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INCOMPLETE ENVIRONMENTAL REGULATION, IMPERFECT COMPETITION, AND EMISSIONS LEAKAGE

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ABSTRACT

For political, jurisdictional and technical reasons, environmental regulation of industrial pollution is often incomplete: regulations apply to only a subset of facilities contributing to a pollution problem. Policymakers are increasingly concerned about the emissions leakage that may occur if unregulated production can be easily substituted for production at regulated firms. This paper analyzes emissions leakage in an incompletely regulated and imperfectly competitive industry. When regulated producers are less polluting than their unregulated ounterparts, emissions under incomplete regulation can exceed the level of emissions that would have occurred in the absence of regulation. Converseley, when regulated firms are relatively more polluting, aggregate emissions under complete regulation can exceed aggregate emissions under incomplete regulation. In a straightforward application of the theory of the second best, I show that incomplete regulation can welfare dominate complete regulation of emissions from an asymmetric oligopoly. The model is used to simulate greenhouse gas emissions from California's electricity sector under a source-based cap-and-trade program. Incomplete regulation that exempts out-of-state producers achieves approximately a third of the emissions reductions achieved under complete regulation at more than twice the cost per ton of emissions abated.

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1 Introduction

For political, jurisdictional and technical reasons, environmental regulation of industrial pollution is often incomplete: rules apply to only a subset of the sources contributing to a pollution problem. When some firms in a polluting industry are subject to market-based environmental regulation (such as a pollution tax or pollution permit trading program) while others are exempt, the production costs of regulated producers will increase relative to their unregulated rivals. If unregulated production can be easily substituted for production at regulated firms, emissions reductions achieved by regulated producers may be substantially offset, or even eliminated, by increases in emissions among unregulated producers.

Regulations that tax or cap industrial greenhouse gas (GHG) emissions at the state, national or regional level are an increasingly important example of environmental regulation that is ineluctably incomplete. There are at least two reasons for this. First, equity concerns make complete regulation of GHG emissions broadly objectionable.[1] The second reason has more to do with the prevailing stalemate in climate policy negotiations. Political support for regulations that aim to limit anthropogenic GHG emissions varies significantly across jurisdictions. Regional programs, such as those recently initiated by the European Union, California, and a coalition of Northeastern US states, are emerging in response to gridlock and policy inaction at higher levels of governance.[2]

The global nature of the climate change problem creates challenges for regional initiatives. In particular, emissions "leakage" has become a defining issue in the design and implementation of regional climate policy.[3] Leakage refers to increases in production and associated emissions among

[1] It is generally agreed that, at least for the forseeable future, binding emissions targets should only be established for the countries responsible for the majority of past and current GHG emissions (i.e. developed countries).

[2] States and regional coalitions are taking a leading role in responding to global climate change. In January 2005, the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) began operating as the largest multi-country, multi-sector greenhouse gas emission trading scheme in the world. In December 2005, seven states in the Northeastern U.S. signed an agreement that caps carbon dioxide (CO_2) emissions from power plants in the region. In August of 2006, California passed legislation that caps greenhouse gas emissions across all sectors in the state. A coalition of western states and Canadian provinces has also emerged to address broader regional climate policy objectives. While some states pursue policies to address global warming, others have taken an opposite tack and explicitly passed laws against any mandatory reductions in greenhouse gas emissions. These states include Alabama, Illinois, Kentucky, Oklahoma, West Virginia and Wyoming. (Senate Congressional Record, October 30, 2003: S13574).

[3] Concerns that incomplete industrial participation will undermine the effectiveness of these regional initiatives

unregulated producers that occur as a direct consequence of incomplete environmental regulation (RGGI, 2007; CEC 2006). This paper develops a framework for analyzing emissions leakage in the context of an incompletely regulated and imperfectly competitive industry.

An analysis of incomplete environmental regulation and emissions leakage should ideally reflect the institutional realities of the industries most often targeted by incomplete environmental regulation. The majority of emissions that are subject to regional, market-based regulations come from industries that are often characterized as imperfectly competitive (important examples include restructured electricity markets and cement).[4] Wholesale forward commitments are common in many of these industries. Although these stylized facts play an important role in determining market outcomes, past studies analyzing the potential effects of incomplete participation in regional climate change initiatives assume that incompletely regulated industries operate as perfectly competitive spot markets.[5] This paper demonstrates the importance of industry structure in determining both the extent to which leakage occurs and the welfare implications of incomplete regulation.

