-shelf" estimates of important structural parameters (such as the fixed costs of entry or the elasticity of import supply). It is often the case that the econometric literature is not up to the task; models are often parameterized using outdated values or educated

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below optimal levels.

[8] All of these papers assume assume Cournot competition. All but one analyze the European cement sector.

guesses. We believe our paper is unique in that we use econometrically-derived values of these primitives to assess the industry response to alternative permit allocation designs.

## 3 Empirical application: The Portland cement industry

Energy intensive and trade exposed industries are increasingly concerned with permit allocation design issues. These industries argue that if the costs of complying with mandatory emissions regulations go uncompensated, they will be forced to shift production to unregulated jurisdictions, outsourcing both jobs and emissions. In the context of Federal climate change regulation, proposed "stop-gap" measures aim to mitigate these adverse impacts by offering rebates to certain emissions intensive sectors in the form of free allowance allocations. Under current legislative proposals, eligibility for these free permits would be based upon the average emissions intensity of an industry's production process and the industry's exposure to import competition.

In this paper, we choose to focus on a particularly important trade exposed and emissions intensive industry: the US Portland cement industry.[9] Cement is the binding agent in concrete and is used widely in building and highway construction. The basic production process for making cement revolves around a kiln where limestone is subjected to very high temperatures. Under such intense heat, limestone undergoes a chemical transformation to the precursor of cement, known as clinker. Cement is produced by grinding up the clinker and adding gypsum.

Cement producers are among the largest industrial emitters of airborne pollutants, second only to power plants in terms of pollutants regulated by cap-and-trade programs (i.e. NOx, $SO_2$, and $CO_2$). Planned increases in the stringency of NOx emissions regulation, combined with new regulations of cement kiln dust and proposed regulations of greenhouse gas emissions, are expected to significantly increase the operating costs of domestic cement producers.

Cement is a very fine powder, with a low value to weigh ratio. Because Portland cement pulls water out of the air over time, it is hard to store for long periods of time. These high storage requirements, in combination with low unit values, means that overland transport is not economical; cement markets are highly regional. The US Geological Survey classifies roughly 27 cement markets

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[9] For more detail on the cement industry, see Ryan (2009).

encompassing the United States. Each of these regional markets are highly concentrated; a regional market is served by four or five producers on average.

Transportation costs for importing via ship or barge are much lower than shipping overland. Currently, the U.S. meets close to 30 percent of domestic demand with foreign imports, primarily from Asia, Canada, and Mexico. These cement imports are used to satisfy cyclical increases in domestic demand when domestic capacity constraints bind and to arbitrage production cost disparities across countries.

Capacity is the single most important characteristic of a domestic cement producing facility. Fixed costs account for over 50 percent of overall production costs. Because Portland cement plants operate under conditions of high fixed costs, high returns to scale, and high industry concentration, a dynamic oligopoly model is arguably the most appropriate model of strategic interaction.

## 4 Baseline Model

In this section, we introduce the benchmark model in which industry emissions are unconstrained. We begin by specifying a theoretical model that captures the salient features of cement production technology characteristics, industry dynamics, and other factors that significantly influence producers' operating and investment decisions. Cement kilns vary in terms of capacity and emissions rates. Capacity factors are high and multi-plant economies of scale are non-existent. The industry is characterized by simultaneous entry, exit, investment, and production decisions of a small number of firms in regional markets. Firms behave strategically and have rational expectations about the future when making decisions. Our model is in the tradition of Maskin and Tirole (1988) and Ericson and Pakes (1995), who provide an elegant theoretical framework of industry dynamics that can account for these features.

The model consists of a description of the state space, actions and payoffs at each point in the state space, and transitions between states across time. The model is a discrete time, infinite horizon model, where each period is equal to one year.

## 4.1 State Space

The basic building block of the model is a regional market. We assume that each firm operates independently across markets.[10] Each market is fully described by the $\overline{N} \times 1$ state vector, $s_t$. In the base model, $s_{it}$ is the capacity of the $i$-th firm at time $t$, and $\overline{N}$ is the exogenously-imposed maximal number of active firms. Firms with zero capacity are considered to be potential entrants. Time is discrete and unbounded. Firms discount the future at rate $\beta = 0.9$. For the purposes of exploring the comparative merits of the various allocation schemes considered in this paper, we restrict attention to $\overline{N} = 2$.[11]

We also allow firms to be differentiated in their emissions rate in a basic fashion. Firms with different emissions rates will undertake different strategies in the presence of emissions regulation. Incumbent firms are assigned one of three levels of emissions, corresponding to a low-emissions plant, a medium-emissions plant, or a high-emissions plant, while new entrants are assigned the lowest emissions rate. In the cement industry, these classifications roughly correspond to new state-of-the-art plants, older dry process plants, and very old wet process plants. We assume that firms cannot influence their emissions rates, and therefore this part of the state space only evolves as cleaner plants replace dirty plants in the market. While crude, this dimension of heterogeneity allows us to model and capture the effects of emissions abatement as the industry evolves from dirtier firms to cleaner firms. These emissions rates are explaining in more detail below in Section 4.3.4.

## 4.2 Timing

Each decision period is one year. In each period, the sequence of events unfolds as follows:

- Potential entrants receive a private draw from the distribution of entry costs. Incumbents receive private draws on the fixed cost of investment/divestment and their scrap value for exiting.

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[10] This assumption explicitly rules out more general behavior, such as multimarket contact as considered in Bernheim and Whinston (1990) and Jans and Rosenbaum (1997).

[11] In future work, this limitation will be relaxed.

- All firms simultaneously make entry, exit, and investment decisions.
- Incumbent firms compete over quantities in the product market. If necessary, firms obtain permits to cover their emissions.
- Firms enter and exit, and investments mature.

We assume that firms who decide to exit produce in the period before leaving the market, and that adjustments in capacity take one period to realize.

## 4.3 Industry structure

The payoff to each firm is a function of the current state space, $s$, and actions, $a$, undertaken in that period, $\pi(s, a)$. Firms obtain revenues from the product market and incur costs from production, entry, exit, investment, and any related pollution permits transactions. We assume within a given market firms face a constant elasticity of residual demand curve.

### 4.3.1 Residual demand

Firms compete in quantities in a homogeneous goods product market. We assume that within a given market, firms face a constant elasticity residual demand curve:

$$\ln Q(\alpha) = \alpha_0 + \alpha_1 \ln P, \tag{1}$$

where $Q$ is the aggregate market demand minus import supply and $\alpha_1$ is the elasticity of residual demand. In regional markets with access to import terminals, this residual demand function is more price elastic than the market demand function.

### 4.3.2 Production cost structure

Production costs are given by the following function:

$$C_i(q_i; \delta) = \delta_0 + \delta_1 q_i + \delta_2 1(q_i > \nu s_i)(q_i - \nu s_i)^2. \tag{2}$$

Fixed costs of production are given by $\delta_0$. Variable production costs consist of two parts: a constant marginal cost, $\delta_1$, and an increasing function that binds as quantity approaches the capacity constraint. We assume that costs increase as the square of the percentage of capacity utilization, and parameterize both the penalty, $\delta_2$, and the threshold at which the costs bind, $\nu$. This second term, which gives the cost function a "hockey stick" shape common in the electricity generation industry, accounts for the increasing costs associated with operating near maximum capacity, as firms have to cut into maintenance time in order to expand production beyond utilization level $\nu$.

Each firm maximizes their static profits given the outputs of the competitors:

$$\max_{q_i} \; P\left(q_i + \sum_{j \neq i} q_j; \alpha\right) q_i - C_i(q_i; \delta), \tag{3}$$

where $P(Q; \alpha)$ is the inverse of Equation 1. In the presence of fixed operation costs the product market may have multiple equilibria, as some firms may prefer to not operate given the outputs of their competitors. However, if all firms produce positive quantities then the equilibrium vector of production is unique, as the best-response curves are downward-sloping.

