Market-based Emissions Regulation and Industry Dynamics

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Abstract

We assess the long-run dynamic implications of market-based regulation of carbon dioxide emissions in the US Portland cement industry. We consider several alternative permit allocation schemes, including mechanisms that use production subsidies to partially offset compliance costs and border tax adjustments to penalize emissions associated with foreign imports. Our results highlight two general countervailing market distortions. First, following Buchanan (1969), reductions in product market surplus and allocative inefficiencies due to market power in the domestic cement market counteract the social benefits of carbon abatement. Second, trade-exposure to unregulated foreign competitors leads to emissions "leakage" which offsets domestic emissions reductions. Taken together, these forces can result in social welfare losses under policy regimes that fully internalize the emissions externality. In contrast, market-based policies that incorporate design features that mitigate the exercise of market power and emissions leakage can deliver significant welfare gains.

1 Introduction

In the absence of a coordinated global agreement to curtail greenhouse gas emissions, regional market-based climate change policy initiatives are emerging. Examples include the Emissions Trading Scheme (ETS) in the European Union and California's greenhouse gas (GHG) emissions trading program. In these "cap-and-trade" (CAT) programs, regulators impose a cap on the total

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quantity of emissions permitted and distribute a corresponding number of tradeable emissions permits To mitigate potentially adverse competitiveness impacts, and to engender political support for the program, it has become standard to allocate some percentage (or all) of these emissions permits for free to industrial stakeholders (Joskow and Schmalensee, 1998; Hahn and Stavins, 2010). In this paper, we explore both the static and dynamic implications of several different permit allocation mechanisms.

A particularly appealing quality of the cap-and-trade approach to regulating industrial emissions is that, provided a series of conditions are met, an emissions trading program designed to equate marginal abatement costs with marginal damages will achieve the socially optimal outcome (Coase, 1960; Dales, 1968; Montgomery, 1972).[1] Unfortunately, policy makers do not work in first-best settings where the conditions required for optimality are always satisfied. Real-world policy settings are typically characterized by several pre-existing distortions that complicate the design of efficient policy. In this paper, we focus on two distortions in particular.

First, the majority of emissions regulated under existing and planned emissions regulations come from industries that are highly concentrated.[2] In a seminal paper, Buchanan (1969) argues that a first-best policy designed to completely internalize external damages should be used only in "situations of competition," as concentrated industries are already producing below the socially-optimal level, and the loss of consumer and producer surplus induced by further restricting output can overwhelm the gains from emissions mitigation. An important counterpoint is offered by Oates and Strassmann (1984) who argue that, practically speaking, the welfare gains from a Pigouvian tax (or a first-best cap-and-trade program) will likely dwarf the potential losses from non-competitive behavior. There has been surprisingly little work done to empirically investigate this trade-off between incentivizing pollution abatement and exacerbating the pre-existing distortion associated with the exercise of market power in concentrated industries subject to GHG regulations.

Second, regional climate change policies are textbook examples of "incomplete" regulation. When an emissions regulation applies to only a subset of the sources that contribute to the environmental problem, regulated sources can find it more difficult to compete with producers operating in jurisdictions exempt from the regulation. Shifts in production and associated "emissions leakage" can substantially offset, or paradoxically even reverse, the reductions in emissions achieved in the

[1]Conditions include zero transaction costs, full information, perfectly competitive markets, and cost minimization behavior.

[2]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.

regulated sector. This leakage is particularly problematic when emissions damages are independent of the location of the source, as is the case with GHGs..[3]

These distortions have engendered a lively policy debate about how to design and implement carbon policy. In response, policy makers have been exploring alternative approaches to (partially) compensating compliance costs, thus mitigating the competitiveness impacts of the emissions regulation, via free emissions permit allocations.[4] Under a grandfathering regime, permits are freely distributed to regulated sources based on pre-determined criterion, such as historic emissions. Under so-called "dynamic updating" schemes, permits are allocated in proportion to firm's output in the previous period. This seemingly counterintuitive policy of incentivizing production with emissions permits may actually be socially efficient, as it can help to mitigate product market surplus losses and reduce emissions leakage.[5]

Designing a policy that strikes the appropriate balance between curbing domestic GHG emissions and protecting the competitive position of emissions-intensive manufacturing sector requires detailed knowledge of the structure and dynamics of the industries subject to the regulation. In this paper, we focus on an industry that has been at the center of the debate about U.S. climate change policy and international competitiveness: Portland cement. Cement is one of the largest manufacturing sources of domestic carbon dioxide emissions (Kapur et al., 2009). The industry is highly concentrated, making the industry potentially susceptible to the Buchanan critique. Finally, import penetration in the domestic cement market has exceeded 20 percent in recent years, giving rise to concerns about the potential for emissions leakage (Van Oss and Padovani, 2003; USGS, 2010).

A distinguishing feature of this paper is its emphasis on industry dynamics. We extend the dynamic oligopoly framework developed in Ryan (2012) as the foundation for our analysis. In our model, strategic domestic cement producers compete in spatially segregated regional markets. Some of these markets are trade exposed, whereas other landlocked markets are sheltered from foreign competition. Firms make optimal entry, exit, and investment decisions in order to maximize their expected stream of profits conditional on the strategies of their rivals. Conditional on capital investments, producers compete each period in homogeneous quantities. Regional market structures evolve as firms enter, exit, and adjust production capacities in response to changing market conditions.

[3]The damaging effects are greenhouse gas emissions are global; damages are a function of the level of emissions, but not the location. However, the same processes that generate GHG emissions also generate more locally-damaging co-pollutants such as particulates, volatile organic compounds, sulfur dioxide. Accounting for the effects of these local co-pollutants is beyond the scope of this analysis.

[4]Implicit in our discussion is that the government auctions off the balance of the permits each period.

[5]See also, Bernard et al. (2007).

Our model is estimated using twenty five years of detailed data on the Portland cement industry. In the benchmark model we estimate, carbon emissions are unconstrained. We use this model to simulate counterfactual industry responses to proposed emissions regulations. Conditional on our maintained assumptions, our approach allows us to assess both the efficiency and distributional implications of a market-based policy intervention in an industrial context characterized by both imperfect competition and exposure to competition from unregulated imports. We first consider auctioning without rebates which is isomorphic to a carbon tax in our setting. We then analyze outcomes under two partial rebating schemes: grandfathering and dynamic updating of free permit allocations based on an industry-specific efficiency benchmark. Finally, we consider the effects of levying a border tax adjustment which taxes imports at their average carbon content rate. Following Greenstone et al. (2011), we consider a range of values for the social cost per ton of carbon dioxide (CO_2), ranging from approximately \$5.00 to \$65 per ton.

Our primary finding is that an emissions trading program that requires domestic firms to fully internalize the emissions externality would induce social welfare losses over a wide range of carbon damage values. Taken together, reductions in domestic economic surplus and emissions leakage exceed the benefits of carbon mitigation. Welfare losses turn to gains when the social cost of carbon is only partially internalized. This can be achieved by setting the emissions price below the true social cost, or via dynamic allocation updating approaches that are currently being implemented in regional greenhouse gas emissions trading programs. However, our findings suggest that current rates of contingent rebating may be overly generous.

Finally, conditional on our assumptions about the structure of the domestic cement sector and the role played by imports, a policy that incorporates a border tax adjustment yields the largest welfare gains. Not only does the tax adjustment penalize the emissions from competitive imports, but it also begins to mitigate the distortions introduced by the exercise of market power in the domestic market. These findings underscore the importance of taking other pre-existing market failures and distortions into account when designing a policy to address an emissions externality.

This paper makes substantive contributions to several areas of the literature. First, we begin to address what Millimet et al. (2009) identify as a "striking gap in the literature on environmental regulation."V̇ery little work has been done to bring recent advances in the structural estimation of dynamic models to analyses of more long-run industrial responses to environmental regulation. This paper uses an empirically tractable structural model of the cement industry to analyze the dynamic efficiency properties of market-based emissions regulations. This approach complements the previous literature, which has used either highly stylized theoretical models (Conrad and Wang, 2003; Lee, 1999; Requate, 2005; Sengupta, 2010; Shafter, 1999) or numerical simulation models

(Demailly and Quirion, 2007, Fischer and Fox, 2007; Jensen and Rasmussen, 2000; Szabo et al, 2006; US EPA, 1996).

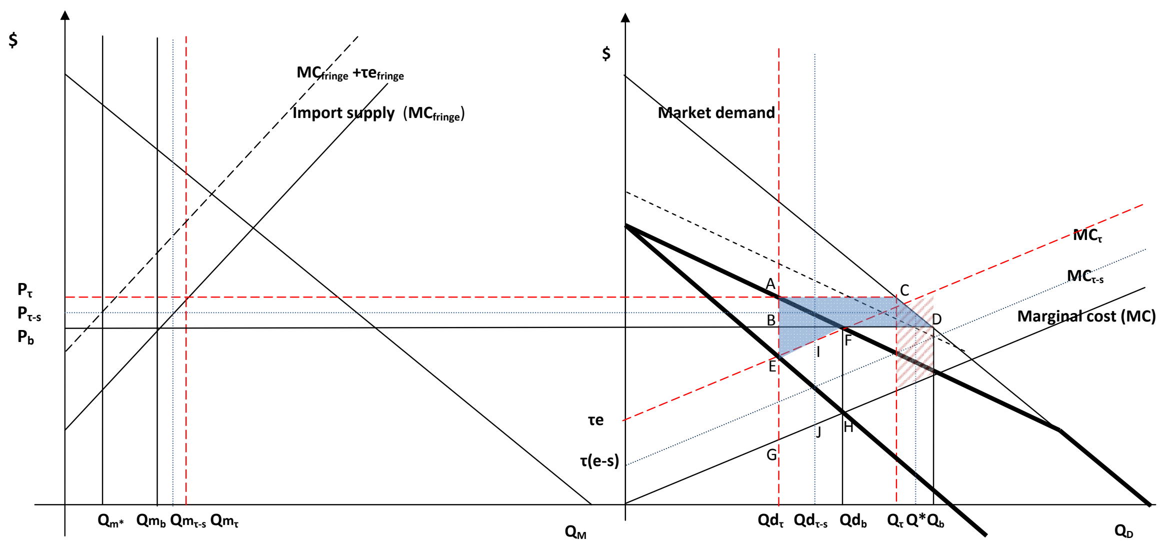
Second, this paper complements a growing body of work that examines the impacts of emissions trading programs on highly concentrated, trade-exposed, and emissions-intensive industries. Several of these studies have assessed impacts of the EU ETS on European cement producers. For example, Szabo et al. (2006) and Demailly and Quirion (2006) use a bottom-up model of the cement industry to examine impacts of alternative policy designs on industry profits, emissions, and emissions leakage. More recently, Ponssard and Walker (2008) specify a static oligopoly model of a regional European cement industry to examine the short run responses of European cement producers to the ETS. All of these studies find striking differences in impacts across grandfathering, auctioning, and rebating regimes. This paper differs from prior work in some important respects. First, we estimate an empirically tractable dynamic model of the U.S. cement sector in order to obtain estimates of key parameters such as investment costs. This approach emphasizes dynamic industry responses to policy interventions, and the interplay between emissions regulations and pre-existing distortions associated with the exercise of market power in cement market. This paper also places greater emphasis on evaluating the implications of theoretical insights from the literature on second-best policy design and optimal taxation in a very applied, empirical setting. In keeping with , Buchanan (1969), we find that the welfare maximizing carbon price falls well below the social cost of carbon.

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. Even though parametric methods have been used in single agent problems, its application to dynamic industry models with discrete entry, exit and investment decisions has been limited to date (Doraszelski and Pakes, 2007; Arcidiacono et al., 2012).