A partial equilibrium model of an industry in which non-identical oligopolists compete in both spot and forward markets is used to analyze emissions leakage. The introduction of incomplete, market-based environmental regulation (*i.e.* a pollution tax or cap-and-trade program) affects producers' relative marginal operating costs. This has implications for aggregate production,

have plagued the design and implementation of regional programs. In Europe, the possibility that reductions achieved domestically will be partly offset by increased emissions resulting from relocation of production outside the region has been identified as a "main concern" by stakeholders and policy makers. Stakeholders in the planning process of the Regional Greenhouse Gas Initiative have argued strongly that the program should not be implemented before the leakage issue had been adequately addressed.

[4]Emissions from restructured electricity markets represent the majority of emissions currently targeted by regional GHG cap-and-trade programs in the United States and Europe. Numerous studies provide empirical evidence of the exercise of market power in these industries (see, for example, Borenstein *et al.* 2002; Bushnell *et al.* 2008; Joskow and Kahn, 2002; Puller, 2007; Sweeting, 2007; Wolfram, 1999). Empirical papers that assess the implications of the exercise of market power in other energy intensive sectors targeted by these regional programs include Ryan (2008) and Rosenbaum and Sukharoman (2001).

[5]See, for example, Bernstein et al. (2004), Breslow and Goodstein (2005), CEEEP (2005), Burtraw et al. (2005). Questions about how estimated impacts of incomplete environmental regulation might change if modeling assumptions were modified to better reflect the structure of restructured electricity markets have been raised at stakeholder workshops (RGGI Workshop on Electricity Markets, 2004; Bouttes, J.P. "Predictability in European electricity markets." Presentation to the EU Ad Hoc Group 1. March 29, 2006), in written responses to program analysis (Slater Consulting, "Initial Questions and Comments on the Resources for the Future report 'Allocations of CO_2 Emission Allowances in the Regional Greenhouse Gas Cap-and-Trade Program', March 29, 2005), policy briefs (CEC, 2005) and working papers (Wilson et al. 2005).

relative market shares, and industry emissions. Emissions leakage is greater when emissions rates per unit of production are high and/or when demand is more elastic. Within the context of the model and its assumptions, the more competitive the industry, the greater the emissions leakage.

Although there is growing debate about the extent to which emissions leakage can undermine the effectiveness of incomplete environmental regulation, it is generally assumed that incomplete participation (and associated emissions leakage) unambiguously reduces welfare gains from environmental regulation (CCAP, 2005; RGGI, 2007;). In a straightforward application of the theory of the second best, I demonstrate that this need not be the case when the polluting industry is an asymmetric oligopoly. When Cournot oligopolists with non-identical production costs exercise market power, production is inefficiently allocated across firms and aggregate industry output may fall below the social optimum. Introducing incomplete environmental regulation can mitigate both of these distortions (*vis a vis* complete regulation). Industry output under incomplete regulation will exceed output under complete regulation. Furthermore, allocative production inefficiencies will be reduced if the firms that are exempt from environmental regulation are more efficient than their regulated counterparts. Conversely, if regulated firms are more efficient than exempt producers, the introduction of incomplete regulation can exacerbate pre-existing allocative inefficiencies.

The analytical model presented in this paper serves two purposes: it is used to develop intuition about how observable industry characteristics determine the extent to which emissions leakage occurs under incomplete regulation, and it serves as a foundation for building more detailed numerical models that can be used to analyze the potential for leakage in applied policy settings. In section 5, I demonstrate how the theoretical framework can be used to inform policy design.