### 4.3.3 Investment Costs

Firms can change their capacity through costly adjustments. The cost function associated with these activities is given by:

$$\Gamma(x_i; \gamma) = 1(x_i > 0)(\gamma_{i1} + \gamma_2 x_i + \gamma_3 x_i^2) + 1(x_i < 0)(\gamma_{i4} + \gamma_5 x_i + \gamma_6 x_i^2) \tag{4}$$

Firms face both fixed and variable adjustment costs that vary separately for positive and negative changes. Fixed costs capture the idea that firms may have to face significant setup costs, such as obtaining permits or constructing support facilities, that accrue regardless of the size of the kiln. These fixed costs are drawn each period from the common distribution $F_\gamma$ and are private information to the firm. Divestment sunk costs may be positive as the firm may encounter costs in order to shut down the kiln and dispose of related materials and components. On the other hand, firms may receive revenues from selling off their infrastructure, either directly to other firms or as scrap metal.[12] These costs are also private information, and are drawn each period from the common distribution $G_\gamma$.

### 4.3.4 Emissions rates

To estimate production technology-specific carbon dioxide emissions rates, we follow the basic protocols developed by the World Business Council for Sustainable Development's Cement Sustainability Initiative (WBC, 2005). Direct carbon dioxide emissions from cement production result from three processes: fossil fuel combustion, calcination of raw materials, and escape of cement kiln dust.

The cement industry exhibits one of the highest unit energy consumption values, in terms of MMBtu/dollar value of shipments, in the U.S. industrial sector. Currently, a combination of coal and petroleum coke makes up 76 percent of the fuel consumption mix. Waste fuels and natural gas account for 9 and 3 percent, respectively. Electricity makes up the difference. Baseline projections for the domestic cement industry assume that the fuel mix will be dominated by coal for the foreseeable future.

Carbon dioxide emissions from the combustion of fuel depend almost exclusively on the carbon content of the fuel, which is generally known with a high degree of precision. The preferred approach to estimating $CO_2$ emissions from fuel combustion involves requires data on fuel consumption, heating values, and fuel specific carbon dioxide emission factors. Because of the dominant role played by coal/pet coke, our benchmark emissions calculations are based on coal/petcoke emissions factors. For these calculations, we assume an emissions factor of 210 lbs carbon dioxide/mmbtu.[13]

The Portland Cement Association (PCA) collects plant level data regarding fuel inputs and fuel efficiency (i.e. BTUs per ton of cement). These data are summarized by kiln type. We use the 2006 PCA survey data, together with average carbon dioxide emissions factors, provided by

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[12] One online example of a used market for cement equipment is www.usedcementequipment.com. While the prices used equipment may be low, or even nominally zero, transportation and cleanup costs are typically high, occasionally into the millions of dollars depending on the size and type of equipment.

[13] Fuel-specific emissions factors are listed in the Power Technologies Energy Data Book, published by the US Department of Energy (2006). The emissions factors (in terms of lbs CO2 per MMBTU) for petroleum coke and bituminous coal are 225 and 205, respectively. Here we use a factor of 210 lbs CO2/MMBTU. This is likely an overestimate for those units using waste fuels and/or natural gas.

the U.S. Department of Energy, to estimate combustion-based carbon dioxide emissions per ton of clinker, conditioning on kiln type. We consider three classes of kilns in particular: wet process kilns (i.e. older, less efficient technology), dry process kilns with preheater/precalciner, and a best practice energy intensity benchmark (Coito et al., 2005)[14] Appendix 1 explains our emissions rate calculations in more detail.

Calcination is the release of carbon dioxide from carbonates during thermochemical processing (i.e. pyro-processing) of substantial quantities of limestone, clay and sand in large kilns at very high temperatures to produce clinker. To measure carbon dioxide emissions from calcination accurately, emissions factors can be determined based on the volume of the clinker produced and the measured CaO and MgO contents of the clinker. In the absence of this detailed plant-level information, we assume a default rate of 0.525 metric tons of carbon dioxide/metric ton of clinker (WBC, 2005).

Cement kiln dust emissions are calculated based on the volume of dust leaving the kiln and the clinker composition. Absent plant specific data measuring kiln dust emissions, the recommended default is 2 percent of clinker carbon dioxide emissions (IPCC, 2000).

### 4.3.5 Fixed costs of Operation, Entry, and Exit

Firms face fixed costs unrelated to production, given by $\Phi_i(a)$, which vary depending on their current status and chosen action, $a_i$:

$$\Phi_i(a_i; \kappa_i, \tau, \phi_i) = \begin{cases} \kappa_i & \text{if the firm is a new entrant,} \\ \tau & \text{if the firm continues as an incumbent,} \\ \phi_i & \text{if the firm exits the market.} \end{cases} \tag{5}$$

Continuing incumbents must pay an operating cost of $\tau$. Firms that enter the market pay a fixed cost of entry, $\kappa_i$, which is private information and drawn from the common distribution of entry costs, $F_\kappa$. Firms exiting the market receive a payment of $\phi_i$, which represents net proceeds from

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[14] The industry has slowly been shifting away from wet process kilns towards more fuel-efficient dry process kilns. On average, wet process operations use 34 percent more energy per ton of production than dry process operations. No new wet kilns have been built in the United States since 1975, and approximately 85 percent of U.S. cement production capacity now relies on the dry process technology.

shuttering a plant, such as selling off the land or paying for an environmental cleanup. The scrap value is private information, drawn anew each period from the common distribution, $F_\phi$. Denote the activation status of the firm in the next period as $\chi_i$, where $\chi_i = 1$ if the firm will be active next period, whether as a new entrant or a continuing incumbent, and $\chi_i = 0$ otherwise.

Collecting the costs and revenues from a firm's various activities, the per-period payoff function is:

$$\pi_i(s, a; \alpha, \delta, \gamma_i, \kappa_i, \tau, \phi_i) = P(Q; \alpha)q_i - C(q_i; \delta) - \Gamma(x_i; \gamma_i) + \Phi_i(a_i; \kappa_i, \tau, \phi_i). \tag{6}$$

#### 4.3.6 Pollution Permit Costs

We will consider several allocation schemes for granting free permits to firms. The amount of permits required will be proportional to their emissions rates and production, and some fraction of those permits are granted through grandfathering or a dynamic updating scheme. While postponing detailed discussion of these schemes until Section 6, we note here that these schemes modify the profit function in Equation 6 by linking permit costs to production costs.

### 4.4 Transitions Between States

To close the model it is necessary to specify how transitions occur between states as firms engage in investment, entry, and exit. We make two assumptions governing these transitions.

**Assumption 1.** *Changes to the state vector through entry, exit, and investment take one period to occur.*

This is a standard assumption in discrete time models, and is intended to capture the idea that it takes time to make changes to physical infrastructure of a cement plant.

**Assumption 2.** *Investment is deterministic: a firm's capacity vector is always equal to last period's capacity plus (minus) last period's investment (divestment).*

This assumption abstracts away from depreciation, which does not appear to be a significant concern in the cement industry, and uncertainty in the time to build new capacity. While it is conceptually straightforward to add uncertainty over time-to-build in the model, assuming deterministic transitions greatly reduces the computational complexity of solving for the model's equilibrium.

It is worth noting that, although the transitions are deterministic conditional on the vector of actions, firms may not know which actions its rivals will undertake with certainty. Rivals do not observe shocks to investment costs, scrap values, or setup costs, and therefore are uncertain about market structure in the next period.

As discussed above, the states governing the firm-specific emissions rates are fixed in the static sense. These rates are only changed through entry and exit, as new firms have the cleanest technology and can replace dirtier firms that have exited.

### 4.5 Equilibrium

In each time period, firm $i$ makes entry, exit, production, and investment decisions, collectively denoted by $a_i$. Since the full set of dynamic Nash equilibria is unbounded and complex, we restrict the firms' strategies to be anonymous, symmetric, and Markovian, meaning firms only condition on the current state vector when making decisions, as in Maskin and Tirole (1988) and Ericson and Pakes (1995).