2 Conceptual framework

To help illustrate the basic economic forces at work in our more complex empirical setting, we first present a simple, static model. Figure 1 shows a domestic monopoly producer (right panel) facing a competitive fringe of importers (left panel). The thick black lines in the right panel represent both the residual demand curve, computed by subtracting the import supply curve from the market aggregate demand curve, faced by a domestic monopolist and the corresponding marginal revenue curve below it.

Figure 1: Emissions Intensive, Trade Exposed Monopoly



Absent any emissions regulation, the domestic monopolist sets residual marginal revenue equal to marginal cost and produces output Qd_b at price P_b. Foreign producers supply Qm_b at this price. This is the baseline (b) against which we will compare the alternative policy outcomes.

In this baseline case, note that the distortions associated with the exercise of market power in the domestic market manifest in two ways. First, the domestic firm restricts output in order to drive up the equilibrium product price. Second, production is not allocated optimally across domestic and foreign producers; marginal production costs differ significantly across domestic and foreign producers.

Suppose production generates harmful emissions of a global pollutant. For ease of exposition, we assume a constant emissions rate per unit of output (e) and a constant marginal social cost of emissions τ across domestic and foreign production. The curve labeled MC_τ captures both private marginal costs and the monetized value of the damages from the domestic firm's emissions: $MC_\tau = MC + \tau e$. Absent import competition, the socially optimal level of output would be defined by the intersection of MC_τ and aggregate demand.

Competition from foreign imports further complicates the picture. The broken line labeled $MC_{fringe} + \tau e_{fringe}$ represents the total social costs associated with foreign production. The downward sloping broken line in the right panel represents the residual demand curve that incorporates the emissions externality associated with foreign production. The intersection of this residual demand curve and MC_τ defines the efficient product price P^*. The socially optimal import quantity is Qm^*. The socially optimal level of domestic consumption is Q^*.

In this example, we assume the domestic policy maker has the authority to regulate domestic, but not foreign, producers. We first consider a policy regime in which the domestic monopolist is required to pay a fee of τ per unit of emissions. This increases the monopolist's variable operating costs by τe. The monopolist will choose to produce Qd_τ; the equilibrium product price is P_τ. This fee can be motivated either as a Pigouvian tax or a permit price in an emissions trading program in which the monopolist represents a small share of total emissions and permits are either auctioned or allocated lump sum a gratis.

Figure 1 illustrates how this emissions regulation can *reduce* welfare (consistent with the theory of the second best). Intuitively, the costs associated with further restricting domestic production can outweigh the benefits associated with the policy-induced emissions abatement. When domestic producers are required to pay τ per unit of output, domestic production drops even farther below optimal levels, and the allocative efficiency in production (i.e. across foreign and domestic suppliers) is exaggerated. This results in a form of "rent leakage," whereby the policy induces a transfer of surplus from domestic to foreign stakeholders. Moreover, the policy-induced increase in foreign production leads to emissions leakage of $e \cdot (Qm_\tau - Qm_b)$. This leakage offsets a portion of the domestic emissions reductions. The benefits of the policy are represented by the area shaded with diagonal lines in Figure 1. If we assume that increases in foreign producer surplus do not factor into the domestic policy maker's objective function (because they accrue outside her jurisdiction), the costs of the policy are represented by the shaded area in Figure 1. Lost consumer surplus that is not transferred to domestic producers is represented by area $ABCD$. Reductions in domestic producer surplus that are not transferred to the government as tax revenue are given by BEF.

Although the Pigouvian tax τ results in welfare loss in the case illustrated by Figure 1, this need not be the case. As the marginal social cost of emissions increases and/or the import supply responsiveness attenuates, the policy-induced benefits (i.e. reduced emissions damages) can begin to outweigh the costs (i.e. lost producer and consumer surplus).

In the more detailed analysis that follows, we will be interested in analyzing the welfare implications of augmenting an emissions price τ with a domestic production subsidy s. Intuitively, the subsidy acts to mitigate the distortions associated with the exercise of market power. Traditionally, it has been assumed that environmental regulators do not have the authority to subsidize the production of the industries they regulate (Cropper and Oates, 1992). However, policy makers have started to experiment with rebating tax revenues (in the case of an emissions tax) or allocating emissions permits (in the case of a cap-and-trade program) on the basis of production. These contingent rebates affect marginal production incentives, and can thus be used to mitigate the distortions introduced by the exercise of market power.

The equilibrium outcome under a market-based emissions regulation that incorporates an output-based rebate (or subsidy) is denoted $\tau - s$ in Figure 1. The monopolist's profit maximizing choice of output under contingent rebating is $Qd_{\tau-s}$. Although the level of aggregate domestic consumption under this policy is the optimal quantity Q^*, allocative efficiency is not achieved. Foreign imports capture too much of the domestic market share; the marginal cost of domestic production is much lower than the marginal cost of importers when evaluated at the equilibrium price, whereas the social planner would equate the two.

This highlights an important economic point: one generally needs as many policy instruments as market failures in order to achieve efficiency. While the tax on emissions and the production subsidy address the emissions externality and the exercise of market power in the domestic product market, respectively, an additional policy instrument is needed to address the asymmetry in compliance requirements across domestic and foreign producers. Below, we will also consider a border tax adjustment that is designed to penalize emissions generated by foreign production. In principle, one can find the optimal combination of these three instruments in order to maximize total welfare. In practice, the optimal balance can be difficult to strike. In this analysis, we will emphasize design alternatives that are most likely to be viable in applied policy settings.

2.1 Welfare decomposition

As compared to Figure 1, there will be many more moving parts in the more applied welfare analysis that follows. In order to understand the interplay between the emissions regulation and pre-existing distortions associated with the exercise of market power in regional cement markets, there will be expositional advantages to decomposing the net welfare effects of the market-based policies into three parts.

1. Changes in economic surplus The first welfare component captures changes in domestic economic surplus. In Figure 1, the shaded area represents the net change in domestic economic surplus induced by the Pigouvian tax. As we shift our focus to a more complex, dynamic model, the measurement of policy-induced changes in domestic economic surplus will become more complicated. But conceptually, the accounting is the same. We will be capturing changes in domestic producer and consumer surplus plus any changes in tax or auction revenues earned through the government sale of emissions permits or border tax adjustments.

2. Changes in damages from domestic industrial emissions The second welfare component measures changes in costs associated with domestic industrial emissions. In Figure 1, the value of the emissions reduction induced by the Pigouvian tax is $\tau e \cdot (Qd_b - Qd_\tau)$. Augmenting the Pigouvian tax with a production-based tax rebate of s increases emissions. Thus, the addition of the subsidy reduces the benefits of decreased domestic emissions by $\tau e \cdot (Qd_{\tau-s} - Qd_\tau)$.

Now consider the effect of contingent rebating in the context of a domestic cap-and-trade program with a fixed and binding cap. The introduction of the rebate into the industry under consideration cannot increase emissions in aggregate because emissions are constrained to equal the cap. Any increase in emissions from the domestic monopolist must be offset by other sources in the emissions trading program. We assume that the domestic abatement supply curve facing the monopolist is locally flat. As in the tax case, the addition of the subsidy increases social costs associated with domestic emissions by $\tau e \cdot (Qd_{\tau-s} - Qd_\tau)$. Under the emissions trading regime, this cost manifests as an increase in abatement costs elsewhere in the economy, rather than an increase in damages from emissions.

3. Emissions leakage If the introduction of an emissions regulation increases production—and thus emissions—among producers in unregulated jurisdictions, this emissions "leakage" will offset some of the emissions reductions achieved among regulated sources. The third welfare component measures the costs of emissions leakage in monetary terms. In Figure 1, the area $\tau e_{fringe}(Qm_\tau - Qm_b)$ denotes the monetary cost of this leakage under the market-based regulation that does not incorporate rebating. This cost is reduced to $\tau e_{fringe}(Qm_{\tau-s} - Qm_b)$ under rebating.

To more accurately simulate the response of domestic cement producers to alternative policy interventions, several of the simplifying assumptions that facilitate the graphical exposition must be released. We highlight two of these assumptions here. First, whereas the model assumed a domestic monopolist, regional cement markets in the United States are supplied by more than one domestic firm. Much of the intuition underlying the simple static monopoly case should apply in the case of a static oligopoly (Ebert, 1992). However, the oligopoly response to market-based emissions regulation can be more nuanced in certain situations.[6]

A second modification pertains to industry dynamics. Figure 1 depicts static, short-run responses to market-based policy intervention. Over a longer time frame, firms can alter their choice of production scale, technology, entry, exit, or investment behavior in response to an environmental policy intervention. The welfare impacts of a market-based emissions policy can look quite different across otherwise similar static and dynamic modeling frameworks. We are particularly

[6]For example, if firms are highly asymmetric and the inverse demand function has an extreme curvature, it is possible (in theory) for the optimal tax rate to exceed marginal damage (Levin, 1985).

interested in how these emissions regulations affect welfare through these dynamic channels.

On the one hand, incorporating industry dynamics into the simulation model can improve the projected welfare impacts of a given emissions regulation. Intuitively, the short run economic costs of meeting an emissions constraint can be significantly reduced once firms are able to re-optimize production processes, adjust investments in capital stock, and so forth.

On the other hand, incorporating industry dynamics may result in estimated welfare impacts that are strictly smaller than those generated using static models. In the policy context we consider, there are two primary reasons why this can be the case. First, in an imperfectly competitive industry, emissions regulation may further restrict already sub-optimal levels of investment, thus exacerbating the distortion associated with the exercise of market power. Second, a dynamic model captures an additional channel of emissions leakage. In a static model, firms may adjust variable input and output decisions such that less stringently regulated production assets are used more intensively. This leads to emissions leakage in the short run. In our dynamic modeling framework, the emissions regulation can also accelerate exit and retirement of regulated production units. This further increases the market share claimed by unregulated imports, thus increasing the extent of the emissions leakage to unregulated jurisdictions or entities.

3 Policies, institutions and data

The US domestic Portland cement industry has been at the center of the debate about domestic climate change policy and international competitiveness. Cement is one of the largest manufacturing sources of domestic carbon dioxide emissions (Kapur et al, 2009). Carbon regulation could result in major changes to the industry's cost structure. If we assume a cost of carbon in the neighborhood of $20/ton, complete internalization of the emissions externality would increase average variable operating costs by approximately 50 percent.[7]

The cement industry is an interesting and important setting to study the complex interactions between industrial organization and environmental policy design. The industry is highly concentrated in regionally-segregated markets, making it potentially susceptible to the Buchanan critique. The top five companies collectively operate 54.4% of U.S. clinker capacity with the largest company representing 15.9% of all domestic clinker capacity. Moreover, import penetration in the domestic cement market has exceeded 20 percent in recent years, giving rise to concerns about the potential for emissions leakage (Van Oss, 2003; USGS Mineral Commodity Summary 2010).

[7] On average, domestic cement producers emit close to one ton of carbon for each ton of cement produced. Marginal costs of cement production are estimated to be in the range of $40/ton (Ryan, 2012).

3.1 The US Portland cement industry

Portland cement is an inorganic, non-metallic substance with important hydraulic binding properties. It is the primary ingredient in concrete, an essential construction material used widely in building and highway construction. Demand for cement comes primarily from the ready-mix concrete industry, which accounts of over 70 percent of cement sales. Other major consumers include concrete product manufacturers and government contractors.

Cement competes in the construction sector with substitutes such as asphalt, clay brick, rammed earth, fiberglass, steel, stone, and wood (Van Oss, 2003, ENV). Another important class of substitutes are the so called supplementary cementitious materials (SCMs) such as ferrous slag, fly ash, silica fume and pozzolana (a reactive volcanic ash). Concrete manufacturers can use these materials as partial substitutes for clinker.[8]

Figure 2 summarizes aggregate trends in the industry since 1960. This figure helps to illustrate how domestic cement demand is subject to the cyclic nature of the U.S. economy in general and the level of construction activity in particular. Because of its critical role in construction, demand for cement tends to reflect population, urbanization, economic trends, and local conditions in the cement industry.