California is actively developing a state cap-and-trade system under the auspices of a new state law requiring that greenhouse gas emissions be reduced to 1990 levels by 2020.[6] The the-

[6] California's Assembly Bill 32 established a statewide GHG emissions cap for 2020, based on 1990 emissions. California is also part of the Western Climate Initiative (WCI), a collaborative of several western United States and Canadian provinces with a goal of developing a regional strategy to reduce greenhouse gas emissions. As of October 2008, California is the only state in the WCI to be actively designing a state-level cap-and-trade program for greenhouse gases. Allegedly, more than half half the states involved inthe Western Climate Initiative are unlikely to ever approve the rules and regulations to allow them to actually participate in the proposed WCI program ("Montana Inaction On GHGs May Signal Collapse Of Regional Trading Plan", September 23, 2008, Carbon Control News).

oretical framework is modified to reflect features of California's electricity market. Parameter values are defined using detailed, facility-level data. A cap-and-trade program with a fixed permit price is added to the model. The potential for emissions leakage in California's electricity sector, which accounts for 23 percent of the state's greenhouse gas emissions, is investigated. Equilibrium outcomes under three scenarios are simulated: a benchmark case where CO_2 emissions are unregulated, a source-based cap-and-trade program regulating emissions from all electricity producers in the western United States, and a source-based cap-and-trade program that affects only California electricity producers.

Simulation results suggest that a complete cap-and-trade program, with an assumed price of \$25/ton of CO_2, would deliver emissions reductions of 9-11 percent in the short run through reordering the dispatch of existing production capacity. Simulations that assume California's electricity producers behave strategically in the wholesale electricity market predict that incomplete environmental regulation (*i.e.* a policy that regulates the emissions of only in-state producers) would achieve 35 percent of the emissions reductions achieved under complete regulation. In simulations that assume perfectly competitive wholesale electricity markets, this number drops to 25 percent. The implied cost per ton of emissions reduced is more than twice as high when participation in the environmental regulation is incomplete.

The paper proceeds as follows. Section 2 provides a brief review of related literature. Section 3 introduces the theoretical framework and derives some basic theoretical results. Section 4 uses a stylized duopoly example to further illustrate the implications of the model. Section 5 demonstrates how this framework can be used to analyze leakage and related welfare effects in the context of a regulation designed to reduce California's GHG emissions. Section 6 concludes.

2 Incomplete environmental regulation of an imperfectly competitive industry

This work is preceded by several papers in the industrial organization literature that analyze complete, market-based environmental regulation of an imperfectly competitive industry. Oates and

Strassmann(1984) consider the welfare consequences of introducing a Pigouvian tax into a monopolized industry. They conclude that losses in production efficiency are likely to be more than compensated for by welfare gains from improved environmental quality. Levin(1985), Simpson (1995), and Van Long and Soubeyran (2005), among others, investigate second-best Pigouvian taxes.[7] Others have analyzed the interaction of complete, competitive permit markets and oligopolistic product markets (Malueg,1990; Mansur, 2007(Mansur 2007); Sartzetakis, 1997, 2004). Without exception, this literature assumes that all producers are subject to environmental regulation. This paper extends this body of work to the increasingly relevant case of incomplete regulation.

A second-best framework has also been used to analyze the response of public utility commissions to environmental regulations imposed by federal and state agencies. Earlier papers have investigated the extent to which public utility regulators can use their limited authorities to improve upon existing environmental regulations in their service territories (Burtraw *et al.* ,1997; Dodds and Lesser,1994). I investigate similar themes here, albeit in the context of an imperfectly competitive (versus economically regulated) industry.

Finally, this paper is germane to the literature that considers the linkages between pollution regulation and comparative advantage (Baumol, 1971; Copeland and Taylor, 2003). Copeland *et al.* (1994), among others, have hypothesized that an increase in the stringency of environmental regulation will, at the margin, affect plant location decisions and international trade. Brunnermeier and Levinson (2004) provide a review of the empirical literature that examines the effects of environmental regulation on firms' location and investment decisions. Although earlier studies find little evidence of this so-called "pollution haven" effect, more recent studies provide some evidence in support of this hypothesis (see, for example, Becker and Henderson, 2000; Greenstone, 1997).