Each firm's strategy, $\sigma_i(s)$, is a mapping from states to actions:

$$\sigma_i : s \to a_i. \tag{7}$$

In the context of the present model, $\sigma_i(s)$ is a set of policy functions which describes a firm's production, investment, entry, and exit behavior as a function of the present state vector. In a Markovian setting, with an infinite horizon, bounded payoffs, and a discount factor less than unity, the value function is:

$$V_i(s; \sigma(s), \theta) = \max_{\sigma_i(s)} \left\{ \pi_i(s, \sigma(s); \theta) + \beta \int V_i(s'; \sigma(s'), \theta) \; dP(s'; s, \sigma(s)) \right\}, \tag{8}$$

where $\theta$ is the vector of payoff-relevant parameters, $\pi_i(s, \sigma(s); \theta)$ is the per-period payoff function, and $P(s';\sigma(s),s)$ is the conditional probability distribution over future state $s'$, given the current state, $s$, and the vector of strategies, $\sigma(s)$. The value function represents the expected discounted stream of payoffs accruing under optimal behavior given the strategies of competitors, denoted by $\sigma_{-i}(s)$.

Specifically, in each period incumbent firms can exit the market, change their capacity through investment or divestment, or do nothing. Ignoring current-period profits from the product market, at the profit-maximizing investment, $x_i^*$, the value of investing is:

$$\max_{x_i^*}\left[-\gamma_{1i}-\gamma_2 x_i^*-\gamma_3 x_i^*+\beta\int V_i(s';\sigma(s'),\theta)dP(s_i+x^*,s'_{-i};s,\sigma(s))\right]. \tag{9}$$

The value of exiting is given by the firm's draw from the exit value distribution, $\phi_i$, and the value associated with not making any changes is:

$$\beta\int V_i(s';\sigma(s'),\theta)dP(s_i,s'_{-i};s,\sigma(s)). \tag{10}$$

The behavior of the firm is dictated by which of these three mutually exclusive activities gives the highest payoff.

Potential entrants must weigh the benefits of entering at an optimally-chosen level of capacity against their draws of investment and entry costs. Firms only enter when the sum of these draws is sufficiently low. I assume that potential entrants are short-lived; if they do not enter in this period they disappear and may never enter in the future. This assumption is for computational convenience, as otherwise one would have to solve an optimal waiting problem for the potential entrants.[15] Potential entrants will enter if the following inequality holds:

$$\max_{x_i^*}\left[-\gamma_{1i}-\gamma_2 x_i^*-\gamma_3 x_i^*+\beta\int V_i(s';\sigma(s'),\theta)dP(s_i+x^*,s'_{-i};s,\sigma(s))\right]-\kappa_i\geq 0. \tag{11}$$

Markov perfect Nash equilibrium requires each firm's strategy profile to be optimal given the

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[15] See Ryan and Tucker (2006) for an example of such an optimal waiting problem.

strategy profiles of its competitors:

$$V(s;\sigma_i^*(s),\sigma_{-i}(s),\theta)\geq V(s;\sigma_i'(s),\sigma_{-i}(s),\theta), \tag{12}$$

for all $s$ and all possible alternative strategies, $\sigma_i'(s)$. This equilibrium concept places significant structure on the optimal behavior of firms; the inequality in Equation 12 forms the basis of the empirical estimator.

Doraszelski and Satterthwaite (2005) discuss the existence of pure strategy equilibria in settings similar to the one considered here. The introduction of private information over the discrete actions guarantees that at least one pure strategy equilibrium exists, as the best-response curves are continuous. There are no guarantees that the equilibrium is unique. Given that, we report how we solve for the equilibria reported in the paper so that our results are reproducible.

# 5 Methods

## 5.1 Estimation

We make use of estimates of the cost structure of the cement industry that were obtained in Ryan (2009). In that paper, Ryan recovered the demand curve for different cement markets and the costs of production, investment, entry, and exit. Table 5.1 enumerates the parameters used in the simulation below. See Ryan (2009) for a description of the data and details of the estimation procedure.

Some of the parameters from the model above are omitted. Divestment costs are not reported, as divestment is virtually never observed in the data and thus the estimates are estimated poorly. Fixed costs of production and operation are also not reported, as these are set to zero. The reason is that we do not observe periods of operation without production or shutdown without exit (mothballing) which are required to separately identify those parameters from the distribution of exit costs.

Table 1: Simulation Parameters

| Parameter | Value |
|---|---|
| **Demand Parameters** | |
| Constant | 20.38 |
| Elasticity of Demand | -2.96 |
| | |
| **Discount Factor** | |
| $\beta$ | 0.9 |
| | |
| **Production Parameters** | |
| Capacity Cost | 1.157E10 |
| Capacity Cost Binding Level | 1.896 |
| Marginal Cost | 30 |
| | |
| **Investment Parameters** | |
| Fixed Cost Mean | 1,798 |
| Fixed Cost Standard Deviation | 420 |
| Marginal Cost | 233 |
| | |
| **Exit Cost** | |
| Scrap Distribution Mean | -67,490 |
| Scrap Distribution Standard Deviation | 55,167 |
| | |
| **Entry Distribution** | |
| Entry Cost Mean | 172,680 |
| Entry Cost Standard Variance | 41,559 |

### 5.2 Computation

In order to compute the equilibrium of the game, we make use of parametric approximation methods. In particular, we interpolate the value function using cubic splines. The reasons behind using parametric methods are twofold. First, the game has a continuous state space, given by the vector of capacities of the firms. By using parametric methods, we can allow firms to deterministically choose their capacity in a continuous space. Second, parametric approximation methods can be useful to improve computational speed. Previous work has already suggested the potential benefits of using parametric approximation methods (Pakes and McGuire, 1994).

Parametric value function methods have been explored in a single agent dynamic programming context.[16] However, they have not been widely used in dynamic games, particularly in games in which players take discrete actions, such as entry and exit (Doraszelski and Pakes, 2007). In our application, we find the method to perform well compared a discrete value function method. In particular, the parametric methods allows us to treat capacity as a continuous state, which improves the convergence properties of the game.[17]

The procedure we use is similar in spirit to the discrete value function iteration approach. In both methods, the value function is evaluated at a finite number of points. At each iteration and for a given guess of the value function, firms' strategies are computed optimally (*policy step*). Then, the value function is updated accordingly (*value function step*). This process is repeated until the value function and the policy functions do not change significantly.

The difference between the discrete value function iteration and our iterative approach is that we approximate the value function with a flexible parametric form. In particular, given a guess for the value function $V^k$ at pre-specified grid points, we interpolate the value function with a multi-dimensional uniform cubic spline, which can be computed very efficiently (Habermann and Kindermann, 2007).[18] This interpolation defines an approximation of the value function in a continuous space of dimension equal to the number of active firms. For a given number of firms

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[16] For a general treatment of approximation methods used in the context of dynamic programming, see Judd (1998). An assessment of these methods in a single agent model can be found in Benitez-Silva et al. (2000).

[17] This is mainly driven by the fact that firms take deterministic actions with respect to the continuous state.

[18] For a detailed treatment of splines methods, see de Boor (2001).

active $N_A$ in the market, the value function at any capacity vector $s$ is approximated as,

$$\hat{V}_i^k(s) = \sum_{j=1}^{(J+2)^A} \phi_{N_A,ij} B_{N_A,j}(s), \tag{13}$$

where $J$ is the number of grid points, $\phi_{N_A,ij}$ are the coefficients computed by interpolating the values $V^k$ when there are $A$ active firms, and $B_{N_A}, j(s)$ is the spline weight given to coefficient $\phi_{N_A,ij}$ when the capacity state equals $s$.

In the *policy step*, optimal strategies are computed over this continuous function. For a given firm, we compute the conditional single-dimensional value function, given the capacity values of the other firms, $\hat{V}_i^k(s_i|s_{-i})$. This formulation allows us to represent the single-dimensional investment problem of the firm. The following expression defines the expected value function of the firm conditional on staying in the market and investing to a new capacity $s_i'$. Firms maximize,

$$\max_{s_i'} \quad \pi_i(s_i, s_i'|s_{-i}) + \sum_{s_{-i}' \in S_{-i}} Pr^k(s_{-i}'; \sigma^k(s)) \hat{V}_i^k(s_i'|s_{-i}'). \tag{14}$$

We compute the optimal strategy by making use of the differentiability properties of the cubic splines, which allows us to compute the first-order conditions with respect to investment. Given that the cubic spline does not restrict the value function to be concave, we check all local optima in order to determine the optimal strategy of the firm.[19] Conditional on optimal investment strategies, we then compute the new policy function with respect to the entry, investment and exit probabilities, which gives us an updated optimal policy $\sigma^{k+1}$. This allows us to compute a new guess for the value function $V^{k+1}$ in the *value function step.*

The process is iterated until the strategies for each of the firms and the value function in each of the possible states do not change more than an established convergence criterion, such that $\parallel \sigma^{k+1} - \sigma^k \parallel < \epsilon_\sigma$ and $\parallel V^{k+1} - V^k \parallel < \epsilon_V$.