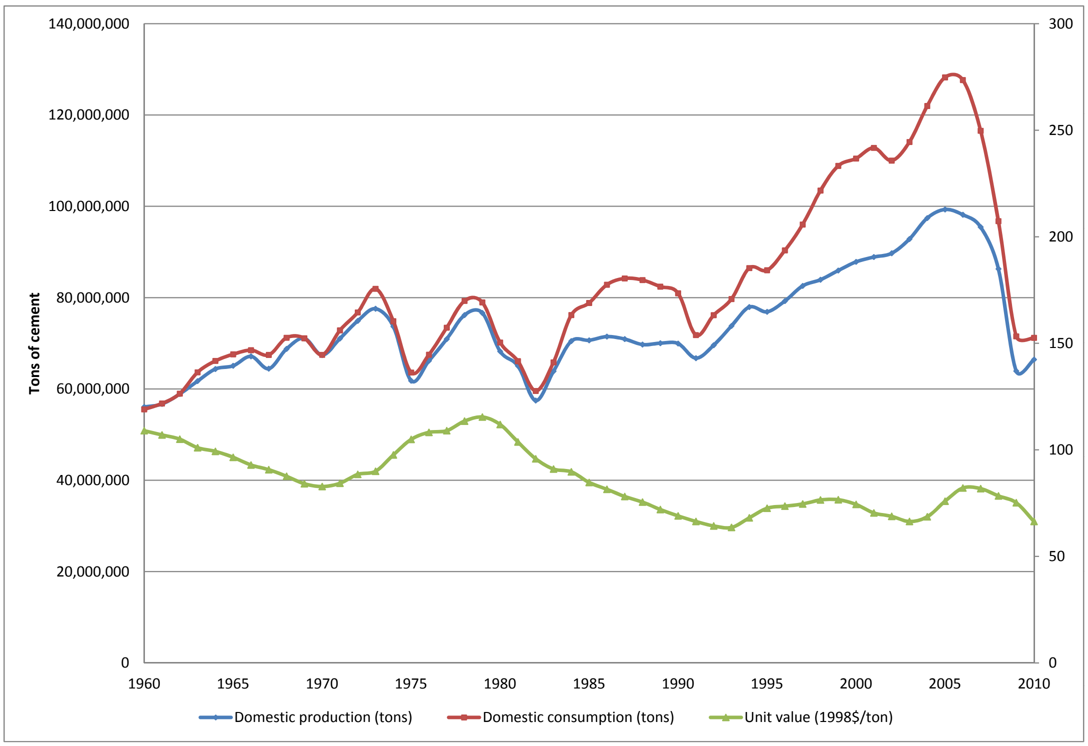
The US cement industry is fragmented into regional markets. This fragmentation is primarily due to transportation economies. The primary ingredient in cement production, limestone, is ubiquitous and costly to transport. To minimize input transportation costs, cement plants are generally located close to limestone quarries. Land transport of cement over long distances is also not economical because the commodity is difficult to store (cement pulls water out of the air over time) and has a very low value to weight ratio. It is estimated that 75 percent of domestically produced cement is shipped less than 110 miles (Miller and Osborne, 2010).[9]

Carbon dioxide emissions from cement production Cement producers are among the largest industrial emitters of airborne pollutants, second only to power plants in terms of the criteria pollutants currently regulated under existing cap-and-trade programs (i.e. NOx and SO_2). The cement industry is also one of the largest manufacturing sources of domestic carbon dioxide emissions

[8]The substitution of SCM for clinker can actually improve the quality and strength of concrete. Substitution rates range from 5 percent in standard Portland cement to as high as 70 percent in slag cement. These blending decisions are typically made by concrete producers and are typically based on the availability of SCM and associated procurement costs (Van Oss, 2005, facts; Kapur et al, 2009).

[9]Most cement is shipped by truck to ready-mix concrete operations or construction sites in accordance with negotiated contracts. A much smaller percent is transported by train or barge to terminals and then distributed.

Figure 2: Historic Trends in U.S. Cement Production and Consumption



(Kapur et al, 2009). Worldwide, the cement industry is responsible for approximately 7 percent of anthropogenic CO2 emissions (Van Oss, 2003, ENV).

Cement production process involves two main steps: the manufacture of clinker (i.e. pyroprocessing) and the grinding of clinker to produce cement. Carbon dioxide emissions from cement manufacturing are generated almost exclusively in the pyroprocessing stage. A mix comprised of limestone and supplementary materials is fed into a large kiln lined with refractory brick. The heating of the kiln is very energy intensive (temperatures reach temperatures of 1450°C) and carbon intensive (because the primary kiln fuel is coal). Carbon dioxide is released as a byproduct of the chemical process that transforms limestone to clinker. Once cooled, clinker is mixed with gypsum and ground into a fine powder to produce cement.[10] Trace amounts of carbon dioxide are released during the grinding phase.

Carbon dioxide emissions intensities, typically measured in terms of metric tons of emissions per metric ton of clinker, vary across cement producers. Much of the variation is driven by variation in fuel efficiency. The oldest and least fuel efficient kilns are "wet-process" kilns. As of 2006, there were 47 of these wet kilns in operation (all built before 1975) (PCA PIS, 2006). "Dry process" kilns are significantly more fuel efficient, primarily because the feed material used has a lower moisture content and thus requires less energy to dry and heat. The most modern kilns, dry kilns equipped with pre-heaters and pre-calciners, are more than twice as fuel efficient as the older wet-process kilns.

Emissions Abatement Several recent studies assess the potential for carbon emissions reductions in the cement sector.[11] Using different scenarios, baseline emissions and future demand forecasts, all reach similar conclusions. Although there is no "silver bullet," there are four key levers for carbon emissions reductions.

The first set of strategies involve energy efficiency improvements. The carbon intensity of clinker production can by replacing older equipment with current state of the art technologies. In the United States, it is estimated that converting wet installed capacity to dry kilns could reduce annual emissions by approximately 15 percent. Converting from wet to the semi-wet process would deliver an additional 3 percent reduction (Mahasenan et al., 2005).

A second set of carbon mitigation strategies involve substitution. One approach is to simply increase the use of substitute construction materials such as wood or brick, thus reducing demand

[10]The US cement industry is comprised of clinker plants (kiln only operations), grinding-only facilities, and integrated (kiln and grinding) facilities.Almost all of the raw materials and energy used in the manufacture of cement are consumed during pyroprocessing. We exempt grinding only facilities from our analysis.

[11]A comprehensive list of studies can be found at http://www.wbcsdcement.org/pdf/technology/References%20FINAL.pdf

for cement. Alternatively, the amount of clinker needed to produce a given amount of cement can be reduced by the use of supplementary cementitious materials (SCM) such as coal fly ash, slag, and natural pozzolans.[12] It is estimated that the increased use of blended cement could feasibly reduce carbon emissions by a third over the time frame we consider (Mahasenan et al., 2005).

Fuel switching offers a third emissions abatement strategy. Less carbon intensive fuels, such as waste derived fuels or natural gas, could replace coal as the primary kiln fuel. The potential for CO_2 mitigation by fuel switching in the North American cement industry is estimated to be on the order of 5 percent of current emissions (Humphreys and Mahasenan, 2001).

Finally, carbon dioxide emissions can be separated and captured during or after the production process and subsequently sequestered. This abatement option is unlikely to play a significant role in the near term given that sequestration technologies are in an early stage of technical development or acceptance and are relatively costly.

Ideally, a model designed to simulate industry response to an emissions regulation would accurately capture all viable carbon abatement strategies. Unfortunately, our econometric approach is not well suited to modeling responses that have yet to be observed in the data. Consequently, fuel switching and carbon sequestration are not represented in our analysis. Although these options are not expected to play as significant a role as efficiency improvements or substitution, this omission will bias up our estimates of the economic costs imposed of the emissions regulations we analyze.

Trade Exposure Whereas overland transport of cement is very costly, sea-based transport of clinker is relatively inexpensive. In the 1970s, technological advances made it possibly to transport cement in bulk quantities safely and cheaply in large ocean vessels. Since that time, U.S. imports have been growing steadily. Figure 2 highlights an increasing reliance on imports to meet domestic demand. Since 1980, import market share increased from below 3 percent to over 25 percent in 2006. China is currently the largest supplier of imported cement (accounting for 22 percent of imports), followed by Canada, Korea, and Thailand (USGS, 2010 fact sheet).

Exposure to import competition in regional markets has given rise to growing concerns about unilateral climate policy. For example, an industry trade group has warned that, in the absence of measures that either relieve the initial cost pressure or impose equivalent costs of imports, California's proposed cap on greenhouse gas emissions will "render the California cement industry economically unviable, will result in a massive shift in market share towards imports in the short run, and will precipitate sustained disinvestment in the California cement industry in the long

[12] When part of the cement content of concrete is replaced with supplementary cementitious materials, the extent of the emissions reduction is proportional to the extent to which SCM replaces clinker. Substitution rates as high as 75 percent are possible.

run."[13]

3.2 Market-based emissions regulation

We analyze both static and dynamic industry response to the introduction of market-based emissions regulation. Our primary focus is a multi-sector, nation-wide cap-and-trade program. A defining feature of the program is a cap which imposes a binding constraint on the quantity of carbon emissions released by sources in the program. A corresponding number of pollution permits are issued. To remain in compliance, regulated sources must hold permits to offset uncontrolled emissions. These permits are traded freely in the market place.

Having defined the emissions cap, the regulator must decide how to allocate or distribute the emissions permits. We are particularly interested in exploring the efficiency implications of alternative emissions permit allocation approaches. The first policy design we analyze is a cap-and-trade program in which permits are allocated via a uniform price auction. In the context of an economy-wide greenhouse gas emissions trading program, a cap-and-trade program that incorporates auctioning has its proponents.[14] Within our modeling framework, this policy design is functionally equivalent to a carbon tax.

Many industry stakeholders vehemently oppose a policy regime that would auction all permits (at least in the near term).[15] In existing and planned emissions trading programs, the majority of permits are distributed a gratis to regulated firms. In a "grandfathering" regime, permits are freely allocated according to pre-determined factors (such as historic emissions). Several studies have demonstrated that a pure grandfathering regime would grossly overcompensate industry for the compliance costs incurred under proposed Federal climate change legislation. Goulder, Hafstead, and Dworsky (2010) estimate that grandfathering fewer than 15 percent of the emissions allowances in a Federal greenhouse gas emissions trading program would significantly mitigate the impact of the carbon regulation on industry profits. Under the grandfathering regime we analyze, we assume that a number of permits equal to 50 percent of annual baseline emissions are grandfathered each year to incumbent cement producers.

[13] Letter from the Coalition for Sustainable Cement Manufacturing and Environment to Larry Goulder, Chair of the Economic and Allocation Advisory Committee. Dec. 19, 2009.

[14] For example, in 2007, the Congressional Budget Office Director warned that a failure to auction permits in a federal greenhouse gas emissions trading system "would represent the largest corporate welfare program that has even been enacted in the history of the United States, "Approaches to Reducing Carbon Dioxide Emissions: Hearing before the Committee on the Budget U.S. House of Representatives", November 1, 2007. (testimony of Peter R. Orszag)

[15] The US Climate Action Partnership (USCAP) is a non-partisan coalition comprised of 25 major corporations and 5 leading environmental groups. In January 2009, the group issued its "Blueprint for Legislative Action" in which it urged Congress to use some portion of allowances to buffer the impacts of increased costs to energy consumers, and to provide transitional assistance to trade-exposed and emissions intensive industry.

In recent years, a third design alternative has emerged. Emissions permits are allocated for free to eligible firms using a continuously updated, output-based formula.[16] The incentives created by this dynamic allocation updating rule are quite different with those associated with grandfathering or auctioning; updating confers an implicit production subsidy. The particular form of updating we analyze is based on an "efficiency benchmarking" approach that is currently under consideration in Europe, Australia, and California. The number of emissions permits allocated per unit of output is based on an industry-specific benchmark level of emissions intensity.

