MARKET-BASED EMISSIONS REGULATION AND INDUSTRY DYNAMICS

Meredith Fowlie
Mar Reguant
Stephen P. Ryan

Working Paper 18645
http://www.nber.org/papers/w18645

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
December 2012

The authors gratefully acknowledge the support of NSF grant SES-0922401. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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JEL No. L5,Q5

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Meredith Fowlie
Department of Agricultural & Resource Economics
University of California, Berkeley
301 Giannini Hall
Berkeley, CA 94720-3310
and NBER
fowlie@berkeley.edu

Mar Reguant
Knight Management Center
Stanford Graduate School of Business
655 Knight Way
Stanford, CA 94305
and NBER
mreguant@stanford.edu

Stephen P. Ryan
Department of Economics
University of Texas at Austin
BRB 3.134D
2225 Speedway Stop C3100
Austin, TX 78712-1690
and NBER
sryan@utexas.edu

An online appendix is available at:
http://www.nber.org/data-appendix/w18645

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

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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 policy designs, 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 result in social welfare losses under policy regimes that fully internalize the emissions externality. In contrast, market-based policies that incorporate design features to mitigate the exercise of market power and emissions leakage can deliver 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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[*] UC Berkeley and NBER, Stanford GSB and NBER, and University of Texas at Austin and NBER. We thank Brian Copeland, Larry Goulder, Tom Holmes, Ryan Kellogg, Alberto Salvo, James Schmitz, and numerous seminar participants for very useful comments. The authors gratefully acknowledge the support of NSF grant SES-0922401.

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, many of the industries currently regulated under existing and planned emissions regulations 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 emissions 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

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[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. 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 sectors 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. 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 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.

Our model is estimated using twenty five years of detailed data on the Portland cement industry.

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[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] We assume that the government auctions off any permits that are not allocated for free.

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

In the benchmark model we estimate, GHG emissions are unconstrained. We use this model to simulate the dynamic industry response to counterfactual emissions regulations. 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 penalizes imports according to their average carbon content rate.

Our primary finding is that an emissions trading program that requires domestic firms to fully internalize the emissions externality would induce significant social welfare *losses* over a wide range of carbon damage values.[6] Echoing Buchanan (1969), the combination of welfare losses associated with the increased exercise of market power in the product market and/or increased foreign emissions in scenarios without border tax adjustments exceed the benefits of carbon mitigation. Losses are particularly acute for the auction/carbon tax scenario, as firms face the highest cost burden in this scenario. These costs induce firms to exit and disinvest, which further concentrates the ownership of productive capacity in the product market. The magnitude of the losses is substantial, with an average welfare loss on the order of several billion dollars. Schemes that adjust free permit allocations dynamically contingent upon cement production generally do best; the implicit production subsidy helps mitigate losses in the product market. At higher prices, border tax adjustments welfare dominate, as this tax on imports controls the flow of production to unregulated jurisdictions, becoming a cost-effective mechanism for reducing overall carbon emissions.

In theory, these policy-induced welfare losses could turn to gains if the social cost of carbon is only partially internalized by firms. Output-based, dynamic permit allocation updating embeds this idea, as firms face only a fraction of their true compliance costs. More directly, a policy maker could design a policy that ensures the permit price falls below the social cost of carbon. To investigate this, we solve for the optimal level of carbon prices, and the associated level of welfare gains, under the various regimes we consider. For a social cost of carbon of $21 per ton, we find the optimal permit price in all schemes is zero, as the product market losses dominate any gains from carbon mitigation at this social cost. At a higher social cost of carbon ($55 per ton), welfare gains can be achieved by allowing the permit price to vary from the social cost.

Finally, our results underscore the importance of accounting for dynamic industry responses to market-based emissions policies. To demonstrate this, we contrast our dynamic model with a static modeling framework in which firms can alter production levels, but industry structure

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[6] 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.

(i.e. technological characteristics, production capacities, etc.) is held fixed. These two modeling frameworks imply very different welfare impacts. Consider the case of a carbon price \$21 per ton (the current U.S. standard in monetizing the social costs of carbon). At this price, the static model predicts equivalent, negative, and negligible welfare impacts under the grandfathering and auctioning regimes. If firms cannot adjust production capacity in response to this carbon price, the domestic production response is minimal. These small, negative welfare impacts turn positive with the imposition of a border tax adjustment, due to positive terms-of-trade effects. These results contrast starkly with the dynamic model, which predicts welfare losses in excess of one billion dollars under auctioning. Firms disinvest in response to the policy-induced increase in operating costs, which in turn greatly exacerbates the distortions associated with the exercise of market power. Notably, equilibrium outcomes differ substantively across grandfathering and auctioning regimes. Because grandfathered permit endowments depend on installed capacity, disinvestment is significantly attenuated under grandfathering, and the negative welfare impacts are reduced. In contrast to the static case, the grandfathering regime welfare dominates the BTA regime at a carbon price of \$21.

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." Very 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 (e.g. Conrad and Wang (1993); Lee (1999); Requate (2005); Sengupta (2010)) or numerical simulation models (e.g. Fischer and Fox (2007); Jensen and Rasmussen (2000); Walton (1996, 2009)).

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. 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 a 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

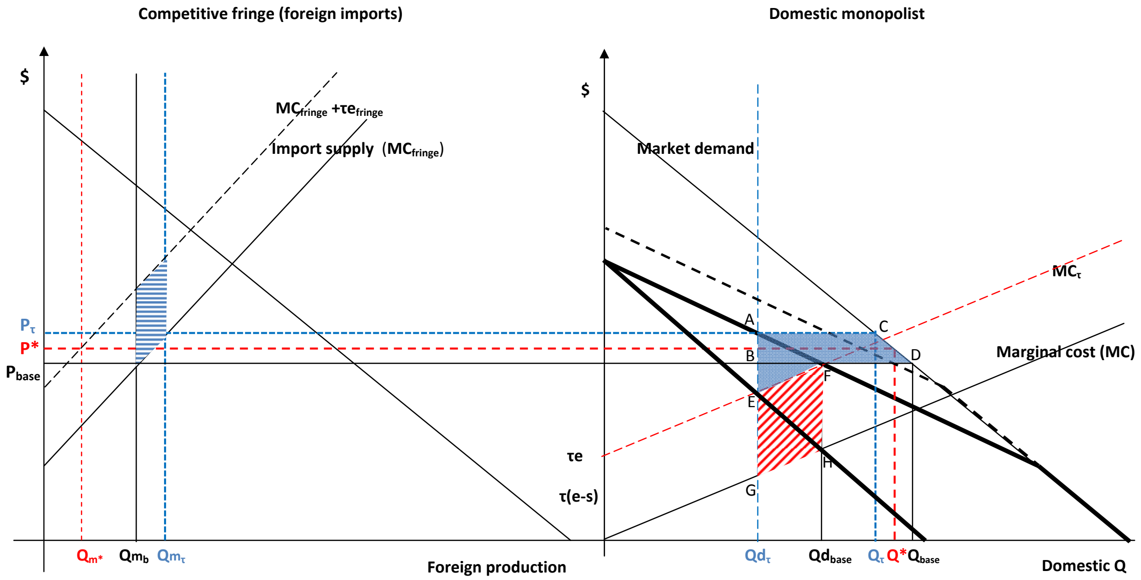
To build some intuition for the basic economic forces at work in our empirical setting, we first present a simple, static model. Figure 1 shows a domestic monopoly producer (right panel) facing a competitive fringe of importers (left panel). The thick black, kinked line in the right panel represents the residual demand curve faced by a domestic monopolist. This curve is constructed by subtracting the import supply curve from the market aggregate demand curve. The thick black line below it represents the corresponding marginal revenue curve.

Absent any emissions regulation, the domestic monopolist sets residual marginal revenue equal to marginal cost and produces output Qd_{base} at price P_{base}. Foreign producers supply Qm_{base} at this price. This is the baseline 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.