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[19] Given that the cubic spline is defined by a cubic polynomial at each of the grid intervals, this implies that at most there will be $2(J-1)+2$ candidate local optima, where $J$ is the number of grid points.

# 6 Counterfactual policy settings

With parameter estimates in hand, we now proceed to use the model to simulate industry response to the introduction of an emissions trading program that caps emissions of the most prevalent of greenhouse gases: carbon dioxide. The introduction of such a program would result in potentially significant increases in the marginal operating costs of cement producers. For example, consider a $CO_2$ permit price of $15/ton, which is roughly the price of a ton of carbon in the EU-ETS in early 2009. The costs of holding permits to offset the $CO_2$ emissions released per ton of cement produced are approximately $17, $14, and $12 at wet process, dry process, and best practice kiln technologies, respectively. To put these cost increases in perspective, marginal production costs for capacity-unconstrained firms are on the order of $30 per ton.

Domestic cement industry emissions of $CO_2$ can be reduced in a number of ways. Options include increasing reliance on imports, replacing older kilns with newer and cleaner production technologies, switching to less carbon intensive fuels, reducing the clinker content of finished cement through the use of additives, or incorporating alternative kiln feeds such as slags and fly ash or bottom ash. Data limitations prevent us from being able to model input and fuel substitution capabilities accurately at the plant level. Consequently, these compliance options are currently omitted from the portfolio of compliance strategies we model explicitly. In our model, compliance is achieved via capital turnover, a reallocation of production from more to less emissions intensive incumbents, a decrease in consumption, and the purchase of permits from other industries with relatively low marginal abatement costs. In future work will also allow for imports and reallocation of production to other, potentially unregulated, jurisdictions.

In what follows, we describe the counterfactual scenarios we analyze. These scenarios vary along several dimensions, including the elasticity of residual permit supply, the stringency of the assumed cap, initial conditions in the product market, and the manner in which emissions permits are distributed to firms.

### 6.1 Base Case

In the base case, industry emissions are unconstrained. This serves as a baseline for comparison of outcomes under the counterfactual scenarios we describe below.

### 6.2 Auctioning

In this scenario, emissions allowances are auctioned in a uniform price auction. Firms must purchase permits from the permit market or at auction in the current period, as they are not allowed to bank permits. The per-period production profit function becomes:

$$\pi_{it} = P\left(q_{it} + \sum_{j \neq i} q_{jt}; \alpha\right) q_{it} - C_i(q_{it}; \delta) - \tau(E) e_i q_{it},$$

where $\tau$ is the equilibrium permit price, $e_i$ is the firm's emissions rate and $E$ represents aggregate industry emissions.

### 6.3 Grandfathering

Under grandfathering, some proportion of the required permits are allocated for free to firms each period. Firms' permit allocation schedules defining the number of permits the firm will receive each period over the duration of the program are based on pre-determined operating characteristics or production decisions. The key aspect of these allocations is that they are exogenous to the firms' production and pollution decisions going forward—with the exception that if a firm chooses to exit the market, it forfeits its future allowance allocation entitlements.

In a grandfathering regime, the per period profit function becomes:

$$\begin{aligned} \pi_{it} &= P\left(q_{it} + \sum_{j \neq i} q_{jt}; \alpha\right) q_{it} - C_i(q_{it}; \delta) - \tau(E)(e_i q_{it} - A_i), \\ \sum_i A_i &= \overline{A}. \end{aligned}$$

where $A_i$ is the number of permits the firm receives for free from the regulator and $\overline{A}$ represents the total amount of emissions that are allocated for free.

In the grandfathering regime we consider, the share of emissions allowances allocated to a firm is equal to its share of the installed kiln capacity at the outset of the program. This implies that new entrants are not entitled free permits in the market.

## 6.4 Contingent allocation updating

Under "contingent allocation" regimes, allocation updating rules established ex ante are used to determine how a firm's permit allocations will be periodically updated over the course of the trading program. Allocation updating introduces an incentive to do more of whatever activity it is that determines future permit allocations. Updating is typically contingent upon a firm's production choices (such as output levels or fuel inputs). Perhaps the simplest allocation updating rule distributes the permits to be allocated next period according to product market shares in the current period.

Following Burtraw and Chen (2009), we adopt a "closed loop" approach to modeling of an allocation updating regime. The per period profit function becomes:

$$\pi_{it} = P\left(q_{it} + \sum_{j \neq i} q_{jt}; \alpha\right) q_{it} - C_i(q_{it}; \delta) - \tau(E)(e_i q_{it} - \phi_i(q_{it})\overline{A}.), \qquad (15)$$

where $\phi_i(q_{it})$ denotes the share of the free emissions allocated to firm $i$.

Implicit in Equation 15 are two simplifying assumptions. First, the quantity of permits a firm receives in the current period depends on its production level in that same period. Second, the size of the implicit subsidy per unit of output is taken to be exogenous to firms' production decisions. Together, these assumptions simplify the dynamic problem considerably, while still allowing us to capture the dynamic implications of the grandfathering mechanism to a significant extent.

We consider two different means of updating emissions allocations. In the first "output-based" updating regime, emissions allowances are allocated according to market share:

$$\phi_i(q_i) = \frac{q_i}{\sum_i q_i}.$$

In the second, "emissions-based" regime, more polluting firms receive a larger permit allocation.

This might occur if firms owning older, less efficient kilns insist that they should be entitled to a larger allowance allocation so as to compensate them for their higher compliance costs. In this case:

$$\phi_i(q_i) = \frac{e_i q_i}{\sum_i e_i q_i}.$$

In both cases, firms receive permits as long as they are producing in the market. Therefore, new entrants also receive an allocation proportional to either their output or their emissions.

### 6.5 Permit market structure

We simulate outcomes under the three aforementioned permit allocation regimes under two different assumptions about the elasticity of the residual supply curve for emissions allowances.

In the "global" permit market scenario, we assume that this industry is a relatively small player in a very large emissions market. Changes in industry net supply/demand for permits cannot affect the equilibrium market price: $\tau'(E) = 0$. From the perspective of the firm, the introduction of a global cap-and-trade program is functionally equivalent to a carbon tax (with or without revenue recycling).

In the "regional" permit market scenarios, the industry faces an upward-sloping supply curve for permits. This supply curve is defined by the marginal abatement cost curves of the other sources in the program. We define the following variables: historic emissions in the cement industry ($H^c$), historic emissions of the fringe ($H^f$), cement industry emissions $E^c$, fringe emissions $E^f$ and the aggregate cap on emissions $\overline{E}$. Suppose that when the marginal abatement cost curves of all the other sources in the program are summed horizontally, the resulting aggregate MAC curve is given by $\tau = \alpha(H^f - E^f)$. Then the inverse permit supply curve facing the cement market would be $\tau = \alpha(H^f - \overline{E} + H^c) + \alpha E^c$.

In order to calibrate this model, we choose parameter values that yield equilibrium permit prices that are similar to those assumed in our global permit market simulations. We also choose a fairly steep $\alpha$ parameter so as to demonstrate the theoretical implications of an upward sloping- versus perfectly elastic- fringe supply curve. These parameter values are not intended to represent any existing or planned regional market in particular. In future work, we plan to calibrate this component of the model using parameter values from existing or planned policy settings, such as the regional $CO_2$ emissions trading program being designed under the auspices of California's proposed climate change policies.