Finally, border tax adjustments offer an alternative approach to mitigating emissions leakage in trade-exposed, emissions intensive industries. These import taxes are intended to penalize the emissions embodied in foreign imports, thus "leveling the carbon playing field." Although border tax adjustments face formidable legal challenges (see, for example, Fischer and Fox (2009)), we consider this policy design feature due to its attractive efficiency properties.[17]

4 Model

The basic building block of the model is a regional cement market.[18] We set $\overline{N}$ to be the maximal number of firms. Each market is described by two state vectors, s and e, of size $\overline{N}$ each. The vector s describes the productive capacity of the firms at the market. Firms can adjust their capacity over time, by means of entry, exit and investment. Firms with zero capacity are considered to be potential entrants.

The vector e describes the emissions rate of each firm. We assume that there are three discrete levels of emissions rates, corresponding to the three major types of production technology in the cement industry. Existing incumbents are modeled as having one of the three technologies, while new entrants are always endowed with the frontier technology.

Firms obtain revenues from the product market and incur costs from production, entry, exit, and investment. Each decision period is one year. Time is thus discrete and unbounded. Firms

[16]Proposed federal climate change legislation included a provision to allocate permits to eligible industries using an output-based formula. These free allocations are intended to compensate both direct compliance costs (i.e. the cost of purchasing permits to offset emissions) and indirect compliances costs (i.e. compliance costs reflected in higher electricity prices). Under California's Assemly Bill 32, implementing agencies have recommended that free allocation to industry will, "to the extent feasible, be based on output-based GHG efficiency "benchmarks" and "update" to reflect changes in production each year for industry with leakage risk" (Greenhouse Gas Cap-and-Trade Regulation Status Update May 17, 2010 California Air Resources Board).

[17]For example, in a market with no frictions, a carbon tax with a border tax adjustment is an effective way to induce full internalization of pollution damages.

[18]The model borrows heavily from Ryan (2012), to which we add imports, emissions technologies and environmental policies.

discount the future at rate $\beta = 0.9$. In each period, first, incumbent firms decide whether or not to exit the industry based on their entry cost shock. Second, potential entrants receive both investment and entry cost shocks, while incumbents who have decided not to exit receive investment cost shocks. All firms then simultaneously make entry and investment decisions. Third, incumbent firms compete over quantities in the product market. Finally, firms enter and exit, and investments mature.

We assume that firms who decide to exit produce in this period before leaving the market, and that adjustments in capacity take one period to realize. We also assume that each firm operates independently across markets.[19]

4.1 Static payoffs

Firms compete in quantities in a homogeneous goods product market. Firms face a constant-elasticity aggregate demand curve:

$$\ln Q_m(\alpha) = \alpha_{0m} + \alpha_1 \ln P_m, \tag{1}$$

where Q_m is the aggregate market quantity, P_m is price, α_{0m} is a market-specific intercept, and α_1 is the elasticity of demand.

For firms in trade-exposed regional markets, the effective residual demand that they face is more elastic and potentially kinked, as they also face an import supply curve given by:

$$\ln M_m(\rho) = \rho_0 + \rho_1 \ln P_m, \tag{2}$$

where M_m measures annual import supply in market m and ρ_1 is the elasticity of import supply. Here we assume that the elasticity of import supply is an exogenously determined parameter.[20] For clarity, we omit the m subscript in what follows.

In the model, each firm chooses the level of annual output that maximizes their static profits given the outputs of the competitors, subject to capacity constraints that are determined by dynamic

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

[20] In fact, firms that own a majority of the domestic production capacity in the United States are also among the largest importers. These dominant producers presumably use imports to supplement their domestic production as needed, and to compete in markets where they do not own production facilities. Domestic cement producers have noted that increased domestic ownership of import facilities has contributed to a "more orderly flow of imports into the U.S."

Grancher, Roy A. "U.S. Cement: Record Performance and Reinvestment", Cement Americas, Jul 1, 1999 capacity investment decisions:

$$\overline{\pi}(s,e,\tau;\alpha,\rho,\delta)\equiv\max_{q_i\le s_i}\ P\left(q_i+\sum_{j\ne i}q_j^*+M^*;\alpha\right)q_i-C_i(q_i;\delta)-\varphi(q_i,e_i,\tau),\tag{3}$$

where $P(Q;\alpha)$ is the inverse of residual demand. The profit $\overline{\pi}(s,e,\tau;\alpha,\rho,\delta)$ defines the equilibrium static profits of the firm for a given level of capacity and emissions technologies. If all firms produce positive quantities then the equilibrium vector of production is unique, as the best-response curves are downward-sloping.

The cost of output, q_i, is given by the following function:

$$C_i(q_i;\delta)=\delta_{i1}q_i+\delta_2 1(q_i>\nu s_i)(q_i/s_i-\nu)^2.\tag{4}$$

Variable production costs consist of two parts: a constant marginal cost, δ_{i1}, which we allow to vary across kiln types, and an increasing function that binds as quantity approaches the capacity constraint.[21] We assume that costs increase as the square of the percentage of capacity utilization, and parameterize both the penalty, δ_2, and the threshold at which the costs bind, ν. 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 ν.

The term $\varphi(q_i,e_i,\tau)$ represents the environmental compliance costs faced by the firm. The carbon cost, τ, is an exogenous parameter intended to capture the monetized damages associated with an incremental (one ton) increase in carbon emissions.[22] The policy designs we analyze can best be classified into one of four categories: standard auction design/carbon tax; grandfathering (i.e. lump sum transfer); output-based rebating; and an auctioning regime augmented with a border-tax adjustment.

[21]Note that we do not consider fixed costs of production and operation. The reason is that we do not observe sufficient periods of operation without production (mothballing) which are required to separately identify those parameters from the distribution of exit costs.

[22]The exogeneity assumption seems appropriate as the domestic cement industry is a relatively small player in a potential economy-wide emissions market, such that changes in industry net supply/demand for permits cannot affect the equilibrium market price. Keohane (2009) estimates the slope of the marginal abatement cost curve in the United States (expressed in present-value terms and in 2005 dollars) to be 8.0 x 10^7 \$/GT CO_2 for the period 2010–2050. Suppose this curve can be used to crudely approximate the permit supply function. If all of the industries deemed to be "presumptively eligible" for allowance rebates reduced their emissions by ten percent for this entire forty year period, the permit price would fall by approximately \$0.25/ ton.

Emissions tax or emissions trading with auctioned permits The first policy regime we analyze is an emissions tax or an emissions cap-and-trade program in which all emissions permits are allocated via a uniform price auction. In the tax regime, regulated firms must pay a tax τ for each ton of emissions. In the emissions trading regime, the equilibrium permit price is τ; a change in the net supply or demand for permits from the domestic cement industry does not affect this price.

The environmental compliance cost to the firm becomes:

$$\varphi(q_i, e_i, \tau) = \tau e_i q_i. \tag{5}$$

Grandfathering In this policy scenario, a share of emissions permits are allocated for free to incumbent firms that pre-date the carbon trading program. Firm-specific permit allocation schedules (i.e. the number of permits the firm will receive each period) are determined at the beginning of the program and are based on historic emissions. We assume that incumbent firms receive a lump-sum, annual permit allocation equal to 50 percent of historic annual emissions.

The environmental compliance cost to the firm becomes:

$$\varphi(q_i, e_i, \tau) = \tau(e_i q_i - A_i), \text{ with } \quad \sum_i A_i = \overline{A}, \tag{6}$$

where A_i is the total emission permits that the firm receives for free from the regulator; $\overline{A}$ represents the total amount of emissions allocated for free to domestic cement producers. We assume that the share of emissions allowances allocated to firm i (i.e. $A_i/\overline{A}$) is equal to its share of the installed kiln capacity at the outset of the program.

Note that the first order conditions associated with static profit maximization under auctioning are identical to those under grandfathering. This highlights the so-called "independence property," which holds that firms' short run production and abatement decisions will be unaffected by the choice between auctioning permits or allocating them freely to firms in lump sum (Hahn and Stavins, 2010).

When permits are grandfathered in a cap and trade program, policy makers must decide ex ante how to deal with new entrants and firms who exit. In our simulations, we assume that a firm forfeits its future entitlements to free permits when it exits the market, thus breaking this independence property.[23] We assume that new entrants are not entitled to free permits.[24]

[23]Note that if firms were to keep all their permits indefinitely then this mechanism would be dynamically welfare-equivalent to the auctioning scheme, although distributionally different, so the independence property would apply.

[24]In practice, policies regarding free permit allocations to free entrants and former incumbents vary. In the EU ETS, policies governing the free allocation of permits to entrants vary across member states. Most states require forfeiture

Output-based allocation updating/rebating The third policy regime we analyze incorporates output-based rebating in the interest of mitigating emissions leakage and associated adverse competitiveness impacts. Permits are allocated (or tax revenues are recycled) per unit of production based on an industry-specific emissions intensity benchmark. We adopt the benchmark that was chosen for European cement producers in the third phase of the EU ETS (2013-2020): 0.716 permits per metric ton of clinker. [25]

The environmental compliance cost to the firm becomes: becomes:

$$\varphi(q_i, e_i, \tau) = \tau(e_i q_i - 0.716 q_i). \tag{7}$$

Emissions allowances are thus allocated (or tax revenues are rebated) according to market share.

Following Bushnell and Chen (2009), the rebate a firm receives in the current period depends on its production level in that same period. Thus, we do not explicitly account for the fact that firms will discount the value of the subsidy conferred by rebating if the rebate is paid in a future period. This assumption simplifies the dynamic problem considerably, while still allowing us to capture the dynamic implications of the mechanism to a significant extent.

Border tax adjustment with auctioned permits The fourth and final policy design that we consider layers a border tax adjustment (BTA) atop the standard tax/auctioning regime. This BTA mechanism imposes a tax on emissions embodied in cement imports equal to the tax imposed on domestic emissions. This effectively levels the carbon playing field with international competitors.

The BTA regime is equivalent to the auctioning regime in terms of the function $\varphi(q_i, e_i, \tau)$. However, domestic firms now face a different residual demand, as the import supply is shifted to the left as follows:

$$\ln M(\rho, \tau) = \rho_0 + \rho_1 \ln(P - \tau e_M), \tag{8}$$

where e_M is the emissions rate on imported cement.

4.2 Dynamic decisions

Firms have the opportunity to adjust capacity in each period. Firms can increase their capacity through costly investments, denoted by x_i.[26] The cost function associated with these investments

of free permit allocations upon closure.

[25] (2011/278/EU). Available from: http://eurlex. europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:130:0001:0045:EN:PDF (accessed 6/30/2011).

[26] Note that we do not consider decreases in capacity in our model. Substantial divestment is virtually never observed in the data and thus the estimates of divestment costs cannot be estimated.

is given by:

$$\Gamma(x_i;\gamma) = 1(x_i > 0)(\gamma_{i1} + \gamma_2 x_i). \tag{9}$$

Firms face both fixed and variable investment costs. 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. Fixed investment costs are drawn each period from the common distribution F_γ, which is distributed normally with mean μ_γ and standard deviation σ_γ, and are private information to the firm.

Firms also make market participation decisions, denoted by a_i. Firms face fixed costs related to their market participation decisions, given by $\Phi(a)$, which vary depending on their current status and chosen action:

$$\Phi(a_i;\kappa_i,\phi_i) = \begin{cases} -\kappa_i & \text{if the firm is a new entrant,} \\ \phi_i & \text{if the firm exits the market.} \end{cases} \tag{10}$$

Firms that enter the market pay a fixed cost of entry, κ_i, which is private information and drawn from the common distribution of entry costs, F_κ. Firms exiting the market receive a payment of ϕ_i, which represents net proceeds from shuttering a plant, such as selling off the land and paying for an environmental cleanup. This value may be positive or negative, depending on the magnitude of these opposing payments. The scrap value is private information, drawn anew each period from the common distribution, F_ϕ. All of the shocks that firms receive each period are mutually independent.