Although this paper is similar to preceding work investigating the pollution haven hypothesis, the application and emphasis are rather different. Researchers analyzing interactions between

[7] In most cases, when producers in an imperfectly competitive industry generate a pollution externality, firms' marginal abatement costs fall below the marginal damage from pollution at the second-best, although there are exceptions. For example, Katsoulacos and Xepapedeas(1995) consider the case of a symmetric polluting oligopoly. They show that if N is endogenous and there are fixed abatement costs, the second-best optimal tax can exceed the marginal damage from emissions in order to discourage excessive entry.

trade policies, environmental regulations, and the comparative advantages of different trading partners have tended to focus on identifying conditions under which reductions in trade barriers can alleviate or exacerbate problems caused by pre-existing, asymmetric environmental regulations. Research addressing the effects of domestic environmental regulations on plant location and production decisions have typically ignored market structure considerations. This analysis of emissions leakage within a single, incompletely regulated industry emphasizes strategic interactions between asymmetric oligopolists. In this context, the introduction of incomplete environmental regulation can either mitigate or exacerbate pre-existing inefficiencies associated with the exercise of market power in a polluting industry.

3 The Model

In this section, I investigate how the emissions and emissions leakage occurring under incomplete environmental regulation are affected by observable industry features: operating costs, emissions rates, regulatory participation requirements, and the degree of competitiveness. A partial equilibrium, asymmetric oligopoly model is introduced. The model is kept intentionally simple; only the most essential industrial features are represented. The objective here is to develop a clear, intuitive understanding of how incomplete regulation affects firm behavior in the short run.[8] In section 5, institutional details specific to a particular policy context will be incorporated and some of the more stylized assumptions are released.

[8] Understanding how market-based regulation affects electricity prices and asset utilization rates in the short run is a essential first step towards understanding how these policies will affect asset values and investment in the longer term. Furthermore, given the political momentum behind a more co-ordinated Federal (or larger regional) climate policy, emissions leakage is arguably a more pressing concern in the near term.

3.1 The basic framework

I assume Cournot non-cooperative behavior among N strategic firms.[9] This is a fairly conventional assumption. Much of the literature analyzing heavily polluting industries such as electricity and cement employs a static oligopoly framework in which firms are assumed to compete in quantities.[10] Furthermore, recent empirical work suggests that firm conduct in these industries is consistent with the Cournot model.[11]

I first analyze a one-stage game in which firms with different production technologies compete in a spot market. I then consider a two-stage game in which the firms compete in both spot and forward markets. This extends the work of Allaz and Vila (1993) and Bushnell (2007) to accommodate asymmetric oligopolists.

Industrial production generates a negative pollution externality. Damages are assumed to be independent of the location of the emissions source. Firms vary both in terms of their production costs and emissions characteristics. Note that both kinds of asymmetry are important. A defining advantage of market-based environmental policy instruments (as compared to more traditional, prescriptive approaches such as emissions standards) is their ability to efficiently coordinate abatement activity across firms with non-identical abatement costs. Asymmetry in production costs gives rise to allocative production inefficiency in oligopolistic markets; this inefficiency will play an important role in determining the welfare impacts of incomplete participation.

In order to isolate the interactions between incomplete industrial participation in environmental regulation and strategic behavior in the product market, several standard assumptions are adopted. I assume that the regulator does not have the authority to regulate output distortions

[9] Supply function equilibrium (SFE) models are another popular option for modeling wholesale electricity markets (see, for example, Green and Newbery, 1992; Hortascu and Puller, 2006). Willems et al. (2007) compare these two modeling approaches using data from the German electricity market. They find that the two models perform equally well. They suggest using Cournot models for short term analyses because market details can be more easily accommodated.

[10] See, for example: Bergman and Andersson, 1995; Borenstein and Bushnell, 1999; Cardell et al, 1997; Chen and Hobbs, 2005; Bushnell et al. 2008 ; Demailly and Quirion, 2006; Puller, 2007; Willems, 2007.