Now suppose that 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.

Figure 1: Emissions-Intensive, Trade-Exposed Monopoly



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 socially 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 is a price-taker and permits are either auctioned or allocated lump sum for free, as in grandfathering.

Figure 1 illustrates how this emissions regulation can *reduce* welfare (consistent with the theory of the second best). Intuitively, the costs associated with further exacerbating the exercise of market power in the domestic market 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. The policy-induced reduction in consumer surplus that is not transferred to domestic producers is represented by area $ABCD$. In this trade-exposed market, the introduction of the emissions regulation increases the import market share. This induces "rent leakage," or transfer of surplus from domestic to foreign stakeholders. 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. Policy-induced reductions in domestic producer surplus that are not transferred to the government as tax revenue are given by $BGHF$.

Of course, the primary purpose of the emissions policy is to reduce emissions and associated damages. The value of the emissions reductions achieved domestically is represented by area $EFGH$ (shaded with diagonal lines) in the right panel of Figure 1. In this case, the policy-induced loss in domestic economic surplus exceeds this value by an amount represented by the shaded area $AEFCD$.

A comprehensive measure of the welfare impact must also account for the impacts of the policy on foreign emissions. Here we assume that the policy-induced increase in import supply is met entirely by an increase in foreign production levels (versus a reallocation of foreign production across jurisdictions). Emissions leakage is represented by the shaded region in the left panel.

Taken together, the total welfare loss induced by the policy is represented by area $AEFDC$ plus the damages associated with emissions leakage (represented by the shaded area in the left panel).

Although a complete internalization of the carbon externality by domestic producers results in a net welfare loss in Figure 1, this is not always the case in an industrial context characterized by both imperfect competition and exposure to competition from unregulated imports. As the marginal social cost of emissions increases and/or the import supply responsiveness attenuates, the policy-induced benefits, such as reduced emissions damages, can outweigh the costs such as foregone 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. This policy feature alleviates the market power distortion by stimulating domestic output, while also mitigating, or even eliminating, emissions and rent leakage. It has traditionally 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.[7]

Figure 1 depicts the equilibrium outcome under a market-based emissions regulation that augments the emissions fee τ with an output-based rebate (or subsidy) s. The production subsidy incentivizes an increase in domestic production (domestic output is $Qd_{\tau-s}$). In addition to mitigating the exercise of market power, rent and emissions leakage are reduced because the subsidy acts to improve the terms of trade (vis a vis the regime that administers only the emissions fee).

Although the level of aggregate domestic consumption Q^* and the equilibrium product price P^* in this output-based rebating scenario are equal to those in the first best case, allocative efficiency is not achieved. Foreign imports still capture too much of the domestic market share; the marginal cost of domestic production is much lower than the marginal cost of importers. 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.

In the analysis that follows, we will also consider the possibility of augmenting the emissions fee with a border tax adjustment that penalizes the emissions embodied in imports from unregu-

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[7] For example, in Sweden, revenues from an emissions tax are fully refunded to the industries that paid the tax on the basis of their energy use (Sterner and Hoglund, 2000). In existing and planned emissions trading programs in Australia, California, and Europe, permits are freely allocated to trade-exposed industries on the basis of output.

lated foreign jurisdictions. In principle, a border tax adjustment (BTA) provides a direct means of internalizing emissions from foreign production. In practice, the use of BTAs in this context are intensely controversial.[8]

2.1 Welfare Decomposition

As compared to Figure 1, there will be many more moving parts in our modeling of the dynamic industry response to market-based GHG regulations. Decomposing the net welfare effects of the market-based policies into components will help to highlight the the interplay between the emissions regulation and pre-existing distortions associated with the exercise of market power in regional cement markets.

Changes in domestic economic surplus (W1) The first welfare component captures policy-induced changes in domestic economic surplus. In Figure 1, this component is represented by the sum of area $EFGH$, the loss in consumer surplus that is not transferred to domestic producers, and area $BGHF$, the loss in producer surplus that is not transferred to the government as tax or permit auction revenues. 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.

Changes in damages from domestic industrial emissions (W2) The second welfare component measures changes in the damages associated with domestic industrial emissions. In Figure 1, the value of the emissions reduction induced by the Pigouvian tax is $\tau e \cdot (Qd_b - Qd_\tau)$. This is represented by the diagonally shaded area $EFGH$. 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 $\tau e \cdot (Qd_{\tau-s} - Qd_\tau)$.

As noted above, the emissions charge τ can also be motivated as a permit price in the context of a domestic cap-and-trade program with a fixed and binding cap. Although domestic production levels—and associated emissions—can vary across the policy regimes we consider, we assume that aggregate system-wide emissions are constrained to equal the cap. In other words, any subsidy-induced increase in emissions from the domestic monopolist must be offset by other sources and

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[8] Questions about the legality of BTAs under the law of the WTO, and the potential for trade partner retaliation, are among the factors working to dissuade countries from adopting these measures.

sectors 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.

Emissions leakage (W3) 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.

2.2 Applying the Framework

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 relaxed. We highlight two of these assumptions here.

First, whereas figure 1 features 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.[9]

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 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 con-

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[9] 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).

sider, 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.[10]

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, making it potentially susceptible to the Buchanan critique. The top five companies collectively operate 54.4 percent of U.S. clinker capacity with the largest company representing 15.9 percent 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 and Padovani, 2002; USGS, 2010).

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.

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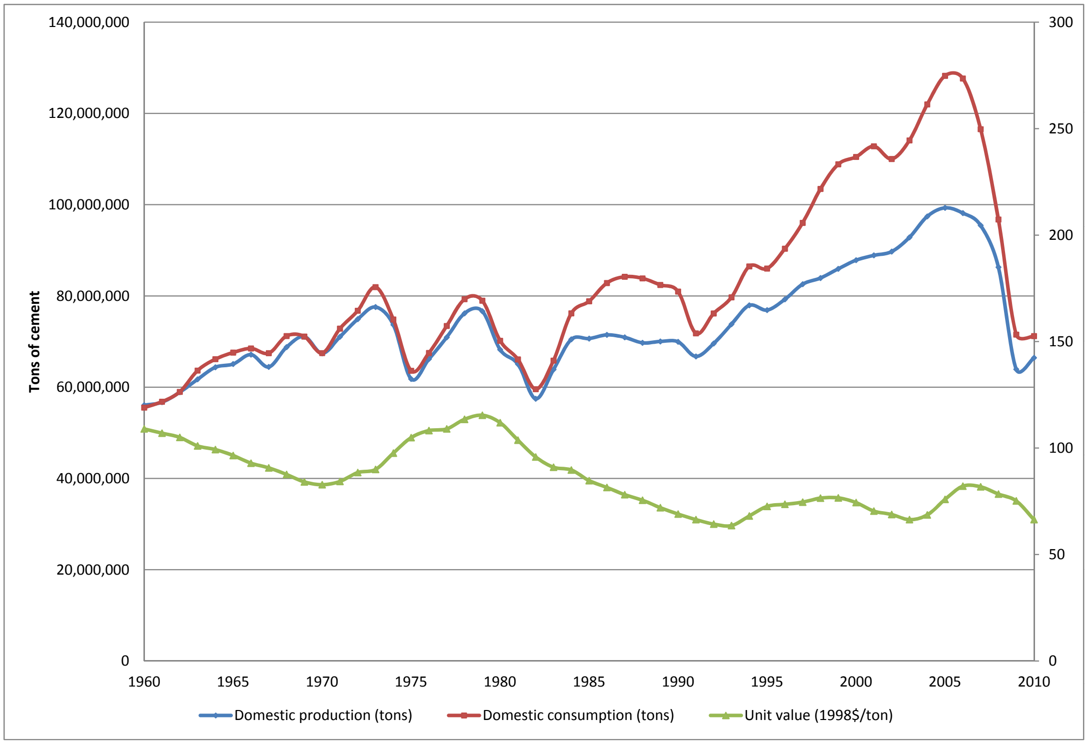
[10] On average, domestic cement producers emit close to one ton of carbon for each ton of cement produced. Marginal costs of cement production are estimated to be in the range of $40/ton (Ryan, 2012).