Collecting the costs and revenues from a given firm, the per-period payoff function is:

$$\pi_i(a,x,s,e,\tau;\theta) = \bar{\pi}_i(s,e,\tau;\alpha,\rho,\delta) - \Gamma(x_i;\gamma_i) + \Phi(a_i;\kappa_i,\phi_i). \tag{11}$$

where θ denotes the vector of parameters in the model, expect for the carbon cost τ.

To close the dynamic elements of the model it is necessary to specify how transitions occur between states as firms engage in investment, entry, and exit. We assume that changes to the state vector through entry, exit, and investment take one period to occur and are deterministic. The first part 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. The second part 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.[27]

[27] It is conceptually straightforward to add uncertainty over time-to-build in the model, but assuming deterministic transitions greatly reduces the computational complexity of solving for the model's equilibrium.

4.3 Equilibrium

In each time period, firm i makes entry, exit, production, and investment decisions. 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 and their private shocks when making decisions, as in Maskin and Tirole (1988) and Ericson and Pakes (1995). The detailed equilibrium Bellman equations are relegated to the online appendix.

To compute the equilibrium, we develop parametric approximation methods for the computation of dynamic games. In particular, we interpolate the value function using cubic splines. For the interested reader, a detailed description of the methodology to compute the equilibrium is relegated to the online appendix.

4.4 Welfare measures

We focus exclusively on outcomes in the domestic cement industry. Within a regional cement market, it is useful to decompose the net welfare impact of a policy intervention into the three components introduced in Section 2.

We define the following per-period equilibrium welfare measures:

$$w_1(s,e,\tau;\theta) = \int_0^{Q*} P(z;\alpha)dz - P(Q^*;\alpha)Q^* + \sum_i \Pi_i(a^*,x^*,s,e,\tau;\theta) + \sum_i \varphi(q_i^*,e_i,\tau), \quad (12a)$$

$$w_2(s,e,\tau;\theta) = w_1(s,e,\tau;\theta) - \tau\sum_i e_i q_i^*, \quad (12b)$$

$$w_3(s,e,\tau;\theta) = w_2(s,e,\tau;\theta) - \tau e_M M(P^*;\gamma). \quad (12c)$$

The welfare measure w_1 captures changes in the private economic surplus accruing from domestic cement consumption (i.e. net consumer surplus, net producer surplus and carbon revenues). w_2 accounts for both economic surplus changes plus the costs of domestic emissions. Finally, w_3 adds a penalty for emissions leakage.

We will focus on comparing the net present value of these welfare measures to the baseline case in which no emissions regulation is in place but emissions are damaging. Define $w_0(s,e,\tau;\theta)$ as the per-period welfare when firms produce as if there were no carbon policy in place but emissions are still creating a damage of τ. The net present value (NPV) welfare measures that we consider are:

$$W1 = \sum_{t=1}^{T} \beta_S^t \big(w_{1t}(s,e,\tau;\theta) - w_{0t}(s,e,\tau;\theta)\big), \quad (13)$$

where β_S is social discount factor. $W2$ and $W3$ are analogously defined.

5 Data and Estimation

The econometric estimation of the parameters is based on the benchmark model, in which the price of emissions is set to zero ($\tau = 0$), i.e. there is no compliance cost due to emissions regulation. Once estimated, this model can be used to simulate the dynamic industry response to market-based emissions regulations that affect firms' production and investment choices primarily through operating costs provided certain assumptions are met. In particular, we will assume that firms' response to a given operating cost change is independent of whether the cost change is caused by emissions regulation or other exogenous factors (such as changes in energy prices or other inputs).

Our approach to estimating the parameters of the model builds directly on Ryan (2012), although there are some noteworthy differences in our approach. We update the data used to estimate the model; our study covers the period 1980-2006. As we explain below, in order to use more recent industry data, we must adopt an alternative approach to defining regional markets. Heterogeneity in marginal costs and emissions rates across kiln-types is represented in the model. Finally, whereas Ryan (2012) ignores the role of imports, we will explicitly capture the responsiveness of imports to changes in domestic operating conditions. The interested reader is referred to Ryan (2012) for additional details regarding the data and estimation.

We first present the data. Then, we present estimation of the parameters. The parameters of the model can be divided in three broad categories. First, those concerning the domestic market (demand and cost structure). Second, we estimate the parameters related with international markets (import supply). Finally, we present our calibration the parameters related with the environmental policy (carbon costs and emissions rates).

5.1 Data

Our data on the Portland cement industry from two main sources: the U.S. Geological Survey (USGS) and the Portland Cement Association. The USGS collects establishment-level data from all domestic Portland cement producers. These data, aggregated regionally to protect the confidentiality of the respondents, are published in an annual Minerals Yearbook. Kiln-level data are available from the Plant Information Survey (PIS), an annual publication of the Portland Cement Association. The PIS provides information on the location, vintage, kiln-type, primary fuel, and operating capacity of each operating kiln.

Figure 2 helps to summarize some important aggregate trends over the study period (1980-2006). Throughout the mid-1980s and into the early 1990s, domestic production and consumption remained relatively flat. In the mid-1990s, domestic capacity - and production- reached unprecedented levels as demand increased steadily and new capacity was brought online. One striking trend over the study period, highlighted by this figure, is the increase in the share of the domestic market supplied by foreign imports. That real cement prices remained stable over the period 1990-2005, even as domestic demand reached historic highs, is often attributed to increased competition from foreign imports (USGS Minerals Yearbook, various years).

Firm-level data on entry, exit, and capacity adjustment is an important input to our analysis. We obtain kiln-level information from the annual PIS and cross-validate this information using the annual summaries published by the USGS. Over the twenty-five year study period, we observe 12 plant entries and 51 exits, with an implied entry and exit rate of 0.4% and 1.7%, respectively. We observe 144 capacity increases (i.e. investment in one or more new kilns). We observe 95 capacity decreases. The implied capacity adjustment rate exceeds 8 percent.

We choose not to use the regional definitions adopted by the USGS in our analysis. In recent years, increased consolidation of asset ownership has led to higher levels of data aggregation. Conversations with the experts at USGS indicate that the current approach to regional data aggregation groups plants that are unlikely to compete with each other (Van Oss, personal communication). We instead base our regional market definitions on the industry-accepted limitations of economic transport as well as company-specific SEC 10k filings which include information regarding markets served by specific plants. The USGS data on prices and quantities are weighted by kiln capacity in each region. For example, if kiln capacity in USGS market A is equally divided between regional markets we define to be B and C, production quantities in market A are equally divided between our defined markets B and C.

We report some regional market-level summary statistics using PCA data from 2006 in Table 1. The table helps to highlight inter-regional variation in market size, emissions intensity, and trade exposure. Notably, the degree of import penetration varies significantly across inland and coastal areas. Whereas several inland markets are supplied exclusively by domestic production, imports now account for over half of domestic cement consumption in Seattle. Import penetration rates tend to be highest along the coasts versus inland waterways.

Table 1: Descriptive Statistics for Regional Markets (based on 2006 data)

Market	Number of Firms	Capacity	Emissions Rate	Import Market Share
Atlanta	6	1285	0.97	0.12
Baltimore/Philadelphia	6	1497	0.99	0.12
Birmingham	5	1288	0.94	0.35
Chicago	5	972	0.98	0.04
Cincinnati	3	875	0.93	0.21
Dallas	5	1766	1.05	0
Denver	4	998	0.95	0
Detroit	3	1749	1.02	0.19
Florida	5	1297	0.93	0.35
Kansas City	4	1661	0.95	0
Los Angeles	6	1733	0.93	0.18
Minneapolis	1	1862	0.93	0.2
New York/Boston	4	1033	1.16	0.45
Phoenix	4	1138	0.93	0.13
Pittsburgh	3	614	1.08	0
Salt Lake City	2	1336	1.01	0
San Antonio	6	1318	0.95	0.3
San Francisco	4	931	0.93	0.18
Seattle	2	607	1.05	0.65
St Louis	4	1358	1.05	0

5.2 Domestic market parameters

Following Ryan (2012), we estimate the demand equation:

$$\ln Q_{mt} = \alpha_m + \gamma_1 \ln P_{mt} + \gamma_2 X_{mt} + \varepsilon_{1mt}. \tag{14}$$

The dependent variable is the natural log of the total market demand in market m in year t. The coefficient on market price, γ_1, is the elasticity of demand. We instrument for the potential endogeneity of price using supply-side cost shifters: coal prices, gas prices, electricity rates, and wage rates. The matrix X_{mt} includes demand shifters such as population and economic indicators.

We estimate (14) using limited information maximum likelihood. As in Ryan (2012), this preferred specification includes market-specific fixed effects α_m in lieu of demand shifters. Our estimate of the elasticity of aggregate demand is -2.02.[28] Because the data used to estimate (14) are highly aggregated, our demand elasticity estimate is somewhat noisy (the estimated standard error is 0.26). Moreover, the point estimate is somewhat sensitive to alternative specifications and

[28]The estimate is higher in absolute value than some other demand elasticities reported in the literature. For example, Jans and Rosenbaum (1996) estimate a domestic demand elasticity of -0.81. Using data from 12 European countries over the period 1990-2005, Sato, Neuhoff and Neumann estimate a demand elasticity of -1.2. Using USGS data from the Southwestern U.S., Miller and Osborne estimate an aggregate demand elasticity of -0.16. On the other hand, Foster, Haltiwanger, and Syverson (2008) estimate several similar high demand elasticities for homogeneous goods industries, such as -5.93 for ready-mixed concrete, cement's downstream industry.

subsets of excluded instruments (see Appendix **??**) To account for this imprecision, we conduct sensitivity analysis over a range of demand elasticity values.

Table 2 summarizes all parameter estimates used in our simulations.The marginal cost estimate of \$39.59/ton of clinker for wet kilns, and \$38.60/ton for dry kilns, falls well within the range that is typically reported for domestic production (Van Oss, 2003; US EPA, 2005). The magnitudes of the fixed costs are reasonable at face value, and in conjunction with the estimated variances, are in accord with the observed rates of investment, entry, and exit in the cement industry.

Investment costs are roughly in line with the accounting costs cited in Salvo (2005), which reports a cost of \$200 per ton of installed capacity. Our numbers are slightly higher, which in line with the idea that these costs represent economic opportunity costs as opposed to accounting costs. The implied cost of a cement plant is also in line with plant costs reported in newspapers and trade journals. For example, on October 15, 2010, it was reported that the most recent expansion of the Texas Industries New Braunfels cement plant, increasing capacity from 900 thousand tons per year to 2.3 million tons per year, was pegged at a cost of \$276M in 2000 dollars, which implies a cost of \$197 per ton of installed capacity.[29]

5.3 Import supply parameters

Given our interest in understanding how policy-induced operating cost increases could affect import penetration rates, it will be important to separate the import supply response to changes in domestic operating costs from the domestic market demand response.

We estimate the following import supply schedule using limited information maximum likelihood:

$$\ln M_{mt} = \phi_0 + \phi_1 \ln P_{mt} + \phi_{2m} + \phi_3' \ln Z_{mt} + \varepsilon_{2mt}. \tag{15}$$

For inland markets supplied entirely by domestic production, all ϕ coefficients are set to zero. The dependent variable is the log of the quantity of cement shipped to market m in year t. The average customs price of cement is P_{mt}. These data are reported by Customs districts (i.e. groupings of ports of entry). Each port of entry is matched to a regional market described in the previous section. The model is estimated using data from the period 1992-2006.[30]

We instrument for the import price using gross state product, new residential construction building starts, and state-level unemployment. The matrix Z_{mt} includes other plausibly exogenous factors that affect import supply. To capture transportation costs, we subtract the average customs

[29] Source: KGNB Radio, New Braunfels, Texas.
[30] District-level data on imports from earlier years contains many missing values.