[11] In the past, firms in industries targeted by existing and planned incomplete environmental regulation have been able to exercise market power by restricting supply .(Borenstein, Bushnell and Wolak, 2002; Puller, 2007; Sweeting, 2007). Bushnell, Mansur, and Saravia (2008) find that a Cournot model that accounts for vertical arrangement performs particularly well in terms of simulating observed wholesale prices in restructured U.S. electricity markets. Puller (2007) also finds that firm conduct in California's restructured electricity market is consistent with a Cournot pricing game.

directly; she takes the structure of the product market as given. Following Malueg (1990) and Sartzetakis 2004**?**), I assume that firms exercising market power in the product market act as price takers in the permit market. This is an appropriate assumption provided that the industry in question is one of several participating in the cap-and-trade (CAT) program or if regional CAT initiatives are linked to larger international emissions permit market.[12]

Firms' emissions rates per unit of production are exogenous to the model. Thus, emissions abatement is achieved by dispatching units in a way that favors relatively clean generators rather than via production process changes or pollution control equipment retrofits (Levin, 1985; Simpson, 1995; Mansur, 2007(Mansur 2007)).[13] I make the standard assumptions that all participants are risk neutral, all forward contracts are binding and observable, and that all prices are efficiently arbitraged (Allaz and Vila, 1993). Factor markets are assumed to be perfectly competitive. Finally, to simplify the theoretical analysis, I assume an interior solution.[14] My focus is thus limited to the short-run marginal effects of a change in environmental regulation (and thus operating costs) on production and pollution levels when all plants are operating and none are capacity constrained (*i.e.* producing at full capacity). Several of these assumptions are relaxed in the subsequent simulation exercise.[15]

3.2 The one-stage game

This section introduces the one-stage model with N producers (indexed by $i = 1...N$), one homogenous good Q , and one pollutant E. The i^{th} firm's constant marginal production cost is given

[12] The EU ETS covers a variety of sectors, including electricity, iron and steel, oil and gas, building materials, pulp and paper. Similarly, California is designing a multi-sector cap-and-trade program. There is language in both the RGGI program and the California legislation that authorizes linking these regional markets to larger regimes, such as the EU Emissions Trading Program. However, there are likely to be significant obstacles to establishing these linkages in practise.

[13] In the case of most greenhouse gases, opportunities to reduce emissions rates of existing plants via process changes and end-of-pipe emissions controls are very limited. The bulk of greenhouse gas reductions from the electricity sector, in the short run, will be achieved by reorderng the dispatch of existing units so as to increase the capacity factor at relatively clean generators (rather than from retrofitting existing plants with pollution control equipment). Consequently, an analysis that takes unit-level emissions rates as exogenous captures the short run effects of environmental regulation on electricity production to a significant extent.

[14] This is a strong assumption. In any given hour, some generators will choose not to produce while others will be producing at full capacity. This assumption is relaxed in the simulation exercise.

[15] In the simulation exercises, constant marginal costs and interior solutions are no longer assumed. A competitive fringe is also added to the model. Section 5.2 provides a detailed description of how the simulation model differs from the more stylized theoretical framework developed in this section.

by $C_i'(q_i) = c_i$.[16] Emissions at firm i are proportional to output; $E_i = e_i q_i$. Preferences on the part of consumers are represented by an inverse demand function $P = a - b\sum_{n=1}^{N} q_i$.

Suppose a regulation is introduced that requires some subset of the firms in the industry to purchase emissions permits to offset their uncontrolled emissions. Permits can be bought and sold in a competitive permit market at a price τ. Because the permit price is determined exogenously, the emissions trading program represented here is equivalent to a tax τ per unit of pollution.[17] Let the variable d_i indicate mandatory program participation; $d_i = 1$ if the i^{th} firm is required to comply with the environmental regulation, $d_i = 0$ if firm i is exempt.

Firms are assumed to play Nash equilibrium which, conditional on my assumptions, is unique and stable. The i^{th} firm chooses a production quantity q_i to maximize profits π_i. The vector of production quantities $q^* = (q_1^*, ..., q_n^*)$ is a Nash-Cournot equilibrium for this production game if for each i, q_i^* solves

$$\max_{q_i} p_s(q_i, \sum_{j \neq i}^{N} q_j) q_i - c_i q_i + d_i \tau (A_i - e_i q_i),$$

where A_i represents the initial permit allocation to firm i. Assuming perfectly competitive permit market and an interior solution implies that firms' optimal production quantities are independent of A_i.