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



Cement competes in the construction sector with substitutes such as asphalt, clay brick, rammed earth, fiberglass, steel, stone, and wood (Van Oss and Padovani, 2003). 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.[11]

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

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[11] 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; Kapur et al., 2009).

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).[12]

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 run."[13]

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

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[12] 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.

[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.

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.[14] 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, 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.[15] 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 be reduced 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 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,

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[14] 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.

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

and natural pozzolans.[16] 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 and are relatively costly.

Ideally, a model designed to simulate industry response to an emissions regulation would 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.

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.[17] Within our modeling

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[16] 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.

[17] In the context of an economy-wide greenhouse gas emissions trading program, a cap-and-trade program that incorporates auctioning has its proponents. 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

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).[18] In existing and planned emissions trading programs, the majority of permits are distributed *gratis* to regulated firms. This motivates the study of our second policy regime, "grandfathering," where 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.

In recent years, a third design alternative has emerged. Emissions permits are allocated for free to eligible firms using a periodically updated, output-based formula. This dynamic allocation updating is being used to mitigate leakage and associated competitiveness impacts in trade-exposed, emissions-intensive industries.[19] The incentives created by this dynamic allocation updating rule are quite different as compared to those associated with grandfathering or auctioning because updating confers an implicit production subsidy.

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 because it has the potential to play an important role in leakage mitigation.[20]

1, 2007. (testimony of Peter R. Orszag)

[18] 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.

[19] Proposed federal climate change legislation included a provision to allocate permits to eligible industries using an output-based formula. These free allocations were 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). In California's Greenhouse Gas Emissions Trading Program, permits will be allocated for free to firms in trade-exposed industries based on an industry specific efficiency benchmark and lagged production. A similar approach to permit allocation has been incorporated into Phase II of the EU ETS.

[20] 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.

4 Model

The basic building block of the model is a regional cement market.[21] 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, investment and disinvestment. 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 (wet, dry, state-of-the-art dry) in the cement industry. We observe the technology used by existing incumbent producers. We assume all new entrants are endowed with the frontier technology.

Firms obtain revenues from the product market and divestiture. They incur costs from production, entry, and new investment. We model timing as an infinite horizon model with each discrete decision period being one year. Firms 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.[22]

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

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[21] The model borrows heavily from Ryan (2012), to which we add imports, divestment, emissions technologies, differentiated marginal costs, and environmental policies.

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

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.[23] 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 capacity investment decisions:

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

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.[24] 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.

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[23] 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.

[24] 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.

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.[25] Importantly, we assume a constant real carbon price over our relatively short (30 year) time horizon. In our model, there is no technological innovation over time, nor is there economic growth. Thus, some of the standard justifications for implementing a policy regime in which the compliance cost per unit of emissions increases over time do not apply in our case.

The policy designs we analyze can best be classified into one of four categories: auctioning/carbon tax; grandfathering (i.e. lump sum transfer of permits to the firm); output-based rebating; and an auctioning regime augmented with a border-tax adjustment.

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; under our assumption that cement firms are price-takers in the permit market, 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 are determined at the beginning of the program and are based on historic emissions. In particular, firms receive an annual permit allocation equal to 42.5 percent of their emissions-weighted initial capacity, which effectively translates into approximately 50 percent of historic annual emissions.[26]

The environmental compliance cost to the firm becomes:

$$\varphi(q_i, e_i, \tau) = \tau(e_i q_i - A_i), \tag{6}$$

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[25] 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.

[26] The utilization rate of cement kilns is around 85% in our sample and very homogeneous across plants.

where A_i is the total emission permits that the firm receives for free from the regulator.

Note that the first order conditions associated with static profit maximization under grandfathering are identical to those under auctioning. 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). Dynamically, however, both mechanisms generally generate different long-run outcomes, primarily due to the exit decision being distorted by the transfer of valuable assets to incumbent firms under grandfathering.

When permits are grandfathered in a cap-and-trade program, policy makers must decide ex-ante how to deal with firms who exit and new entrants. We assume that the share of emissions allowances allocated to a firm is proportional the installed kiln capacity at the outset of the program, s_{i0}. However, if firms divest part of their historic capacity, they give up part of their initial allocation, i.e. $A_i = 0.425 \cdot e_i \min\{s_{i0}, s_i\}$.[27] Furthermore, we assume that a firm forfeits its future entitlements to free permits when it exits the market.[28,29] Finally, we assume that new entrants are not entitled to free permits.[30]

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. [31]

The environmental compliance cost to the firm becomes: becomes:

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

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

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[27] We include this feature to better represent some of the trade-offs faced when implementing grandfathering. In the EU ETS, the allocation of free permits is reduced dynamically if firms divest part of their grandfathered capacity.

[28] 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.

[29] In the EU ETS, most states require firms to forfeit their free permits upon closure.

[30] 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.

[31] (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). In California's Greenhouse Gas Trading Program, a more generous benchmark of 0.786 allowances per metric ton of clinker is used.

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 or decrease their capacity through costly investments, denoted by x_i. The cost function associated with these investments is given by:

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

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.[32]

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). We describe the equilibrium Bellman equations in 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. The interested reader can find a detailed description of the methodology in 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

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[32] 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.

components introduced in Section 2.

We define the following per-period equilibrium welfare measures:

$$\begin{aligned} w_1(s,e,\tau;\theta) &= \int_0^{Q*} P(z;\alpha)dz - P(Q^*;\alpha)Q^* + \sum_i \Pi_i(a^*,x^*,s,e,\tau;\theta) + \cdots \qquad (12a) \\ &\quad \cdots + \sum_i \varphi(q_i^*,e_i,\tau) + \tau e_M M, \\ w_2(s,e,\tau;\theta) &= w_1(s,e,\tau;\theta) - \tau \sum_i e_i q_i^*, \qquad (12b) \\ w_3(s,e,\tau;\theta) &= w_2(s,e,\tau;\theta) - \tau e_M M(P^*;\gamma). \qquad (12c) \end{aligned}$$

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 government revenues). This is intended as a measure of domestic economic surplus. We assume that domestic policy makers exclude profits earned outside their jurisdiction from any welfare analysis.

The welfare measure w_2 accounts for both economic surplus changes plus the costs of domestic emissions. In equation (12b), τ represents the social cost of carbon. As a point of departure, we will assume that the policy has been designed in such a way that the carbon price equals the true social cost of carbon. In our analysis, the social cost of carbon remains constant (in real terms) over the time horizon.

Finally, w_3 adds a penalty for emissions leakage. Both domestic emissions and the emissions associated with foreign imports are penalized at the social cost of carbon.

We will focus on comparing the net present value of these welfare measures against the baseline case in which no emissions regulation is in place. We define $w_0(s,e,\tau;\theta)$ as the per-period welfare in the baseline case. The net present value (NPV) welfare measures that we consider are:

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

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

5 Data and Estimation

Our approach to estimating the parameters of the model builds directly on Ryan (2012), although there are some noteworthy differences in our approach. First, we update and extend 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. Second, heterogeneity in marginal costs is now captured in the model. We estimate separate marginal cost parameters for different kiln types. Third, the model is modified to accommodate both capacity expansion and contraction. 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.

In what follows, we first present the data before turning to the 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, 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 percent and 1.7 percent, respectively. We observe 144 capacity increases (i.e. investment in one or more new kilns). We

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

Market	Number of Firms	Capacity	Emissions Rate	Import Market Share
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
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 Francisco	4	931	0.93	0.18
Seattle	2	607	1.05	0.65
St Louis	4	1358	1.05	0

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.