Table 2: Domestic Market Parameters

Parameter	Value
Demand Parameters	
Constant	17.38
Elasticity of Demand	-2.02
Discount Factor	
Discount Factor β	0.9
Production Parameters	
Capacity Cost ($/utilization)	442.79
Capacity Cost Binding Level	1.72
Marginal Cost Wet ($/metric ton)	39.59
Marginal Cost Dry Shifter ($/metric ton)	-0.987
Investment Parameters	
Fixed Cost Mean ($/metric ton)	281
Fixed Cost Standard Deviation	145
Marginal Cost ($/metric ton)	217
Exit Cost	
Scrap Distribution Mean ($)	-67,628
Scrap Distribution Standard Deviation	54,587
Entry Distribution	
Entry Cost Mean ($)	271,809
Entry Cost Standard Variance	46,558

Notes: In 2000 dollars. Demand constant for Atlanta.

price from the average C.I.F. price of the cement shipments. This residual price accounts for the transportation cost on a per unit basis, as well as the insurance cost and other shipment-related charges. The Z_{mt} matrix also includes coal and oil prices to capture variation in production costs. Region dummy variables capture regional differences.

Our preferred point estimate is 2.5 (see Appendix **??**).[31] Unfortunately, because publicly available data on cement imports are noisy and highly aggregated, all available estimates of import supply elasticities are quite noisy. In light of this, we conduct sensitivity analysis over a range of import supply elasticity values.

To construct the residual demand curve faced by domestic producers in a trade exposed market, the import supply at a given price is subtracted from the aggregate demand at that price. The resulting residual demand does not necessarily feature a constant elasticity and potentially features a kink at the price below which importers do not supply any output at the market. Strictly positive imports are observed in coastal markets across all policy simulations.[32]

This partial equilibrium approach to modeling import response is admittedly quite stylized. Importantly, we ignore the possibility that the introduction of climate change policy in the United States could change the level of investment in foreign production capacity, and thus the structure of import supply. We revisit this issue in section 6.

5.4 Environmental parameters

The environmental parameters in the model are the social discount factor β^S, the social cost of carbon τ and the emissions rates of the plants.

Given the uncertainty inherent in the estimation of damages from carbon emissions, it is important to consider a range of values of τ. The range of values we choose to consider, \$5 to \$65 per ton of CO_2, is informed by a landmark interagency process which produced estimates of the social cost of carbon (SCC) for use in policy analysis (Greenstone et al., 2011). Appendix F discusses the outcomes of this process.

For expositional ease, we will assume that the carbon price reflects the true social cost of carbon. Thus, the carbon tax or permit price and the social cost of carbon are assumed to be one

[31] When analyzing the impacts of environmental regulations, the US EPA assumes an import supply elasticity of 3.94 for the cement sector based on Burtraw et al (2010). There are a number of reasons why our import supply elasticity estimate is smaller than estimates constructed by Burtraw et al (2010). These authors use weighted 2SLS, versus LIML, to estimate a very similar import supply specification. Whereas we use data on all cement imports, Burtraw et al. use data on imports from the 5 largest trade partners and drop data on small shipments. Weights are inversely proportional to the size of the shipment.

[32] This is intuitive as the costs of the domestic industry increase in the counterfactuals considered, which weakly raises the market price.

and the same. In section 7, we conduct auxiliary analysis in which we hold the assumed SCC value constant across scenarios associated with different permit prices/tax levels.

Although data limitations prevent us from estimating emissions intensities specific to each kiln in the data set, we can estimate technology-specific emissions rates. Both the IPCC and the World Business Council for Sustainable Development's Cement Sustainability Initiative (WBC, 2005) have developed protocols for estimating emissions from clinker production. We use these protocols to generate technology-specific estimates of carbon dioxide emissions rates. The Appendix C explains these emissions rate calculations in more detail. The emissions rate on imported cement, e_M, is estimated using an import volume weighted average of estimated foreign cement producers' emissions intensities (Worrell et al., 2001).

6 Simulation results

In what follows, we have elected to report simulation results for the range of SCC values that have been deemed policy relevant. However, it is important to keep in mind that the higher the carbon price we consider, the farther out counterfactual is from the data we observe, and the more sensitive our simulation results will be to our modeling assumptions. That said, we believe that our results both help illustrate the general forces shaping the interaction of market structure and carbon regulation and provide the best possible estimates of efficiency and distributional welfare effects under a range of policies.

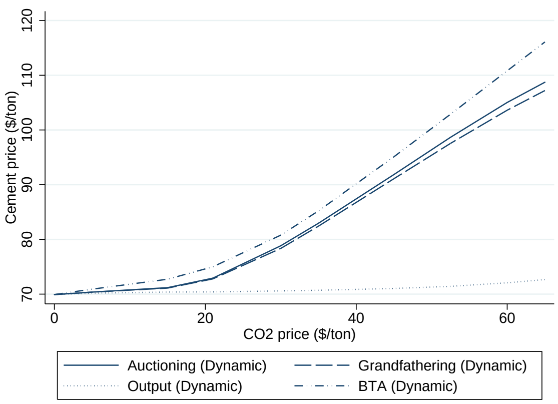
This section begins with a summary of the policy simulations that account for industry dynamics. We then contrast our three welfare measures across the static and dynamic simulation exercises. We discuss the implications for optimal carbon prices and a section that highlights the heterogeneous impacts of the policy across markets. We conclude with additional experiments and considerations.

6.1 Market outcomes

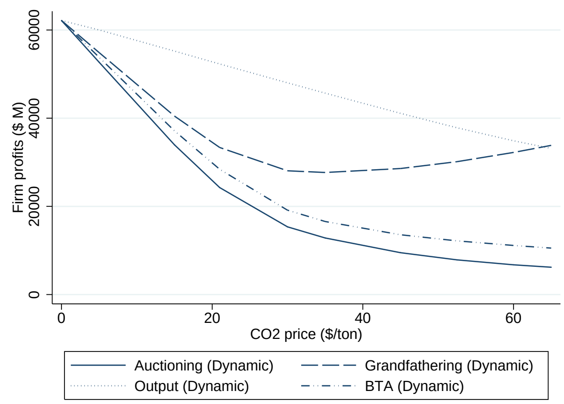
Cement prices Figure 3a plots quantity-weighted average cement prices as a function of the exogenous permit price (or emissions tax) τ. The introduction of market-based emissions regulation increases equilibrium cement prices across the range of τ values we consider. Cement price increases are most pronounced under the auction/tax regime that incorporates a border tax adjustment. Under this policy, domestic firms must bear the complete cost of compliance; no compensation in the form of contingent rebates or lump sum transfers is offered. The tax adjustment ensures that both domestic and international firms face the full cost of the emissions.

Figure 3: Market Outcomes

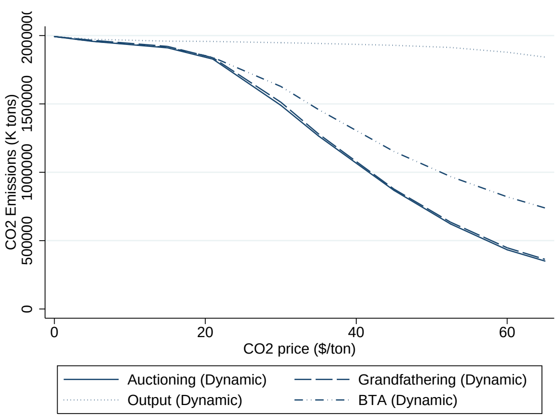
(a) Counterfactual Cement Prices



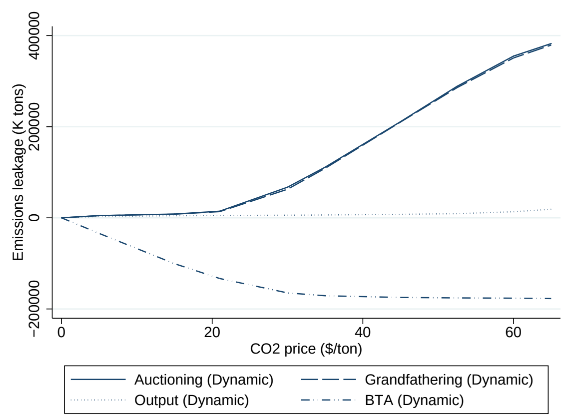
(b) Counterfactual Industry Profits



(c) Counterfactual Domestic Emissions



(d) Counterfactual Emissions Leakage



Note that equilibrium cement prices under the auctioning regime exceed those under grandfathering. Thus, the so-called independence property fails to hold when industry dynamics are incorporated into the model. Under the grandfathering regime, an incumbent firm receives a lump sum transfer each period in the form of free permit allocation. The firm forfeits this entitlement when it chooses to exit. This lowers the exit threshold for incumbents such that exit rates are lower under grandfathering as compared to auctioning. Under the grandfathering regime, cement markets are less concentrated at higher permit prices, and equilibrium cement prices are lower compared to the standard auctioning/emissions tax case.

One striking feature of Figure 3a is that, for a given value of τ, cement prices are much lower under the policy regime that incorporates the output-based rebating. The production subsidy that is implicitly conferred by rebating refunds a significant share of the per-unit compliance costs, thus mitigating the impact of the emissions regulation on cement prices.

Finally, this figure and figures to follow will reveal a lack of industry response to carbon prices below \$20/ton. In the benchmark unregulated case, many domestic firms are capacity constrained and earning scarcity rents. When firms experience a relatively small increase in variable operating costs (such as that induced by a carbon price below \$20), output decisions are virtually unaffected in the short run, although profits are impacted.

Industry profits Figure 3b plots the present discounted profits earned by the regulated domestic cement producers over the range of carbon values we consider. For any given value of τ, profits are most significantly impacted by the auctioning regime because firms must pay the tax (or hold permits) to offset emissions, but receive no rebate or compensation for incurring these costs. The BTA mitigates the loss of domestic market share to foreign producers, thus reducing impacts on domestic producer profits.

Note that discounted industry profits are increasing with τ over the range of higher carbon values in the grandfathering regime. As the carbon price increases, so does the value of the lump sum transfer (in the form of free permits) allocated to incumbent firms. At very high permit prices, some firms will have an incentive to sell permits versus using them to offset their own emissions. This revenue from selling unused permits explains the non-monotonic relationship between domestic profits and the carbon price.

Under dynamic allocation updating, the value of the permit endowment per unit of output scales linearly with τ. Recall that this policy has minimal impact on cement prices (or domestic production). Thus, domestic industry profits are decreasing linearly in τ under the regime that incorporates the contingent rebate.

Domestic emissions Policy makers are very concerned about how industry emissions will be impacted by alternative forms of market-based emissions regulation. Figure 3c shows how emissions from domestic cement producers, summed across all markets and time periods, decreases with τ.

For a given carbon price, the net cost of emitting carbon dioxide (as perceived by firms), is highest under the auctioning regime and lowest under contingent rebating. Consequently, industry emissions are lowest under the auctioning regime and highest under the rebating regime. To the extent that exit rates are lower under the grandfathering regime versus auctioning, domestic production and associated emissions are higher. Augmenting the auctioning regime with a border tax adjustment mitigates the impact of the policy on domestic market share. This increases both domestic production levels and emissions.

Emissions leakage Figure 3d plots the simulated leakage under the four policy regimes we consider. These results suggest that there is potential for significant leakage in the US cement industry. Intuitively, auctioning leads to the highest amount of leakage because it places the highest cost burden on domestic producers. In the long-run, the policy-induced increase in operating costs affects both the intensive margin through reduced production and the extensive margin through accelerated firm exit. In line with the earlier discussion, grandfathering slows the rate of exit vis a vis auctioning, thus slowing the rate of leakage. In line with intuition, output-based rebating significantly reduces the net cost of compliance per unit of output, limiting the extent to which imports outcompete domestic production in trade exposed markets, and virtually eliminating emissions leakage.