The equilibrium interior solution is described by the following N first order conditions:

$$p_s(Q) + p_s'(Q) q_i = c_i \ + d_i \tau e_i \ \forall \ i = 1, .., N.$$

Conditional on demand parameters a and b, permit price τ, and cost and emissions rate vectors $\mathbf{c}$ and $\mathbf{e}$, the Nash-Cournot equilibrium firm-level and aggregate production quantities can

[16] Note that each firm is associated with a single constant marginal cost production technology (versus a portfolio of production technologies).

[17] In this analysis, electricity sector emissions are endogenously determined whereas the permit price is an assumed value. As noted above, this is an appropriate approach when the industry of interest is small relative to the larger permit market (such that changes in industry emissions do not significantly affect the equilibrium permit price). In an extension of the analysis presented here; Bushnell (forthcoming) imposes a cap on electricity sector emissions and allows the permit price to be determined endogenously.

be written as functions of the vector of participation indicators $\mathbf{d}$:

$$q_{i1}^{*}(\mathbf{d}) = \frac{a + \sum_{i=1}^{N}(c_i + \tau d_i e_i) - (N+1)(c_i + \tau d_i e_i)}{(N+1)b} \tag{1}$$

$$Q_1^{*}(\mathbf{d}) = \frac{1}{(N+1)b}\left(Na - \sum_{n=1}^{N} c_i - \tau \sum_{n=1}^{N} d_i e_i\right) \tag{2}$$

These equilibrium conditions are derived in Appendix 1. The subscript 1 indicates that these prices, quantities and aggregate emissions correspond to the equilibrium in the single stage model. In the following, I omit the asterisks.

3.2.1 Emissions and Emissions Leakage in the One-Stage Game

Emissions leakage is defined as the difference between the emissions of unregulated firms under incomplete environmental regulation, and emissions of these firms when no environmental regulation is in place. By [1], leakage can be written:[18]

$$L_1 = \sum_{i=1}^{N}(1-d_i)e_i \left(\frac{\sum_{i=1}^{N} \tau d_i e_i - (N+1)\tau d_i e_i}{(N+1)b} \right) \tag{3}$$

$$= \frac{N_1 N_0}{(N+1)b} \tau \ \overline{e_1} \ \ \overline{e_0}, \tag{4}$$

where $\overline{e_1}$ is the average emissions rate among regulated producers and $\overline{e_0}$ is the average emissions rate among unregulated producers. N_1 and N_0 represent the number of regulated and exempt producers, respectively: $\sum_{n=1}^{N} d_i = N_1$; $\sum_{n=1}^{N}(1-d_i) = N_0$.

[18] A derivation of this expression is included in Appendix 1.

A marginal increase (decrease) in the average emissions rate of regulated or unregulated firms has a positive (negative) effect on leakage. The more elastic demand, the smaller the value of b, the greater the emissions leakage. Finally, note that an increase in industry concentration decreases emissions leakage, all else equal. Intuitively, if the product market is more competitive, a given firm's market share will be more significantly affected by a regulation-induced change in relative marginal operating costs (inclusive of compliance costs), and the regulation-induced shift in emissions will be more substantial.

I turn now to a comparison of equilibrium output and emissions under three different regulatory regimes: a benchmark case in which no environmental regulation is present (*i.e.*, $d_i = 0$ for all $i = 1...N$), the complete participation case (where $d_i = 1$ for all $i = 1...N$), and the incomplete participation case where $d_i \neq d_j$ for some $i \neq j$. Let the superscripts B, $COMP$, and INC denote these three equilibria, respectively. Results are summarized by four propositions. Proofs are presented in Appendix 2.

Proposition 1 $Q^B > Q^{INC} > Q^{COMP}$

This follows directly from Equation [2]. Assuming that $\tau > 0$ and that $e_i > 0$ for at least one regulated firm, the introduction of environmental regulation will increase average marginal operating costs (inclusive of compliance costs) in the industry relative to the benchmark case. This induces a decrease in aggregate production. This effect is greater when participation is complete.

Proposition 2 *Complete regulation unambiguously reduces aggregate emissions.*

This also follows from Equation [2]. It is worth noting that this result contradicts Levin (1985) who finds that a uniform Pigouvian tax imposed on all producers in a Cournot oligopoly can increase industry emissions. For this outcome to arise, the second derivative of the inverse demand function must be very large (implying extreme curvature). In assuming linear demand, the possibility of increased industry emissions is ruled out.