For computational reasons, we focus on markets with five or fewer firms.[33] We report the 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 account for over half of domestic cement consumption in Seattle. Import penetration rates tend to be highest along the coasts versus inland waterways.

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[33] In restricting our attention to those regional markets with five or fewer incumbent firms, we omit four markets from the analysis: Atlanta, Baltimore, Los Angeles, and San Antonio.

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, natural 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.[34] 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 subsets of excluded instruments (see Appendix E). To account for this imprecision, we conduct sensitivity analysis over a range of demand elasticity values.

Table 2 summarizes 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 and Padovani, 2003; Walton, 2009). The magnitudes of the fixed costs are reasonable, 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. 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.[35]

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[34] The estimate is higher in absolute value than some other demand elasticities reported in the literature. For example, Jans and Rosenbaum (1997) estimate a domestic demand elasticity of -0.81. Using data from 12 European countries over the period 1990-2005, Sato et al. (2008) 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 et al. (2008) estimate several similar high demand elasticities for homogeneous goods industries, such as -5.93 for ready-mixed concrete, cement's downstream industry.

[35] Source: KGNB Radio, New Braunfels, Texas.

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)	26,892
Fixed Cost Standard Deviation	10,438
Marginal Cost ($/metric ton)	195
Exit Cost	
Scrap Distribution Mean ($)	-67,314
Scrap Distribution Standard Deviation	53,358
Entry Distribution	
Entry Cost Mean ($)	178,169
Entry Cost Standard Variance	107,066

Notes: In 2000 dollars. Demand constant for Atlanta.

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.[36]

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 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 E).[37] Unfortunately, because publicly available data on cement imports are noisy and highly aggregated, our estimates of import supply elasticities are 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.[38]

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[36] District-level data on imports from earlier years contains many missing values.

[37] 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 (2011). There are a number of reasons why our import supply elasticity estimate is smaller than estimates constructed by Burtraw (2011). 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.

[38] This is intuitive as the costs of the domestic industry increase in the counterfactuals considered, which weakly

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 the import supply response. We revisit this issue in section 6.

5.4 Environmental Parameters

The environmental parameters in the model are 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 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, 2011) 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

Having estimated the parameters of the baseline model in which greenhouse gas emissions are unregulated, we use the model to simulate the dynamic industry response to counterfactual emissions policies. To highlight the importance of accounting for industry dynamics, we contrast the results of our dynamic simulations with a simulation exercise that holds industry structure fixed. To con-

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raises the market price.

struct the static benchmark, we take an approach that is quite standard in *ex ante* policy analysis (of Air Quality Planning et al., 1999). We simulate equilibrium outcomes in a single period and assume that these simulated static outcomes would be observed each year of the 30 year time horizon. In this static model, firms can alter production levels, but production capacity, technology operating characteristics, etc. are held constant at baseline levels.

This section begins with a summary of how key market outcomes (domestic production capacity, cement prices, emissions) are affected by the introduction of market-based policies designed to reduce greenhouse gas emissions. All simulation results are summarized relative to the base case in which greenhouse gas emissions are unregulated. We then summarize the net welfare impacts of the policies. The section concludes with a discussion of optimal carbon pricing and a series of robustness checks.

We report simulation results for the range of SCC values that have been deemed policy relevant (Greenstone et al., 2011). 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 roughly double the estimated marginal operating costs of the average cement producer. The higher carbon prices are, the less reasonable our modeling assumption of partial equilibrium, and all of the implications that come with it, such as the fixity of demand, capital costs, and productive technology, is likely to be. This caveat notwithstanding, evaluating outcomes over this range of SCC values serves to illustrate the countervailing forces that shape interactions between market structure and carbon regulation.

6.1 Simulated Market Outcomes

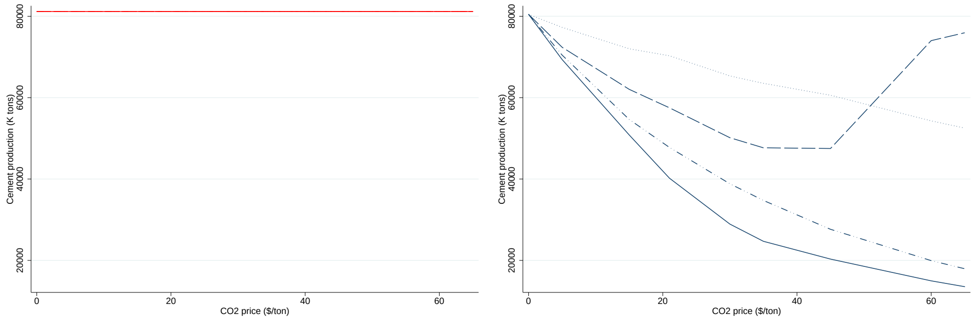
Production capacity Figure 3a plots total domestic production capacity as a function of the exogenous permit price, τ. The left panel, which corresponds to the static simulations, highlights the fact that domestic production capacity is held fixed at baseline levels in the static model.

The right panel shows how domestic production capacity varies with the carbon price once industry dynamics are introduced. Policy-induced reductions in installed capacity are most pronounced under the auctioning/tax regime. Under this regime, domestic producers must pay the tax/hold permits to offset emissions, but receive no rebate or compensation for incurring these costs. As τ increases, a growing number of firms elect to disinvest or exit the market completely. Augmenting this policy with a border tax adjustment mitigates the loss of domestic market share to foreign producers, thus slowing the rate of exit and disinvestment.

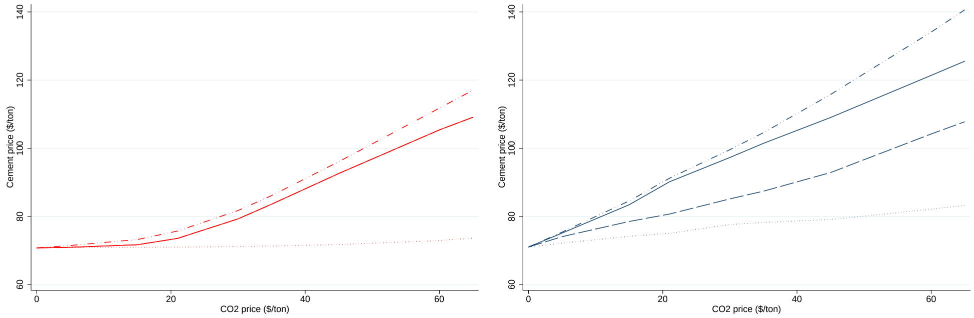
One important result, highlighted by this and subsequent figures, is that equilibrium outcomes under the grandfathering and auctioning regimes differ substantively. In other words, the so-called