Perhaps the most striking result illustrated by Figure 3d is the *negative* leakage under the tax regime that incorporates the border tax adjustment. In other words, the introduction of this policy reduces emissions among foreign producers. To understand why this occurs, recall that these imports are assumed to behave competitively, such that pass through of environmental compliance costs is complete. In contrast, pass though of environmental compliance costs among strategic domestic producers is incomplete. Consequently, when emissions from domestic and foreign producers are penalized at the same rate, the introduction of the emissions policy results in a decrease in the share of the domestic market served by imports. In this case, this implies significant negative leakage.

6.2 Decomposing Changes in Welfare

Our fundamental objective is to investigate the welfare implications of the alternative policy designs we consider. In what follows, the unregulated, emissions-unconstrained case serves as a benchmark. We present the three welfare metrics introduced in the previous section, successively layering in the following components: first, product market welfare consisting of producer profits, consumer surplus, and government revenues (W1); second, benefits accruing to emissions reductions (W2); and finally, costs due to emissions leakage (W3).

To highlight the importance of accounting for industry dynamics, we contrast the results of our dynamic simulations with a simulation exercise that holds fixed industry structure and technology characteristics. A common practice in ex ante policy analysis involves simulating regulatory effects in a static setting, using a representative year as the basis for estimating annual regulatory impacts, and then using that test year to extrapolate outcomes over a longer time horizon (OAQPS, 1999). We adopt this approach here. To generate our "static" results, we simulate a single period market outcome in the unregulated baseline case and under the range of counterfactual policy designs we consider. To facilitate comparisons with our dynamic simulations, these results are expressed as net present values using a social discount rate of three percent. We assume the simulated annual outcomes would be observed each year of the 30 year time horizon we consider.

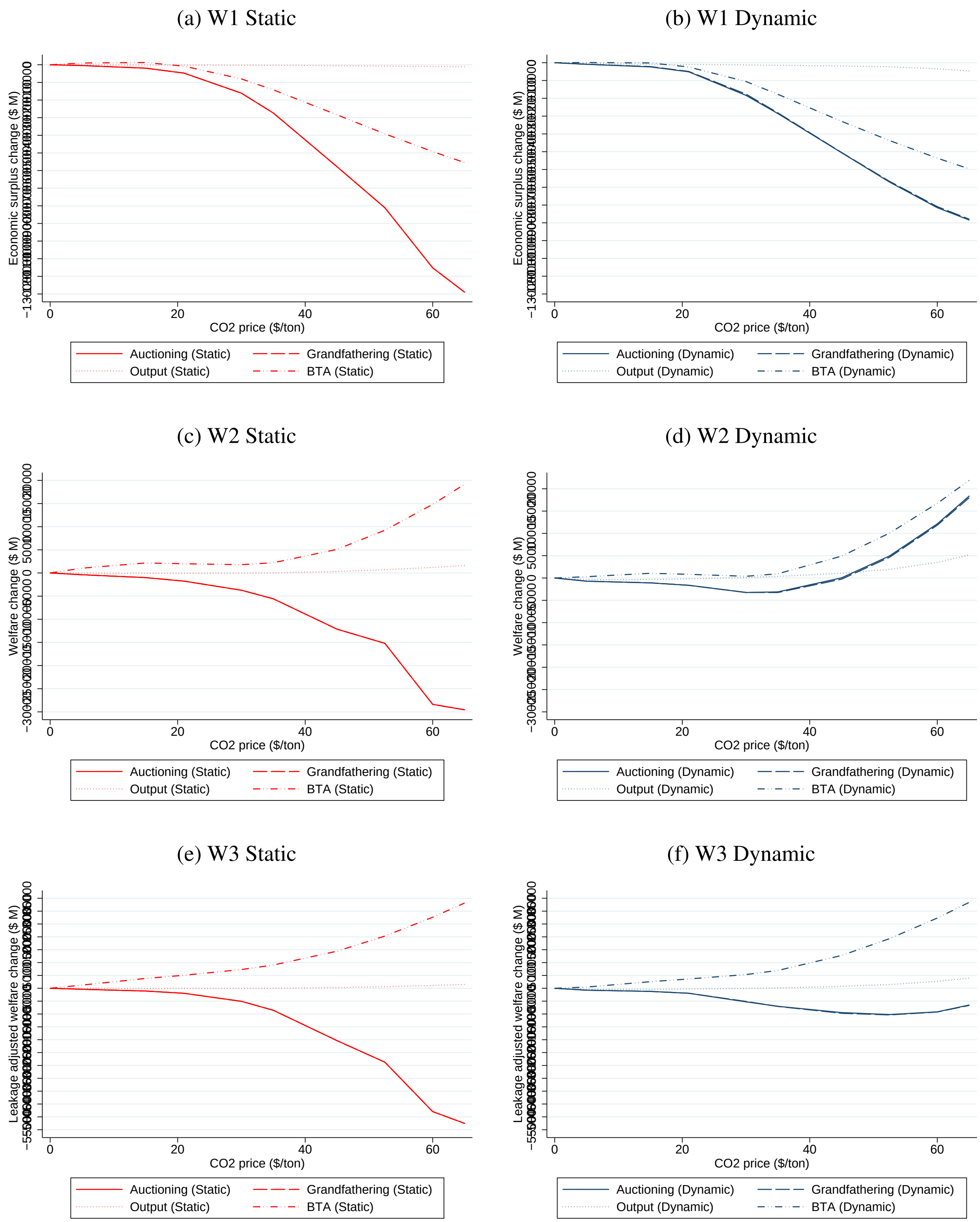
W1: Product Market Surplus Changes in the first welfare metric, W1, capture differences in producer and consumer surplus while also accounting for revenues raised by the government through taxation or permit sales.

Figure 4a summarizes short-run, static impacts on domestic economic surplus. Given that this W1 measure captures none of the benefits from emissions abatement, these impacts are all negative. Impacts are most significant under grandfathering and auctioning regimes. In these static simulations, note that outcomes under the auctioning and grandfathering regimes exhibit the independence property: for any given carbon price, impacts on W1 are identical. Intuitively, this is because the short run incentives in production are identical across these two regimes. The border tax adjustment mitigates impacts on domestic economic surplus, primarily due to the tax revenues collected from foreign producers which mitigates leakage of rents.

Comparisons across static and dynamic simulations highlight how the evolution of industry structure can affect policy outcomes. There are two differences worth highlighting. First, over the upper range of the carbon values we consider, incorporating industry dynamics leads mitigates the impacts of emissions regulation (the grandfathering and auctioning regimes in particular) on domestic economic surplus. In the dynamic model, firms can adjust capacities, invest in cleaner production technologies, etc. This re-optimization response is shut off in the static case.

Finally, whereas outcomes under grandfathering and auctioning are indistinguishable in the static case, we see some differences in the dynamic simulations at higher carbon prices. Firms

Figure 4: Welfare Measures across Mechanisms



receiving a lump sum allocation hold an increasingly valuable resource as carbon prices rise. This creates an incentive for firms to remain in the market (versus exiting) because they would otherwise forfeit their entitlements to free permits in the future.

W2: Domestic Emissions Abatement Welfare measure W2, summarized in Figures 4c and 4d, adds the social benefits associated with reducing CO_2 emissions from domestic cement producers to the impacts on domestic economic surplus captured by W1. Recall that the value of the avoided emissions are assumed to be equal to the prevailing permit price or tax. Thus, the welfare adjustment per unit of emissions abated is increasing along the horizontal axis of Figures 4c and 4d.

Beginning with the static simulations, the benefits from internalizing the emissions externality offset the economic costs under the policy regime that incorporates the border tax adjustment across all carbon values. The same cannot be said for the grandfathering and auctioning regimes. The discontinuity observed above a carbon value of $40/ton occurs because the domestic market becomes fully saturated by imports. Beyond this point, any increase in the carbon price reduces domestic economic surplus, but has no impact on domestic emissions.

The dynamic simulations yield somewhat different results. At higher carbon values, the welfare ordering of policy regimes differs across the static and dynamic simulations. More precisely, policy induced changes in this W2 measure are more positive under grandfathering and auctioning as compared to the policy that incorporates dynamic, output-based updating of permit allocations. The factors that made auctioning and grandfathering unattractive under metric W1 (namely, output contraction and the accelerated exit of domestic producers) make them relatively attractive under metric W2 once we account for the benefit of carbon emissions reductions.

W3: Emissions Leakage Our final welfare metric, W3, augments W2 by accounting for damages associated with emissions leakage. Emissions occurring in other jurisdictions are penalized at the same rate as domestic emissions.[33]

Figures 4e and 4f illustrate the welfare impacts of the policy regimes we consider using this more comprehensive welfare measure. In the static simulations, once leakage is accounted for, welfare losses decline steadily as carbon price rises under grandfathering and auctioning regimes. In contrast, accounting for negative leakage under the regime that incorporates a border tax adjustment results in a steeper increase in welfare gains at high carbon values.

[33] Ignoring co-pollutants, damages from emissions are independent of location. This contrasts to other emissions that have spatially-varying damages. See, for example, Fowlie and Muller (2010).

In the dynamic simulations, accounting for the damages caused by emissions among foreign producers supplying the domestic market pushes net welfare impacts of grandfathering and auctioning policies back into the negative domain over the range of carbon values we evaluate. The welfare ordering of policy regimes no longer reverses across the static and dynamic simulations at higher carbon values.

6.3 Policy comparisons under optimal carbon prices

One important assumption that we have maintained throughout our analysis is that the permit price equals the social cost of carbon. Our results demonstrate how the negative welfare effects of fully internalizing the emissions externality can outweigh the benefits from emissions when emissions intensive producers exercise market power. Exposure to competitive, unregulated imports makes matters worse. As a result, a policy maker looking to maximize welfare will want to set a permit price that is somewhat less than the true social cost. This insight helps explain why a regime that dynamically updates permit allocations to domestic producers based on output welfare dominates a regime that allocates permits to domestic producers in lump sum. Dynamic allocation updating confers an implicit production subsidy to the industry which lowers the effective cost per unit of emissions (as perceived by domestic firms) below the social marginal cost.

Across the four policy regimes we consider, we identify the permit price that maximizes our most comprehensive welfare measure (W3) for a given value of the true social cost of carbon (measured in $ per ton of CO_2). Table 3 reports the welfare maximizing price in Column 1 (in this working paper, this price is selected from a limited number of possible values). The welfare change that results if carbon is priced optimally is reported in Column 2. Column 3 reports the welfare change that results if the permit price is instead constrained to equal the assumed SCC. We repeat this exercise for three values of the true social cost of carbon ($21, $35, $60).

In Column 2 of Table 3, we see that all policy regimes deliver positive welfare gains if the permit price is set optimally. In other words, cost-effective emissions abatement opportunities do exist in the cement industry. Intuitively, the largest gains from releasing the restriction that the permit price equal the SCC manifest in the auctioning and grandfathering regimes. In these cases, the optimal permit price falls well below the true cost of carbon in order to strike the right balance between incentivizing abatement and exacerbating the distortions associated with the exercise of market power and the asymmetric treatment of domestic and foreign emissions. In the auctioning and grandfathering regimes, setting a permit price below the SCC is very similar to coupling a permit price constrained to equal the SCC with a production subsidy. Thus, welfare outcomes under grandfathering and auctioning are very similar to those realized under the regime that incorporates

Table 3: Optimal carbon prices for different mechanisms

	Optimal Carbon Price ($)	Welfare if Optimal Carbon Price (M$)	Welfare if Carbon Price = SCC (M$)
SCC = $ 21			
Auctioning	0.0	0.0	-1933.6
Grandfather	0.0	0.0	-1927.8
Output	0.0	0.0	-295.0
BTA	15.0	3644.4	3620.8
SCC = $ 35			
Auctioning	15.0	271.6	-7003.8
Grandfather	15.0	95.7	-7053.8
Output	52.5	214.7	140.3
BTA	30.0	7981.4	6941.1
SCC = $ 60			
Auctioning	35.0	8411.3	-9152.4
Grandfather	35.0	8044.7	-9201.3
Output	65.0	3302.6	2704.5
BTA	52.5	28306.6	27330.6

Notes: Table for a subset of regional markets with four or less firms. Optimal carbon prices computed on a grid including {0,5,15,21,30,35,45,52.5,60,65}.

output-based updating of permit allocations. [34]

Augmenting the auctioning regime with a border tax adjustment efficiently internalizes the emissions externality associated with foreign production, but it is still the case that a price signal below the true SCC is required in order to account for strategic behavior in the domestic market. In order to efficiently incentivize this abatement, policies must be designed to account for the other market failures and distortions in play.