# 7 Results

In this section, we analyze the effect of introducing a cap-and-trade market to the cement industry. We report results from two sets of counterfactuals. In the first, we consider a global market in which there are no free allowances. We look at the effects of increasing the stringency of the environmental regulation by increasing the carbon price faced by the firms. We explore how implications of this change in stringency vary with assumptions about the configuration of the regional cement market. In the second set of scenarios, we extend our analysis to consider alternative permit allocation regimes: auctioning, grandfathering, output-based allocation updating, and emissions-based allocation updating.

In this paper, we consider only three possible initial industry configurations. We first consider the "de novo" case in which there are no firms in the market at $t = 0$. This counterfactual helps to highlight long-run implications of different permit market designs for the evolution of industry structure when there is no persistence from investment decisions undertaken before the introduction of the regulation. Second, we look at a market with two firms that have symmetric capacities (1,200 tons) but asymmetric emissions rates (1.16 and 0.93 tons of CO2/tons of clinker). Both incumbent firms have emissions rates that exceed that of new entrants. Finally, we consider the case in which there are also two firms but have asymmetric capacities (1,600 and 800 tons respectively).

The market structures we consider here are highly stylized. Restricting our attention to markets populated by no more than two firms has expositional advantages. Our intention with this preliminary exercise is to intuitively explore the implications of different permit market designs in different regional market contexts. Future work will extend this analysis to consider more realistic- and complex- scenarios.

Our analysis of these counterfactual scenarios will emphasize three outcomes in particular:

- Evolution of industry structure : An important emphasis of our analysis is on understanding how industry dynamics evolve differently under different policy scenarios. The implications of alternative policy designs on entry, exit, and new investment are overlooked by more static analyses that take industry structure as given. The long run effects of environmental policy interventions on industry structure can have potentially significant implications for the total cost of the regulation and the distribution of those costs. In what follows, we analyze how industry structure varies across counterfactual scenarios over a thirty year time horizon.

- Cost effective compliance : An important advantage of market-based approaches to achieving emissions reductions (as compared to more prescriptive approaches) is that a market mechanism can be used to coordinate abatement efforts so as to achieve the desired reductions at minimum cost. Permit market efficiency may be compromised when firms act strategically in permit and/or product markets. In each scenario, we compute a measure of average cost per ton of industry emissions abated. More specifically we divide the change in industry emissions (vis a vis the unconstrained benchmark) by the change in total welfare. Here, welfare is defined to be the sum of producer profits, consumer surplus, and auction revenues. This provides a measure of the average cost of reducing industry emissions (measured in \$/ton). A necessary, but far from sufficient, condition for an efficient permit market outcome is that this average cost not exceed the assumed permit price.

- Effects on consumer welfare and product prices: An important consideration in policy debates surrounding permit allocation design pertains to consumer welfare. In particular, various stakeholders have expressed concerns about how the introduction of a binding emissions cap will affect consumer prices. Allocation updating is seen as a politically viable approach to mitigating these price impacts. In each scenario, we investigate the consumer welfare implications of alternative policy designs. In particular, we investigate the extent to which the compliance costs (i.e. the obligation to hold sufficient permits to offset emissions) are passed through to customers.

## 7.1 Effects of increasing carbon price

We compare the baseline case with the introduction of a global cap, with prices ranging from 0 to 45 dollars. Overall, one observes that the more stringent the cap becomes, the smaller the industry, as it becomes less profitable. In a market with pre-existing firms, this implies that the permit price triggers the exit of the incumbent without being attractive enough to provide incentives for entry of newer more efficient plants. However, depending on the industry starting configuration, moderate carbon prices do not affect the total welfare in the industry.

**De Novo market** The results for a new market presented in Table 2 highlight some of the most intuitive effects of increasing the stringency of the emissions cap, which we represent here as an increase in the carbon price. An increase in the carbon price is equivalent to an increase in the marginal cost of the firms, which makes entry less profitable. Therefore, the long-run distribution has lower total capacity and number of firms. We observe that the quantitative effects of an increased carbon price are significant. Even for relatively moderate carbon prices, the industry structure is significantly affected by the environmental regulation.

For example, note that the prices facing consumers increase dramatically with the increase in the permit price. This is driven by two complementary factors: one, an increase in production costs leads firms to produce less, raising prices; and two, the permit prices make the entire market less profitable, leading to lower incentives to enter and invest. For example, compared to the baseline case, the situation with permit prices of $45 per ton of carbon have four times as many periods with no firms in the market, and the average market capacity is less than 25 percent. Both of these forces lead to higher prices and overall welfare decreases of roughly 50 percent.

However, the purpose of these regulations is to decrease emissions, and the obligation to hold permits to offset emissions is very successful in doing, particularly at higher carbon prices. The much smaller industry also has much fewer emissions–a decrease of 80 percent against the baseline. The combination of the large decrease in welfare and the even larger decrease in carbon emissions implies an efficient carbon abatement cost of $32.09 per ton.

Table 2: Global Permit Market, De Novo

| | Baseline | $p_e = 15$ | $p_e = 30$ | $p_e = 45$ |
|---|---|---|---|---|
| Average producer profit ($) | 19,867.528 | 14,708.291 | 11,342.908 | 7,085.502 |
| Consumer Welfare ($) | 615,780.256 | 384,219.196 | 263,159.694 | 187,924.764 |
| Carbon Revenues ($) | 0 | 99,288.1 | 117,218.505 | 116,969.26 |
| Total Welfare ($) | 655,515.313 | 512,923.877 | 403,064.014 | 319,065.029 |
| Periods with no firms (periods) | 1.288 | 1.71 | 2.634 | 5.32 |
| Periods with one firm (periods) | 6.382 | 12.743 | 17.371 | 23.43 |
| Periods with two firms (periods) | 22.329 | 15.547 | 9.994 | 1.25 |
| Average Size of Active Firm (tons) | 1,387.842 | 845.969 | 600 | 600 |
| Average Market Capacity (tons) | 2,297.152 | 1,196.048 | 747.204 | 518.604 |
| Average Market Quantity (tons) | 1,997.234 | 1,039.891 | 649.648 | 450.894 |
| Average Price ($/ton) | 73.977 | 93.141 | 108.223 | 115.917 |
| Average Emissions Price ($/ton pollutant) | 0 | 15 | 30 | 45 |
| Pass-through ($/ton) | 0 | 19.16 | 34.25 | 41.94 |
| Carbon cost ($/ton) | 0 | 22.06 | 27.51 | 32.09 |
| Average Emissions (tons pollutant) | 1,617.759 | 842.312 | 526.215 | 365.224 |
| Discounted Emissions (tons) | 13,084.149 | 6,619.207 | 3,907.283 | 2,599.317 |
| Average Emissions Rate (tons pollutant/ton) | 0.81 | 0.81 | 0.81 | 0.81 |

Firm 1's initial capacity: 0.0 Firm 2's initial capacity: 0.0
Assumed emissions rate of new entrant technology : 0.81

**Existing market with symmetric capacities** Results for an increasing carbon price in a mature symmetric market are presented in Table 3. One of the most striking results of this set of counterfactuals is that a relatively low carbon price ($p_e = 15$) does not trigger exit of firms already in the market. In fact, welfare remains almost unchanged, as firms are producing almost the same amount of quantity and they do not exit the market. Therefore, the introduction of the permit price only implies a transfer between the firms and the regulator. This is the opposite of the situation of a de novo market–highlighting the importance of accounting for dynamics when assessing the welfare effects of imposing these regimes. The reason is that the market is relatively profitable at the starting capacities and firms produce at their maximum capacity. As the tax gets higher, firms start exiting the market. Particularly at $p_e = 45$, the exit rates and the emissions reductions start being very significant.

Increasing the permit price has the expected effect on average emissions intensity–namely a lowering of the average emissions intensity through differential exit of the dirtier firm and a reallocation of production to relatively clean producers.[20] Pass-through is relatively modest, especially in comparison to the de novo case, again due to the fact that pass-through here is driven almost

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[20] In future work, we will report these statistically separately for exiting firms and new entrants.