Figure 3: Market Outcomes

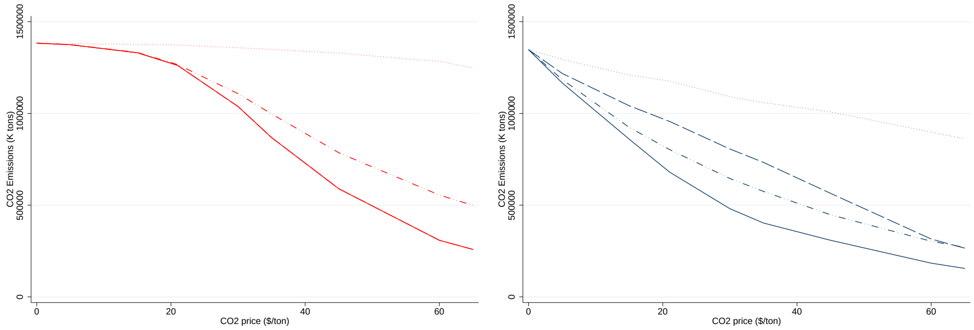
(a) Capacity



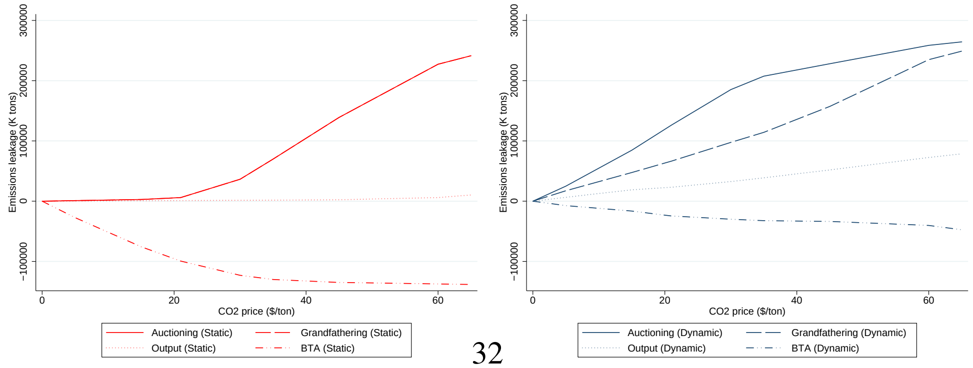
(b) Cement Prices



(c) Domestic Emissions



(d) Emissions Leakage



independence property fails to hold when industry dynamics are accounted for. 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 if it chooses to exit or disinvest. This lowers the exit and disinvestment thresholds for incumbents vis a vis the auctioning regime. At lower values of τ, it is more profitable for some firms to disinvest or exit versus maintain the permit endowment associated with baseline levels of production capacity. But at very high values of τ, permit endowments are so valuable that domestic production capacity remains at baseline levels.

Another noteworthy result is that, at low and mid-range carbon prices, policy-induced reductions in domestic production capacity are minimized under the regime that incorporates output-based rebating. Recall that this contingent rebating confers an implicit subsidy of $\tau \cdot (e_i - 0.716)$ per unit of production. This translates into a reduction in compliance costs (per unit of cement output) of between 62 and 89 percent.[39] Thus, the equilibrium production capacity that corresponds with a carbon price of τ under the output-based rebating regime is the capacity level observed under the auctioning regime at a carbon price of $\tau \cdot (\overline{e} - 0.716)$, where $\overline{e}$ represents the capacity weighted average emissions intensity.

Cement prices Figure 3b plots quantity-weighted average cement prices as a function of τ. In both the static and dynamic simulations, cement price increases are most pronounced under the auction/tax regime that incorporates a border tax adjustment. Under this policy, both foreign and domestic firms bear the complete cost of compliance; no compensation in the form of contingent rebates or lump sum transfers is offered.

Cement price increases are more significant in the dynamic simulations. As firms reduce production capacity through divestment and/or exit in response to policy-induced increase in operating costs, regional cement markets become more concentrated, and the distortions associated with the exercise of market power more pronounced.

Finally, a notable feature in the left panel of Figure 3b is that the cement price is virtually unaffected at carbon prices below $15. In the benchmark case, many domestic firms are capacity constrained and earning scarcity rents. An increase in variable operating costs reduces scarcity rents, but does not affect domestic production levels or equilibrium prices. In contrast, when firms have the ability to disinvestment in response to an increase in operating costs, we observe price impacts even at low levels of τ.

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[39] Emissions intensities among incumbent domestic producers range from 1.16 tons of CO_2 per ton of clinker for wet process kilns to 0.81 tons CO_2 per ton of clinker for the frontier technology.

Domestic emissions Figure 3c shows how the emissions from domestic cement production decrease with τ. The vertical axes measure domestic CO_2 emissions summed across regional markets and time periods. Domestic emissions are lowest under the auctioning regime which provides domestic producers no compensation for the costs they incur to comply with the regulation. This drives down levels of domestic cement production and associated emissions. Augmenting the auctioning regime with a border tax adjustment mitigates impacts on domestic competitiveness, thus increasing both domestic production levels and emissions.

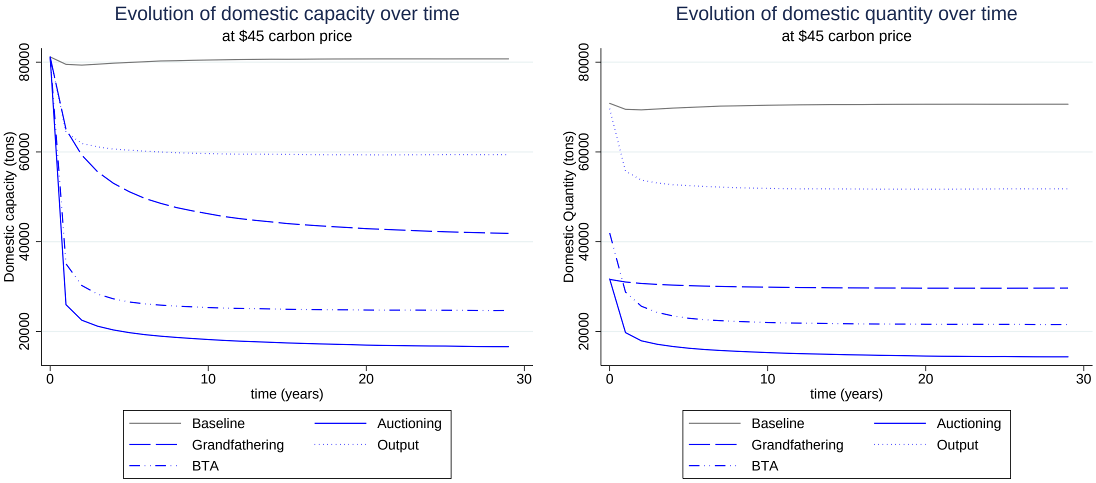
In the static simulations, emissions outcomes are identical across the grandfathering and auctioning regimes. In the dynamic simulations, domestic emissions levels are higher under grandfathering. Intuitively, regional cement markets have a higher expected number of active firms under grandfathering, leading to higher levels of domestic production and associated emissions.

Emissions leakage Figure 3d summarizes policy-induced changes in emissions from foreign producers. Importantly, we assume that any increase in the demand for cement imports is met by an increase in the quantity of cement produced by foreign suppliers, rather than reflecting a reallocation of foreign production to the domestic sector. If this assumption is incorrect, we will overestimate the degree of emissions leakage. We revisit this assumption in the following subsection.

In the dynamic simulations (right panel), emissions leakage is most significant under the auctioning regime. Domestic producers are required to fully internalize the externality with no compensation, whereas the operating cost structure of foreign producers is unaffected. As foreign producers gain market share, emissions from foreign cement production increase vis a vis the baseline. In line with the earlier discussion, grandfathering slows the rate of domestic capacity reduction vis a vis auctioning. This mitigates the extent of emissions leakage. Similarly, output-based rebating significantly reduces the net cost of compliance per unit of output, thus limiting the extent to which imports out-compete domestic production in trade-exposed markets, and mitigating leakage.

Notably, we find *negative* leakage rates under the regime that incorporates a border tax adjustment. In other words, the introduction of this policy reduces emissions among foreign producers relative to the unregulated baseline. Importantly, our model assumes complete pass through of environmental compliance costs by foreign producers whereas pass through 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 cement imports. Because policy-induced increases in the cement price are larger when dynamic industry responses are accounted for, import supply levels

Figure 4: Market Outcomes over time


(a) Capacity over time at $45 SCC

(b) Emissions over time at $45 SCC

are higher at any given carbon price, and the extent of the negative leakage is less (as compared to the static case).

Market outcomes over time Our dynamic simulation model can also be used to generate trajectories of market outcomes over time under alternative policy regimes. Figures 4a and 4b chart the evolution of domestic production capacity and domestic quantity, respectively, assuming a carbon price of $45 per ton of CO_2.