Finally, note that the optimal carbon price under the regime that incorporates dynamic allocation updating can be used to derive the optimal subsidy. For example, when the true social cost of carbon is assumed to be $35/ton, the optimal rebate refunds approximately 56 percent, versus 71 percent, of compliance costs per unit of output.[35]

[34] Differences across auctioning, grandfathering, and the dynamic updating regimes in column 2 are largely an artifact of the restricted set of carbon prices we consider in this optimization exercise.

[35] To see this, note that firms pay $52.5(1-0.71) under the optimal carbon price. This translates to approximately 43.5 percent of the true social cost of carbon.

6.4 Additional experiments and robustness checks

Demand and import elasticities Demand and import supply elasticities play an important role in our policy simulations and welfare comparisons. Unfortunately, publicly available data on producer prices, production quantities, import quantities, etc. are quite noisy. This results in elasticity estimates which are imprecise. In order to assess the robustness of our results, we simulate a subset of markets using a range of elasticity values.

The demand elasticity is a key determinant of the consumer gross surplus in the model and therefore an important element in our welfare measures. The qualitative results are robust to a wide range of demand elasticity values. Table E in Appendix E presents W3 welfare differences for a range of carbon prices and demand elasticities. As one would expect, we find that the negative effects are more striking when demand is more inelastic, due to the Buchanan effect. Negative values are attenuated, or turn positive, for more elastic demand curves.

We also consider a wide range of import supply elasticities. One limitation of our modeling approach is that we assume the import supply elasticity is an exogenous parameter. In other words, we fail to account for the possibility that importing firms could respond to increasing domestic cement prices by expanding investment in import terminals, foreign production capacity, or improved transport practices. By allowing for a more or less responsive supply curve, we capture (albeit crudely) these kinds of responses. Overall, we find that the qualitative results are unaffected by changing the import supply elasticity. An import supply that is more elastic tends to magnify the leakage concerns, specially under grandfathering and auctioning, which are not policies designed to mitigate the leaks.

Differential Changes in Cement Substitutes Table E also helps us address questions about how the outside options for cement consumption change as the carbon price increases. A potential concern with our approach is that our model effectively holds constant demand shifters. A carbon tax or cap and trade program would affect the supply markets for substitutes to cement in different ways. For example, asphalt is a substitute for cement in paving applications, and an important issue is whether or not that product will become differentially more or less expensive than cement as the price of carbon increases.

Explicitly modeling these inter-market interactions would involve the specification and estimation of a more general equilibrium model. This is well outside the scope of this paper. However, one can use Table E to get a rough idea of how our results may change. If it is believed that cement will become differentially more expensive as carbon prices rise, one can simply start the baseline elasticity at the zero carbon price and trace down the table, letting the elasticity increase with the carbon price. While this is not as satisfying as an exercise that explicitly models interactions between climate policy and markets for cement substitutes, it is at least a simple way or representing the degree of sensitivity of our results to our partial equilibrium modeling assumptions.

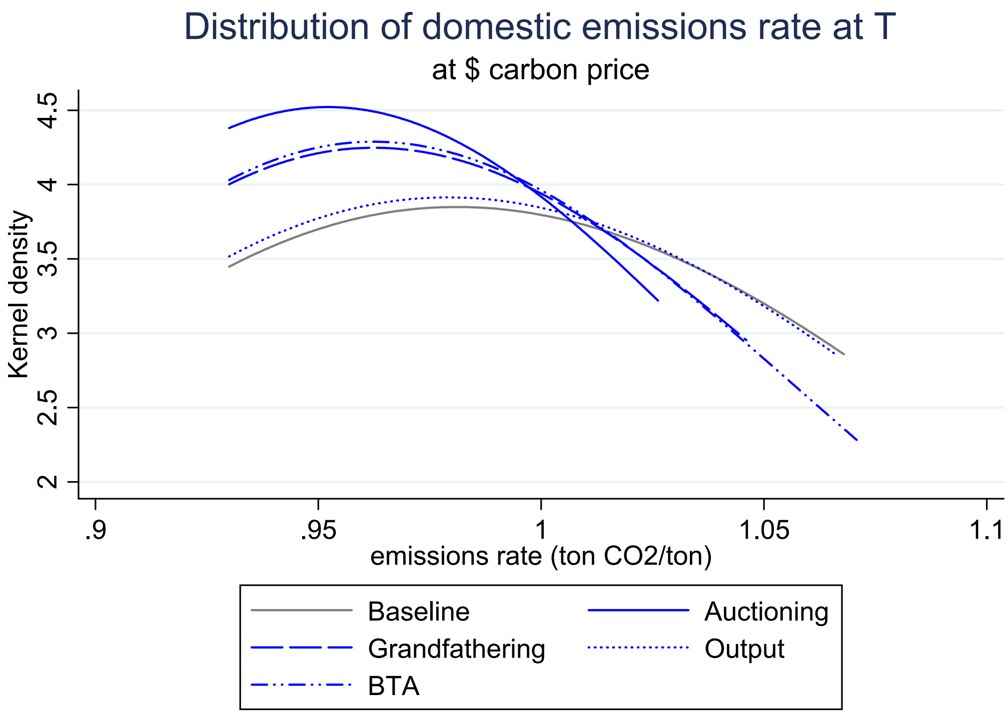
In general, if cement demand becomes more inelastic with carbon prices, the negative welfare results tend to increasingly hold. On the other hand, if cement becomes more elastic, then the benefits of implementing carbon schemes in the cement industry become increasingly welfare-improving, primarily as the Buchanan welfare effects are relatively smaller.

Heterogeneous impacts of environmental regulation The simulation results allow us to examine the impact of a federal environmental regulation on local markets that are differentially exposed to international competition. In the debates over carbon policy design and implementation, it is typically assumed that different industries will be treated differently (in terms of permit allocations, compliance requirements, etc.). But it is generally assumed that domestic firms within a given sector will be treated symmetrically. For example, in the case of the cement industry, implicit output-based updating mechanisms would be implemented in the same way across all regional cement markets. However, given the differences in the industry composition of local markets, as well as the differences in trade exposure, the costs associated with a uniform federal policy can significantly differ across regions.

It is straightforward to compare outcomes across trade-exposed and inland markets. We find that prices increase more rapidly in inland markets, as firms do not face competition from imports and can more readily pass environmental compliance costs through to consumers. The effect is particularly striking at higher carbon prices, in which some coastal markets reach a threshold carbon price beyond which all local demand is served by imports from unregulated areas. This does not happen in inland markets facing no competition from imports. As a consequence, firm profits are more negatively impacted in trade exposed regions. Although this is a quite extreme finding, it highlights one of the major differences between coastal and inland markets.

The welfare impacts across coastal and inland markets are also systematically different. Consumer surplus is more significantly impacted in inland markets. Intuitively, the existence of import competition limits the extent to which domestic producers can pass-through compliance costs. Reductions in domestic producer profits and emissions leakage works against these coastal markets. The overall welfare impact tends to be more negative in coastal markets, except for the BTA scheme.

Figure 5: Distribution of Emissions Rate across Counterfactuals



Technological change Our model captures in a coarse way the evolution of technological improvements through entry by more efficient plants and/or exit of dirty plants. Figure 5 represents the distribution of plant-level emissions rates in the final time period. Under the baseline case (i.e. no emissions regulation), the average capacity weighted emissions intensity is just below 1 ton $CO_2/$ ton clinker. Under a carbon price of $35/ton, the most significant shift in this distribution occurs under the auctioning regime. As older, dirtier kilns exit, and some production is reallocated from relatively high emitting to relatively low emitting domestic producers, the average domestic emissions intensity falls. This shift is far less pronounced under the regime that incorporates dynamic updating. As discussed above, updating mitigates the cost to offset a ton of emissions, thus slowing the rate of exit and capital turnover vis a vis other policy designs.

Limitations Our analysis is predicated on the premise that our structural assumptions, including assumptions about how firms respond to changes in policy incentives, will hold out of sample. We observe significant variation in plausibly exogenous supply and demand shifters across regional markets and across time; this variation is essential to identification. However, our inferences at high carbon prices are quite far from historical experience. To put this in context, consider that a carbon price of $60/ton would more than double the estimated marginal operating costs of the average cement producer. A higher-level concern is that plausible general equilibrium effects of high carbon prices could lead to unforeseen structural shifts in the supply and demand curves characterizing cement outcomes. In sum, the farther out counterfactual is from the data we observe, the more sensitive our simulation results will be to our modeling assumptions.

Finally, data limitations prevent us from estimating market-specific demand and cost parameters. For example, we will use the same average demand elasticity parameter in all regional market simulations, which might trigger immediate investment responses in some markets. In a sense, some markets appear to be in transition at the baseline simulations. To deal with this issue, we first simulate outcomes in each regional market with no carbon policy in place for one period so that capacity levels can adjust to demand if needed. Once these investments have been made, we introduce the carbon policy. This approach is intended to separate the effects of possible misspecification in the model and estimates, which can introduce a non-linear error term, from the effects of the counterfactual policy.[36]

7 Conclusion

We use an empirically tractable dynamic model of the US Portland cement industry to evaluate the welfare impacts of incomplete, market-based regulation of carbon dioxide emissions. We assess the implications of several alternative policy designs, including those that incorporate both an emissions disincentive (a tax or an obligation to hold an emissions permit) and a production incentive.

We find that both the magnitude and the sign of the welfare impacts we estimate depend significantly on how the policy is implemented and what we assume for the social cost of carbon. Under market-based policy regimes that incorporate neither a border tax adjustment nor an implicit production subsidy, our results echo Buchanan (1969). At low to moderate carbon prices, market-based emissions regulation that internalizes the full emissions externality exacerbates the distortions associated with the exercise of market power in the domestic product market to such an extent that reductions in domestic economic surplus exceed the benefits of emissions reductions. Emissions leakage in trade exposed regional markets further undermines the benefits of these pro-

[36] Running the model without this adjustment generates similar qualitative results. If anything, the negative welfare effects from cap-and-trade are exacerbated in these additional counterfactuals. At low carbon prices, welfare can turn negative for all policies considered. The intuition is that small carbon prices can depress investment in these "growing markets," while the scope for environmental benefits (at low carbon prices) is still limited.

grams, to the point that net welfare impacts are negative over the full range of carbon values we consider.

Notably, we find that policy designs that incorporate both an emissions penalty and a production incentive in the form of a rebate welfare dominate more traditional policy designs. Intuitively, the production incentive works to mitigate leakage in trade exposed cement markets and the distortion associated with the exercise of market power. A policy that penalizes emissions embodied in foreign imports induces *negative* leakage given our assumption that imports respond competitively, whereas domestic producers behave strategically. Consequently, this policy delivers sizeable welfare gains at high carbon values.

Policy makers are very interested in understanding how proposed climate change policies would impact strategic, emissions intensive sectors such as the cement industry. The scale and scope of these policy interventions are unprecedented, making it difficult to anticipate how industry will respond and what that response will imply for social welfare. This paper illustrates important forces that shape the interaction of industry structure, trade flows, and proposed carbon regulations. Simulation results provide important insights into the efficiency and distributional properties of leading policy design alternatives.

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