Table 3: Global Permit Market, Symmetric Capacities

| | Baseline | $p_e = 15$ | $p_e = 30$ | $p_e = 45$ |
|---|---|---|---|---|
| Average producer profit ($) | 433,051.162 | 276,442.455 | 142,157.926 | 102,411.184 |
| Consumer Welfare ($) | 747,736.117 | 747,735.654 | 682,893.784 | 449,459.308 |
| Carbon Revenues ($) | 0 | 313,217.496 | 538,825.833 | 418,527.062 |
| Total Welfare ($) | 1,613,838.44 | 1,613,838.06 | 1,506,035.468 | 1,072,808.738 |
| Periods with no firms (periods) | 0 | 0 | 0.001 | 0.004 |
| Periods with one firm (periods) | 0 | 0 | 2.9 | 9.38 |
| Periods with two firms (periods) | 30 | 30 | 27.099 | 20.616 |
| Average Size of Active Firm (tons) | 1,200 | 1,200 | 1,199.956 | 1,199.792 |
| Average Market Capacity (tons) | 2,400 | 2,400 | 2,283.848 | 2,024.296 |
| Average Market Quantity (tons) | 2,086.655 | 2,086.653 | 1,787.059 | 968.682 |
| Average Price ($/ton) | 73.344 | 73.344 | 77.762 | 95.486 |
| Average Emissions Price ($/ton pollutant) | 0 | 15 | 30 | 45 |
| Pass-through ($/ton) | 0 | 0 | 4.42 | 22.14 |
| Carbon cost ($/ton) | 0 | 19 | 36.91 | 46.72 |
| Average Emissions (tons pollutant) | 2,180.555 | 2,180.553 | 1,821.682 | 928.532 |
| Discounted Emissions (tons) | 20,881.186 | 20,881.166 | 17,960.861 | 9,300.601 |
| Average Emissions Rate (tons pollutant/ton) | 1.045 | 1.045 | 1.019 | 0.959 |

Firm 1's initial capacity: 1200.0 Firm 2's initial capacity: 1200.0
Firm 1's emissions rate: 1.16 Firm 2's emissions rate: 0.93

exclusively through production costs, and not through market structure distortions. That is not to say that exit is not significantly influenced by higher permit costs–in the two lowest-cost cases, exit is virtually zero, while it becomes increasingly significant for the dirtier firm at the $30 and $45 per ton price levels. Also noteworthy here is that this leads to a relatively low decrease in overall welfare, as much of the carbon tax is just a transfer from the firms to the government. Countervailing that effect, however, is the fact that emissions have not dropped nearly as much–a 50 percent decrease in discounted summed emissions at the highest permit level relative to the baseline. This results in a relatively high cost per unit of industry emissions abated, even as compared to the de novo case. This case also highlights the necessary of controlling for changes in market structure, as a static analysis would have completely missed the reduction in emissions due to both the smaller market and the differential effects on the exit rate of the clean versus dirty firm.

**Existing market with asymmetric capacities** Table 4 reports the effects of an increasing permit price when the market is characterized by a large, relatively dirty firm a smaller, relatively clean firm. One interesting result is that, with asymmetric firms, the increase in the carbon price has a non-monotonic effect in the average emissions rate in the industry. Depending on the stringency of the regulation, the identity of the firm that tends to exit more shifts. The more dirty firm is the bigger, which implies that absent a carbon regulation, it has a comparative advantage to stay in the market. If the carbon price is not too large, the decrease in profits of the smaller firm triggers a higher exit rate of the small more efficient firm relative to the other. However, as the permit price increases, this tendency shifts, lowering the average industry emissions rate.

An interesting comparison between this situation and one with two firms of equal size is that the baseline in this case has a higher overall welfare. Once the carbon tax is imposed, the overall surplus is lower with in the market with the asymmetric firms. This is true despite the fact that firm exit in the asymmetric case is more rare than in the symmetric case–which is somewhat counterintuitive given that there are higher incentives for the dirtier firm to exit. In equilibrium, however, those incentives balance out with a slightly smaller level of production under the carbon tax. We can see that through the average emissions rate, which are higher when the firms are asymmetric. If the larger firm exited more frequently, the average emissions rate would be lower than in the symmetric case, which does not happen here. Compared to the equilibrium with symmetric firms, there are slightly lower profits, substantially lower consumer surplus and carbon revenues due to lower production and higher prices, and slightly lower overall welfare.

### 7.2 Comparison of alternative allocation designs

We compare the performance of the market under different allocation rules holding the permit price at \$45/ton pollutant.[21] This allows us to observe how the auctioning method performs compared to schemes in which firms are granted permits for free, either as grandfathering or based on dynamic updating schemes. Overall, we find that granting permits for free substantially attenuates the exit in the industry. Therefore, the welfare losses in the industry are much smaller if some permits are given for free.

We consider the case in which a total of 600 permits are given free, which is about 25% of the baseline emissions in the symmetric and asymmetric market. Even for moderate amounts of free permits, we find very significant effects of introducing them. Even at the price of 45\$/ton pollutant,

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[21] We introduce a fairly high permit price so that the differences between the allocation mechanism are exacerbated.

Table 4: Global Permit Market, Asymmetric Capacities

| | Baseline | $p_e = 15$ | $p_e = 30$ | $p_e = 45$ |
|---|---|---|---|---|
| Average producer profit ($) | 418,370.748 | 270,482.734 | 141,014.325 | 99,828.781 |
| Profit Firm 1 ($) | 548,312.07 | 348,335.062 | 136,944.959 | 58,424.583 |
| Consumer Welfare ($) | 796,487.563 | 747,352.016 | 631,559.545 | 434,294.628 |
| Carbon Revenues ($) | 0 | 324,654.324 | 493,296.887 | 403,864.389 |
| Total Welfare ($) | 1,633,229.058 | 1,612,971.808 | 1,406,885.082 | 1,037,816.579 |
| Periods with no firms (periods) | 0 | 0 | 0 | 0.007 |
| Periods with one firm (periods) | 0 | 0.03 | 0.732 | 6.821 |
| Periods with two firms (periods) | 30 | 29.97 | 29.268 | 23.172 |
| Average Size of Active Firm (tons) | 1,331.24 | 1,200.387 | 1,204.471 | 1,129.379 |
| Average Market Capacity (tons) | 2,662.48 | 2,399.196 | 2,374.564 | 2,055.98 |
| Average Market Quantity (tons) | 2,314.866 | 2,085.954 | 1,610.836 | 895.17 |
| Average Price ($/ton) | 70.821 | 73.393 | 80.325 | 98.742 |
| Average Emissions Price ($/ton pollutant) | 0 | 15 | 30 | 45 |
| Pass-through ($/ton) | 0 | 2.57 | 9.5 | 27.92 |
| Carbon cost ($/ton) | 0 | 10.84 | 32.02 | 40.96 |
| Average Emissions (tons pollutant) | 2,472.78 | 2,259.886 | 1,707.423 | 887.379 |
| Discounted Emissions (tons) | 23,512.731 | 21,643.622 | 16,443.23 | 8,974.764 |
| Average Emissions Rate (tons pollutant/ton) | 1.068 | 1.083 | 1.06 | 0.991 |

Firm 1's initial capacity: 1600.0 Firm 2's initial capacity: 800.0
Firm 1's emissions rate: 1.16 Firm 2's emissions rate: 0.93

firms remain in the market once they receive the free allocation.

**De Novo market** Absent any firm at $t = 0$, we assume that there are no grandfathered permits in the grandfathering mechanism. Therefore, auction and grandfathering are equivalent in this case. Similarly, quantity and emissions based updating have the same performance among them, given that all entrants have the same emissions technology. We interpret the results in table 5 as the difference between making a provision of free permits for potential entrants or not.[22]

There are several interesting aspects of Table 5. One is that overall welfare goes up in the dynamic updating case for a de novo market. In this case, the provision of giving permits for free to new entrants increases the presence of firms in the market, as well as the size of the average the firm. In this situation, the reserve of free permits is very substantial relative to the equilibrium output, which makes the firms entering the market net sellers of permits, as can be seen from the negative carbon revenues. It also increases emissions substantially. This comparison highlights the competing roles that emissions reduction plays against serving the needs of the product market.