In our model, there is no technological innovation over time, nor is there growth in domestic cement demand over time. In other words, aside from policy-induced changes in market structure, economic operating conditions are stable over the 30 year time horizon we consider. Consequently, most of the industry response to a counterfactual policy intervention occurs in the years immediately following the policy change. This adjustment is not immediate due to year-to-year variation in firms' draws from the distributions of investment, entry, and exit costs. It is also notable that the adjustment takes longer in the grandfathering case, where incentives to divest are attenuated by the payoffs of keeping free allowances.

One important insight that arises from these graphs is that firms' capacity tends to be binding in the quantity setting game. This fact is matched in the data. This highlights the source of differences observed between auctioning and grandfathering. If there were no capacity constraints, the quantity should be the same in both counterfactuals. It is due to long-run impacts on market structure that differences in markups in the product market can be sustained.

These graphs also show that these outcomes are very stable in the baseline case, which is reassuring that our simulations are internally consistent with our assumption that the economic environment is unchanging in the baseline.[40]

6.2 Decomposing Changes in Welfare

Having considered the effects of counterfactual emissions regulations on specific market outcomes, we next consider the related welfare implications of these policies. Policy-induced welfare changes are decomposed into the three component parts introduced in section 2.

W1: Domestic Economic Surplus Figure 5a illustrates policy-induced changes in our first welfare metric, W1, as a function of the carbon price. This measure captures the effects on domestic producer surplus, domestic consumer surplus, and any revenues raised by the government through emissions taxation or permit sales.

The left panel of Figure 5a corresponds to the static case. Because short run production incentives are identical under grandfathering and auctioning, impacts on domestic economic surplus are identical. The addition of a border tax adjustment improves terms of trade effects, generates border tax revenues, and reduces policy impacts on cement prices.[41] On balance, this mitigates losses in domestic economic surplus at high carbon prices. Because the policy that incorporates output-based rebating has only negligible impacts on domestic production across the range of prices we consider, impacts on domestic economic surplus are minimal.

The right panel of Figure 5a summarizes the corresponding dynamic results. Reductions in domestic economic surplus are most significant under the auctioning regime where we observe the highest rates of exit and disinvestment, the highest cement prices, and the most significant adverse impacts on domestic competitiveness. Under the grandfathering regime, the government collects less auction revenue as compared to auctioning (with or without a border tax adjustment). However, this loss is more than offset by the increase in domestic producer and consumer surplus associated with higher levels of domestic production and lower cement prices.

In contrast to the static case, reductions in economic surplus manifest even at low carbon prices. As discussed above, when firms have the ability to disinvest in response to a policy-induced increase in operating costs, we observe impacts on cement prices, domestic production, and thus

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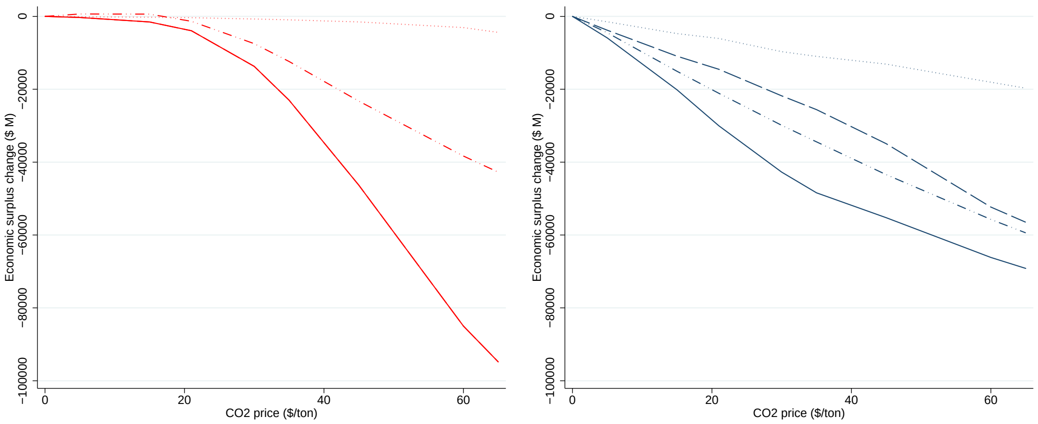
[40] This is not necessarily the case; misspecification bias in our model could imply that firms should systematically be larger or smaller than their empirical counterparts, for example.

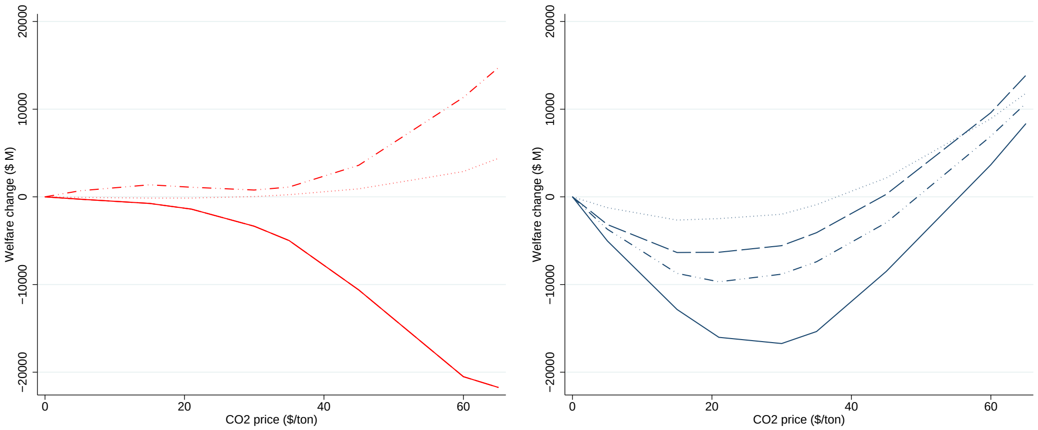
[41] For low carbon prices, this even results in marginally higher producer surplus.

Figure 5: Welfare Measures across Mechanisms

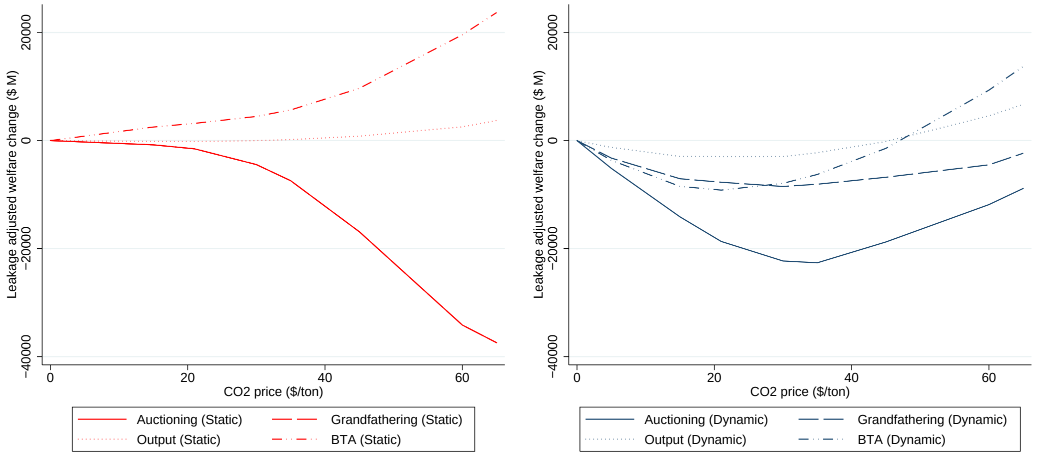
(a) W1: Domestic Industry + Revenues



(b) W2: W1 + Domestic reduction



(c) W3: W2 + Emissions leakage



domestic economic surplus, across the range of carbon prices we consider.

W2: Domestic Economic Surplus + Domestic Emissions Figure 5b plots changes in our second welfare measure which adds the value of domestic CO_2 emissions reductions to the policy induced reductions in domestic economic surplus. In the simulations summarized here, the value per ton of emissions avoided is assumed to be equal to the prevailing permit price or tax. Thus, the monetary value of domestic emissions reductions is constructed by multiplying the emissions reductions summarized in figure 3c by the corresponding permit price.