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[22] In the future, we plan to look at richer industry settings in which there are at least one incumbent and one potential entrant.

Table 5: Comparison of Allocation Mechanisms, De Novo

| | Auction/Grandfathering | Quantity/Emissions |
|---|---:|---:|
| Average producer profit ($) | 7,085.502 | 45,187.162 |
| Consumer Welfare ($) | 187,924.764 | 422,357.874 |
| Carbon Revenues ($) | 116,969.26 | -54,836.272 |
| Total Welfare ($) | 319,065.029 | 457,895.926 |
| Periods with no firms (periods) | 5.32 | 1.059 |
| Periods with one firm (periods) | 23.43 | 2.743 |
| Periods with two firms (periods) | 1.25 | 26.197 |
| Average Size of Active Firm (tons) | 600 | 680.863 |
| Average Market Capacity (tons) | 518.604 | 1,229.584 |
| Average Market Quantity (tons) | 450.898 | 1,069.049 |
| Average Price ($/ton) | 115.917 | 91.578 |
| Average Emissions Price ($/ton pollutant) | 45 | 45 |
| Carbon cost ($/ton) | 32.09 | 34.19 |
| Average Emissions (tons pollutant) | 365.224 | 865.93 |
| Discounted Emissions (tons) | 2,599.317 | 7,304.315 |
| Average Emissions Rate (tons pollutant/ton) | 0.81 | 0.81 |

Firm 1's initial capacity: 0.0 Firm 2's initial capacity: 0.0
Firm 1's emissions rate: 1.16 Firm 2's emissions rate: 0.93

Providing dynamic updating incentives increases the number of two-firm periods from 1.25 out of 30 to 26.197 out of 30, more than doubling average market capacity and production. The average market price declines from $115 per ton of cement to $90 per ton of cement. This leads to an almost seven-fold increase in producer profits and a more than doubling of consumer surplus.

Of course, the consequence of giving so many permits for free pollution is additional pollution. Emissions more than double from 2,599 tons to 7,304 tons. However, the change in overall welfare implies that these two schemes have similar levels of carbon costs: $32.09 in the auction case and $34.19 in the dynamic updating case.

**Existing market with symmetric capacities** In table 6 we observe the effects of different firms once two firms with the same capacity are in the market. The levels of emissions reductions differ substantially across mechanisms. While auctioning and grandfathering trigger very sharp reductions in the emissions levels, output based updating partially offsets the internalization of the permit price. The cost of minimizing the abatement are thus smaller, given that the reduction effort is diminished. Firms have incentives to produce more in the dynamic cases, and this is reflected in the more than doubling of emissions in the first 30 years.

It is important to note the effects of the different allocation mechanisms in the emissions rate.

As expected, the emissions based mechanism, which grants the permits proportional to emissions, does more poorly than the other mechanisms. Furthermore, grandfathering does better in terms of average emissions rate than updating mechanism for this particular market configuration. The reason is that the cleaner plant substitutes production from the dirtier plant, given that they internalize the full cost of the emissions. In the case of output/emissions based updating, firms only internalize part of this cost, and in equilibrium they are still producing at their maximum capacity. As one would expect, the emissions based does slightly worse because the dirty firm exits more often than the cleaner one. However, it is also the one that generates higher consumer welfare and lower cost of reducing emissions.

Reflecting a pattern seen in the other tables, the highest carbon abatement costs are in the mechanisms with the strictest reductions. While the quantity- and emissions-based dynamic updating schemes lead to higher emissions, they also lead to more production and lower prices. The grandfathering case allows us to hold the composition of the first more or less constant in this comparison—it is primarily the incentives for production induced by the dynamic updating that lead to this result, and not a matter of entry or exit over time. This is true here because neither grandfathering nor the dynamic updating schemes have significant industry turnover. This is also reflected in market capacities; it is simply the case that firms in the first two schemes have much more limited incentives to meet the demands of the market, and thus prices are much higher ($95 and $93 compared to $73 and $73). Consequently, consumer welfare is much higher.

Interestingly enough, producer profit is not higher under the dynamic updating schemes. The reason is that firms find it more profitable to sell permits at the margin than they do to produce. Carbon revenues are low, although positive, and producer profits are correspondingly high. On balance, however, overall welfare is maximized when firms are less well off under the dynamic updating schemes.

From the implied efficient carbon abatement cost perspective, the dynamic schemes are much less expensive. Implied abatement costs under auction and grandfathering are on the order of $47 per ton of carbon, as compared to $26-29 under dynamic updating.

Table 6: Comparison of Allocation Mechanisms, Symmetric Capacities

| | Auction | Grandfathering | Quantity | Emissions |
|---|---:|---:|---:|---:|
| Average producer profit ($) | 102,411.193 | 302,259.658 | 181,390.144 | 179,873.16 |
| Consumer Welfare ($) | 449,459.291 | 472,680.578 | 744,556.095 | 746,416.822 |
| Carbon Revenues ($) | 418,527.041 | 22,048.212 | 502,370.227 | 506,187.438 |
| Total Welfare ($) | 1,072,808.717 | 1,099,248.105 | 1,609,706.61 | 1,612,350.579 |
| Periods with no firms (periods) | 0.004 | 0 | 0 | 0 |
| Periods with one firm (periods) | 9.38 | 0 | 0.482 | 0.233 |
| Periods with two firms (periods) | 20.616 | 30 | 29.518 | 29.767 |
| Average Size of Active Firm (tons) | 1,199.792 | 1,200 | 1,197.06 | 1,199.348 |
| Average Market Capacity (tons) | 2,024.296 | 2,400 | 2,374.84 | 2,389.36 |
| Average Market Quantity (tons) | 968.682 | 1,043.872 | 2,064.777 | 2,077.401 |
| Average Price ($/ton) | 95.486 | 92.68 | 73.728 | 73.511 |
| Average Emissions Price ($/ton pollutant) | 45 | 45 | 45 | 45 |
| Carbon cost ($/ton pollutant) | 46.72 | 47.58 | 29.24 | 26.34 |
| Average Emissions (tons pollutant) | 928.532 | 1,051.165 | 2,151.43 | 2,168.569 |
| Discounted Emissions (tons) | 9,300.601 | 10,066.049 | 20,739.871 | 20,824.698 |
| Average Emissions Rate (tons pollutant/ton) | 0.959 | 1.007 | 1.042 | 1.044 |

Firm 1's initial capacity: 1200.0 Firm 2's initial capacity: 1200.0
Firm 1's emissions rate: 1.16 Firm 2's emissions rate: 0.93

**Existing market with asymmetric capacities** The effects of having a big dirty plant and one smaller are presented in table 7. The overall effects are comparable to the symmetric case, although in this case emissions are reduced even more, given that the dirtier plant faces a larger increase of its marginal cost. In fact, the reduction makes the carbon revenue even negative for grandfathering. One can observe that the reduction is such that the bigger plant earns smaller profits than the small plant, even with double capacity, as firms do not use it.

The implied efficient carbon abatement costs here follow a similar pattern to the symmetric case but are uniformly lower. This is due to the fact there is now a way to shift production between the firms which allows for lower-cost abatement than relying on the permit market.

## 8 Conclusion and future work

We present a dynamic model to evaluate the counterfactual effects that different environmental policies would have to the US cement industry. We asses the implications of several mechanisms that have been discussed in policy circles. We examine the effects of a global emissions permit market and contrast the different dynamic implications that auctioning and grandfathering have in this context.

Table 7: Comparison of Allocation Mechanisms, Asymmetric Capacities

| | Auction | Grandfathering | Quantity | Emissions |
|---|---:|---:|---:|---:|
| Average producer profit ($) | 99,828.988 | 375,472.498 | 189,677.159 | 184,558.429 |
| Profit Firm 1 ($) | 58,424.867 | 334,301.339 | 204,211.277 | 220,312.47 |
| Consumer Welfare ($) | 434,293.983 | 451,760.698 | 704,372.17 | 713,062.878 |
| Carbon Revenues ($) | 403,863.56 | -2,085.117 | 453,928.667 | 472,311.021 |
| Total Welfare ($) | 1,037,815.517 | 1,200,620.577 | 1,537,655.155 | 1,554,490.758 |
| Periods with no firms (periods) | 0.007 | 0 | 0 | 0 |
| Periods with one firm (periods) | 6.821 | 0 | 0.075 | 0.47 |
| Periods with two firms (periods) | 23.172 | 30 | 29.925 | 29.53 |
| Average Size of Active Firm (tons) | 1,129.379 | 1,200 | 1,200.94 | 1,206.247 |
| Average Market Capacity (tons) | 2,055.98 | 2,400 | 2,397.898 | 2,387.447 |
| Average Market Quantity (tons) | 895.168 | 975.459 | 1,905.907 | 1,938.634 |
| Average Price ($/ton) | 98.742 | 94.9 | 75.59 | 75.181 |
| Average Emissions Price ($/ton pollutant) | 45 | 45 | 45 | 45 |
| Carbon cost ($/ton pollutant) | 40.96 | 30.94 | 24.83 | 22.88 |
| Average Emissions (tons pollutant) | 887.377 | 995.161 | 2,052.942 | 2,092.879 |
| Discounted Emissions (tons) | 8,974.746 | 9,529.752 | 19,663.392 | 20,071.889 |
| Average Emissions Rate (tons pollutant/ton) | 0.991 | 1.02 | 1.077 | 1.08 |

Firm 1's initial capacity: 1600.0 Firm 2's initial capacity: 800.0
Firm 1's emissions rate: 1.16 Firm 2's emissions rate: 0.93

We find is that the dynamic effects of different allocation mechanisms are very substantial in this industry. The dynamic welfare consequences of various allocation mechanisms are complicated by the equilibrium reactions of firms along their entry, exit, and investment dimensions, which can result in a complex set of outcomes. Our results highlight the competing tensions facing policymakers in these markets: one on hand, there are concerns of serving the product market, and some allocation schemes result in more capitalized markets with more firms and lower prices, which helps obtain this goal. On the other hand, these allocation schemes may result in substantially more emissions than in more strict regimes that result in lower producer and consumer surplus. In some extreme cases, grandfathering acts as a net transfer of permits to the firms, which can be viewed as a government subsidy to pollute. Our analysis shows the complex interplay between these schemes and equilibrium market structure, emissions, and welfare. We think that this paper is an important first step to understanding the interplay between these forces.

In the future, we would like to extend this work in several directions. One interesting avenue of research is to disentangle the effects of firm turnover from the substitution of production among emissions-differentiated firms. Our current results present the composite picture of these two effects, but understanding their separate roles would help clarify our understanding of the way that the allocation mechanisms influence the evolution of equilibrium market structure.

A more substantive undertaking will be the extension of our approach to a larger scale. The ultimate goal of our research is to build a model of the US Portland cement industry which is as close to reality as possible. This undertaking will require us to find new ways to simulate very large markets, on the order of 10 or more strategic actors, which is currently a computational difficultly. The approximation methods used in this paper may be useful in that regard, as they are capable of reducing the complexity of the state space to a smaller number of relevant variables. The approximation methods of Benkard et al. (2008) may also be fruitful in this regard.

In this case, we believe it is going to be very interesting to model the effects of asymmetric grandfathering, in which only incumbent firms receive permits for free. Not granting entrants free permits, contributes to the internalization of the cost of the emissions, and reduces the long-run average emissions in the sector. However, if entrants have cleaner technology, this can delay adoption of new technology, as entrants are relatively worse off than incumbents. We would like to examine the implications of this trade-off in our model.

Finally, we believe one of the major contributions of this project is going to be the inclusion of imports and exports. If there is the possibility of international trade, a reduction of cement production in the affected region can result in increased imports from elsewhere, as the permit price harms the competitiveness of the producers affected by the new environmental regulation. Modeling the fluxes of trade will allow us to assess the relevance of emissions leakage in this industry, which is a concern that has been brought up by industrial associations.

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# 9 Appendix 1

This estimate explains how we construct technology-specific estimates of fuel combustion-based carbon dioxide emissions rates. The industry has slowly been shifting away from wet process kilns towards more fuel-efficient dry process kilns.[23] On average, wet process operations use 34 percent more energy per ton of production than dry process operations. More recently, additional energy efficiency gains have been achieved through the use of preheaters and precalciners, which can reduce energy consumption per ton of cement by an additional 30 percent. Average kiln capacity has also been increasing, leading to further efficiency gains.

An important input to our calculations is the assumed carbon content of the fuel used to produce cement. Because of the dominant role played by coal/pet coke in domestic cement production, our benchmark emissions calculations are based on coal/petcoke emissions factors. We assume an emissions factor of 210 lbs carbon dioxide/mmbtu.[24]

Another important input is the fuel efficiency of the production process. The Portland Cement Association (PCA) collects plant level data regarding fuel inputs and fuel efficiency (i.e. BTUs per ton of cement). These data are summarized by fuel and kiln type. We use the 2006 PCA survey data, together with our assumed carbon dioxide emissions factor, to estimate combustion-based carbon dioxide emissions per ton of clinker, conditioning on kiln type.It is worth noting that PCA measures kiln-level fuel efficiencies in terms of BTUs consumed per ton of clinker equivalent produced. Because not all clinker is necessarily used in finished cement production, clinker is measured in equivalent tons of production: a weighted sum of clinker and finished cement production. The weights for an equivalent energy ton are 92 percent clinker and 8 percent finished cement production. All tons are metric tons.

Our technology-specific emissions rate calculations are explained below. To put these numbers in perspective, the national weighted average emissions rate was estimated to be 0.97 tons carbon dioxide/ton cement in 2001 (Hanle et al, 2005).

**Wet process** In 2006, there were 47 wet process kilns in operation. On average, wet kilns produced 300,000 tons of clinker (per kiln) per year. The PCA 2006 Survey reports an average

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[23] No new wet kilns have been built in the United States since 1975, and approximately 85 percent of U.S. cement production capacity now relies on the dry process technology.

[24] Fuel-specific emissions factors are listed in the Power Technologies Energy Data Book, published by the US Department of Energy (2006). The emissions factors (in terms of lbs CO2 per MMBTU) for petroleum coke and bituminous coal are 225 and 205, respectively. Here we use a factor of 210 lbs CO2/MMBTU. This is likely an overestimate for those units using waste fuels and/or natural gas.

fuel efficiency of 6.5 mmbtu/metric ton of clinker equivalent among wet process kilns. The relevant conversion is then 0.095 metric tons carbon dioxide/mmbtu * 6.5 mmbtu/metric ton of clinker equivalent = 0.62 tons carbon dioxide/ton clinker. When added to process emissions, we obtain our estimate of 1.16 tons carbon dioxide/ton clinker.

**Dry process** In 2006, there were 54 dry kilns equipped with precalciners with an average annual output of 1,000,000 tons of clinker per year. The PCA 2006 Survey reports an average fuel efficiency of 4.1 mmbtu/metric ton of clinker equivalent among dry process kilns with precalciners. Thus, 0.095 metric tons carbon dioxide/mmbtu * 4.1 mmbtu/metric ton of clinker equivalent = 0.39 tons carbon dioxide/ton clinker. Adding this to process emissions results in the estimate for dry-process kilns: 0.93 tons carbon dioxide/ton clinker.

**Frontier technology** To establish estimates for new entrants, a recent study (Coito et al, 2005) establishes a best practice standard of 2.89 mmbtu/ metric ton of clinker (not clinker equivalent). The calculation is then: 0.095 metric tons carbon dioxide/mmbtu * 2.89 mmbtu/metric ton of clinker equivalent= 0.275 tons carbon dioxide/ton clinker. Adding this to process emissions obtains in 0.81 tons carbon dioxide/ton clinker for new kilns.[25]

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[25] This is very similar to the CO2 emissions rate assumed in analyses carried out by California's Air Resources Board in 2008 under a best practice scenario that does not involve fuel switching. If fuel switching is assumed, best practice emissions rates drop as low as 0.69 MT CO2/ MT cement. See NRDC Cement GHG Reduction Final Calculations.