In the static simulations (left panel), benefits associated with reduced domestic emissions do not offset the costs of a policy that incorporates grandfathering or auctioning. In contrast, the value of domestic emissions reductions more than offsets the economic costs under the policy regimes that incorporates a border tax adjustment or the output-based rebate.

The dynamic simulations yield quite different results (right panel). As compared to the static case, the dynamic mechanisms of divestment and exit result in much smaller levels of production; at low carbon prices, the loss in domestic economic surplus is increasing faster than the gain in benefits these domestic emissions reductions. However, as τ increases, the gains from emissions abatement begin to offset losses in economic surplus. All policy regimes yield welfare gains at high carbon prices.

W3: Domestic Economic Surplus + Total Emissions Our preferred policy measure, W3, captures domestic economic surplus and the damages from emissions associated with domestic cement consumption. Damages associated with policy induced increases in foreign emissions are constructed by multiplying the emissions reductions summarized in figure 3d by the corresponding permit price.

Figure 5c plots the policy induced reductions in this most comprehensive welfare measure. In the static simulations (left panel), accounting for the significant levels of emissions leakage observed at values of τ greater than \$20 exacerbate welfare costs of the grandfathering and auctioning regimes. In contrast, accounting for negative leakage amplifies the welfare gains under the policy regime that incorporates a border tax adjustment.

In the dynamic simulations (right panel), accounting for the damages caused by emissions among foreign producers supplying the domestic market pushes most welfare measures in W2 down. Output-based updating is the least-worst (but still negative) policy for the majority of carbon prices, being eclipsed by border tax adjustments only at prices exceeding \$45 per ton. Grandfathering generates marginally greater surplus relative to border tax adjustments for low to moderate

Table 3: Optimal carbon prices for different mechanisms

	Federal τ_f^*	Coastal τ_c^*	Inland τ_i^*	Welfare Δ at τ_f^*	Welfare Δ at $\{\tau_c^*, \tau_i^*\}$	Welfare Δ at τ = SCC
SCC = $ 21						
Auctioning	0.0	0.0	0.0	0.0	0.0	-18673.7
Grandfather	0.0	0.0	0.0	0.0	0.0	-7713.4
Output	0.0	0.0	0.0	0.0	0.0	-2971.2
BTA	0.0	0.0	0.0	0.0	0.0	-9172.0
SCC = $ 55						
Auctioning	10.0	5.0	21.0	2758.2	3705.7	-14154.8
Grandfather	21.0	10.0	50.0	3310.3	4746.0	-5405.0
Output	50.0	50.0	65.0	2950.3	3384.8	2855.7
BTA	25.0	30.0	21.0	10439.1	10662.9	5652.7

Notes: Carbon prices in \$. Welfare in M\$. Optimal carbon prices computed on a grid including {0, 5, 10, 15, 21, 25, 30, 35, 40, 45, 50, 55, 60, 65}.

carbon prices. Auctioning/carbon tax has the worst welfare performance, by far, and generates large and negative welfare impacts over the entire range of carbon values we evaluate. Notably, the highest welfare losses, exceeding \$20 billion, correspond to carbon prices in the middle of the range of expected carbon prices for a US-wide carbon trading scheme.

As noted above, we assume that policy-induced changes in demand for cement imports translate directly into changes in the levels of foreign cement production. This assumption will exaggerate the impacts of these policies on emissions leakage if foreign producers accommodate changes in domestic demand for cement imports by reallocating their output. In this respect, Figures 5b and 5c can be viewed as upper and lower bounds on the welfare impacts of these policies.

6.3 Policy Comparisons Under Optimal Carbon Prices

One important assumption that we have maintained thus far is that the permit price equals the social cost of carbon. Simulation results summarized in the previous section suggest that the negative welfare effects of fully internalizing the emissions externality outweigh the benefits over a range of carbon values. As a result, a policy maker looking to maximize welfare will want to set a permit price that falls below 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 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 compute the permit price that maximizes our most comprehensive welfare measure (W3) for a given value of the true social cost of carbon. We first impose the constraint that all domestic cement producers must be treated symmetrically under the regulation. 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 that firms within a sector will face the same policy incentives.

Given the structural differences across regional markets, as well as the differences in trade exposure, allowing policy incentives to vary across regional markets could be welfare improving. We therefore extend the analysis to consider policy designs that levy different carbon prices for trade-exposed coastal and trade-insulated inland markets.

Table 3 reports welfare maximizing carbon prices and associated welfare changes. In Column 1, we impose the constraint that all cement producers face the same price. Columns 2 and 3 report the optimal prices for coastal and inland regional markets, respectively. The top panel considers the case in which the social cost of carbon is \$21 per ton of CO_2. At this value, there is no positive carbon price at which benefits from emissions reductions exceed the costs. This is true in inland markets and in coastal markets when the emissions externality has been internalized by foreign producers. This implies that the social costs of exacerbating the exercise of market power exceeds any social gains from reducing emissions.

The bottom panel of Table 3 conducts the same analysis when the social cost of carbon is \$55 per ton of CO_2. At this value, we find that all policy regimes deliver positive welfare gains if the permit price is set (optimally) below the social cost of carbon. Under the auctioning regime, 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. When this price is allowed to vary across inland and coastal markets, the price is much lower in trade-exposed markets in order to address the welfare effects of emissions leakage.

Augmenting the auctioning regime with a border tax adjustment efficiently internalizes the emissions externality associated with foreign production, but leaves the distortions associated with the exercise of market power unaddressed. In coastal markets, augmenting the auctioning regime with a border tax adjustment increases the optimal carbon price from \$5/ton to \$30/ton. Note that this is higher than the optimal price in inland markets because coastal markets tend to be relatively more competitive.

Under the regime that incorporates dynamic allocation updating, recall that the implicit subsidy offsets a majority of the compliance cost. We find that, at the federal level, this subsidy is close to optimal, as the optimal price is \$50. However, there is substantial heterogeneity between coastal and inland markets. This subsidy appears to be too low in coastal markets, as output-based updating plays a crucial role attenuating rent and emissions leakage. On the contrary, in a regime in which all domestic firms must be treated symmetrically, this subsidy may be overly generous as suggested by the optimal inland price of \$65, which is the upper bound on the range that we consider.

The welfare change that results if carbon is priced optimally and uniformly within the cement sector is reported in Column 4. Column 5 reports the welfare change that results under the differentiated carbon price. Finally, as a basis for comparison, Column 6 reports the welfare change that results if the carbon price is constrained to equal the assumed SCC. With the exception of the output-based updating regime at a SCC value of \$55, the welfare gains from incomplete internalization of the emissions externality are significant. Gains from differentiating carbon prices across inland and coastal markets are not as large, but are still non-trivial.

6.4 Additional Experiments and Robustness Checks

Demand elasticities The demand elasticity plays an important role in determining, among other outcomes, gross consumer surplus, the extent of the distortion arising from the exercise of market power, and the extent to which leakage occurs under a given emissions policy.

Unfortunately, publicly available data on producer prices and production quantities are highly aggregated and noisy. This results in elasticity estimates which are imprecise. We simulate outcomes in a subset of markets using a range of elasticity values that we cannot confidently rule out given available data. Table 4 presents welfare changes (using the most comprehensive welfare measure W3) for a range of carbon prices and demand elasticities.

For low carbon values, welfare impacts of the policies we consider are more negative when demand is relatively more elastic because effects on gross consumer surplus are relatively more significant. At higher carbon values, negative welfare impacts are attenuated, or turn positive, when demand is more elastic. Intuitively, reductions in emissions play a more significant role in determining welfare impacts at higher carbon prices. The more elastic domestic demand, the greater the impact of a given policy on domestic emissions, and the lower the rate of emissions leakage.

Table 4 can also be used to address (albeit incompletely) concerns about the effects of carbon policy on the structure of domestic cement demand. Whereas our model effectively holds constant demand shifters, we might expect that the emissions policies we consider would affect the prices of cement substitutes (such as asphalt in paving applications). 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 4 to get a rough idea of how our estimates of welfare impacts within the cement sector may change as the structure of demand changes. If cement will become differentially more expensive (as compared to substitutes) 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 provides a simple way of representing the degree of sensitivity of our results to our partial equilibrium modeling assumptions.

Import supply elasticities The import supply elasticity parameter is another key parameter in our model. Similar to the own-price elasticity of domestic cement demand, we have two reasons to be concerned about how our estimated welfare impacts vary with this particular parameter value. First, publicly available data is noisy and highly aggregated, which means that our estimate of the import supply elasticity is very imprecise. Second, we assume the import supply elasticity is an exogenous parameter. In other words, we do not account for the possibility that importing firms could respond to the policy 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.

Table 5 recomputes estimated welfare impacts for a range of import supply elasticity values. Changing the import supply elasticity has two important implications. First, in trade-exposed markets, an increase in the import supply elasticity increases the elasticity of the residual demand curve faced by domestic producers, all else equal. Second, the more responsive is import supply to a change in the cement price, the greater the emissions and rent leakage. At low carbon prices, the first effect dominates and lower elasticities are associated with more negative welfare impacts. At high carbon values, the second effect dominates. A less elastic import supply response is associated with less leakage and smaller welfare losses (or welfare gains in the case of negative leakage).

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, in the form of 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). Over the range of plausible 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 programs, 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. Our results provide important insights into the efficiency and distributional properties of leading policy design alternatives.

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Table 4: Differences in welfare with respect to baseline (W3) for different **demand elasticities**

	5.0	15.0	21.0	35.0	45.0	55.0	65.0
$\eta = 1$							
Auctioning	-1350.0	-3747.0	-5099.4	-8681.1	-11355.3	-11489.9	-10914.2
Grandfather	-1223.4	-3832.1	-5494.2	-8571.4	-11551.1	-11306.4	-10830.3
Output	-303.1	-1137.7	-1259.7	-1051.5	-901.6	-583.3	-315.3
BTA	-764.7	-1747.8	-1890.8	-2094.7	-1555.9	-1060.2	-17.1
$\eta = 1.5$							
Auctioning	-1536.3	-4015.9	-4835.8	-8172.3	-9290.0	-8051.3	-6663.4
Grandfather	-1523.3	-4034.4	-3998.3	-7900.7	-9154.8	-7916.8	-6554.1
Output	-511.2	-838.1	-1003.5	-942.4	-538.6	29.5	721.1
BTA	-981.7	-2236.6	-2014.0	-1773.4	-943.4	-106.9	2045.1
$\eta = 2.0$							
Auctioning	-1506.8	-3764.8	-5378.9	-8474.5	-7442.5	-5677.7	-3809.9
Grandfather	-693.6	-2090.7	-2270.8	-2711.1	-2578.1	-2650.3	-2528.0
Output	-279.1	-1022.1	-1036.6	-845.3	-372.2	560.3	1525.9
BTA	-1009.2	-2413.1	-2307.8	-1647.7	-807.1	1311.5	3958.4
$\eta = 2.5$							
Auctioning	-1515.9	-4019.4	-5553.7	-7470.0	-5745.0	-3505.7	-1305.7
Grandfather	-1496.7	-3723.6	-5437.0	-7369.0	-5657.8	-3530.8	-1642.6
Output	-351.1	-847.4	-1113.3	-637.4	44.2	1257.1	2510.2
BTA	-1047.1	-2244.5	-2465.6	-1688.8	-122.3	2607.0	5939.6
$\eta = 3.0$							
Auctioning	-1616.3	-4329.4	-5877.6	-6637.0	-4285.4	-1584.1	984.3
Grandfather	-1589.7	-4103.6	-5774.1	-6529.5	-4225.8	-1625.0	640.9
Output	-372.5	-1033.7	-1157.9	-418.0	653.1	1859.8	3500.9
BTA	-1170.3	-2544.5	-2834.4	-1585.7	776.2	4172.7	8232.2
$\eta = 3.5$							
Auctioning	-1887.6	-4647.0	-6072.0	-5697.5	-2707.8	545.8	3726.2
Grandfather	-1881.7	-4494.6	-6009.4	-5643.3	-2663.3	444.1	3386.7
Output	-544.5	-1122.8	-1107.8	-17.6	1425.0	3023.0	5001.6
BTA	-1464.2	-2926.1	-2999.5	-1269.8	1808.7	6243.4	10883.5

Notes: Table reports average differences in welfare for a subset of regional markets with three or less firms (Cincinnati, Detroit, Minneapolis, Pittsburgh, Salt Lake City, Seattle).

Table 5: Differences in welfare with respect to baseline (W3) for different **import elasticities**

	5.0	15.0	21.0	35.0	45.0	55.0	65.0
$\eta = 1.5$							
Auctioning	-1540.1	-3656.6	-4140.5	-5960.1	-6144.1	-4671.3	-3170.7
Grandfather	-1536.7	-3671.6	-3943.7	-5894.8	-6101.4	-4566.3	-3146.7
Output	-461.0	-839.5	-972.5	-802.0	-294.0	338.4	1142.1
BTA	-1073.8	-2058.5	-1436.8	-1314.9	-206.4	1631.7	3356.7
$\eta = 2.0$							
Auctioning	-1516.0	-3567.6	-4328.1	-6557.7	-6414.6	-5003.3	-3594.8
Grandfather	-1514.8	-3702.1	-4101.2	-6425.7	-6304.0	-4902.2	-3521.6
Output	-401.9	-1092.5	-995.7	-821.1	-394.7	223.1	977.4
BTA	-1042.0	-1893.8	-1450.7	-981.2	-153.3	1534.2	3690.5
$\eta = 2.5$							
Auctioning	-1335.4	-3208.7	-4475.3	-7612.1	-6575.7	-5357.3	-4074.6
Grandfather	-610.3	-1924.5	-2165.9	-2699.1	-2827.9	-3280.0	-3628.0
Output	-213.6	-896.6	-891.0	-772.6	-530.9	132.6	783.2
BTA	-837.8	-1857.1	-1404.1	-785.3	59.7	1632.0	3693.8
$\eta = 3.0$							
Auctioning	-1406.5	-3264.8	-4597.3	-7815.1	-6763.2	-5633.3	-4588.1
Grandfather	-1401.0	-3034.2	-4437.7	-7830.6	-6647.5	-5619.1	-4887.4
Output	-261.2	-998.6	-978.4	-839.8	-589.3	46.2	657.4
BTA	-929.8	-1829.4	-1415.6	-722.4	94.1	1574.9	3611.5
$\eta = 3.5$							
Auctioning	-1320.7	-3275.3	-4705.4	-7921.4	-6907.9	-5853.4	-5070.1
Grandfather	-1312.5	-3036.4	-4553.1	-7883.9	-6784.5	-5814.9	-5386.1
Output	-201.7	-946.8	-959.2	-835.6	-626.8	-24.1	536.0
BTA	-766.5	-1728.3	-1363.8	-696.7	207.2	1579.9	3561.0
$\eta = 4.0$							
Auctioning	-1244.7	-3295.5	-4824.9	-8044.9	-7039.3	-6045.2	-5333.0
Grandfather	-1191.1	-3095.0	-4684.7	-7932.8	-6906.9	-6005.0	-5654.0
Output	-130.9	-637.2	-939.0	-837.0	-662.8	-84.7	427.8
BTA	-675.9	-1673.8	-1320.8	-687.3	226.3	1628.5	3583.3

Notes: Table reports average differences in welfare for a subset of regional markets with three or less firms that are trade exposed (Cincinnati, Detroit, Minneapolis, Seattle).