Proposition 3 *If $\overline{e_0} > \overline{e_1}$, the introduction of incomplete environmental regulation can result in a net increase in overall emissions.*

It is possible for emissions leakage to exceed the reduction in emissions achieved by regulated firms. The following summarizes the conditions under which the introduction of incomplete regulation will increase industry emissions (derived in Appendix 2):

$$\frac{\overline{e_1^2}}{\overline{e} \cdot \overline{e_1}} < \frac{N}{N+1} \tag{5}$$

The numerator, the sum of the square of the emissions rates of regulated producers, cannot be less than the square of the mean of these emissions rates. Thus, in order for this inequality to be satisfied, the average emissions rate among non-participating firms must be significantly greater than the average emissions rate among regulated firms.

Proposition 4 *If $\overline{e_1} > \overline{e_0}$, aggregate emissions under complete environmental regulation can exceed aggregate emissions under incomplete regulation.*

Emissions under complete participation will exceed emissions under incomplete participation if the following inequality holds:

$$\frac{\overline{e_0^2}}{\overline{e}\ \overline{e_0}} < \frac{N}{N+1} \tag{6}$$

The somewhat counter-intuitive result will only be observed when regulated firms are relatively more polluting. The introduction of the environmental regulation into a Cournot oligopoly market changes firms' relative operating costs and redistributes market share towards firms whose relative costs have decreased. If the firms exempt from the incomplete regulation are cleaner, this reallocation of production may result in lower overall emissions when participation is incomplete. Consequently, incomplete regulation can result in industry emissions that are less than what they would be under complete regulation.[19]

[19] If inequality [6] is satisfied and emissions under complete regulation exceed emissions under incomplete regulation, leakage will still occur. Put differently, production levels and emissions will increase among unregulated producers, but the net reduction in industry emissions will be greater than that achieved by complete regulation.

3.3 The Two-Stage Game

In this section, a forward product market is added to the model. Vertical arrangements are common in several of the major industries currently targeted by incomplete environmental regulation. The effect of forward contract positions on spot market outcomes has attracted particular attention in the context of restructured electricity markets (Bushnell et al, 2008; Wolak et al., 2000). In the dialog surrounding the design and implementation of regional climate policies, policy makers and industry stakeholders have questioned how the introduction of incomplete regulation could affect the forward contract positions taken by regulated and unregulated firms, and thus the patterns of emissions (RGGI Workshop on Electricity Markets, 2004; Wilson et al. 2005).

Following Allaz and Vila (AV), I first derive equilibrium conditions for the spot market production game and then nest that equilibrium outcome in a two-period model in which firms can sell product forward in the first period. Production occurs in the second period spot market. For technical simplicity, I continue to assume an interior equilibrium. Su (2007) proves the existence of a forward market equilibrium in the more general case where producers have nonidentical cost functions and an interior solution is not assumed.

3.3.1 The Spot Market Production Game

Conditional on forward contract positions $\mathbf{f}$, N producers with nonidentical marginal costs c_i engage in Cournot competition in the electricity spot market. The ith firm chooses a level of production q_i to maximize profits:

$$\max_{q_i} \left\{ p_s(q_i, \sum_{j \neq i}^{N} q_j)(q_i - f_i) - c_i q_i + d_i \tau (A_i - e_i q_i) \right\}$$

If the i^{th} producer has already sold f_i in the forward market, she sells only $q_i - f_i$ in the spot market; revenues from the sales of forward contracts are excluded from the spot market production stage profit function. Consequently, when the firm is short on the forward market ($i.e.$ $f_i > 0$) it will be less sensitive to the price elasticity effect of increasing production.

The vector of production quantities $\mathbf{q}^* = (q_1^*, ..., q_n^*)$ is a Nash-Cournot equilibrium for the spot market production game if for each $i = 1, .., N$, q_i^* solves:

$$\max_{q_i} \pi_i \left\{ p_s(q_i, \sum_{j \neq i}^{N} q_j^*)(q_i - f_i) - c_i q_i + d_i \tau (A_i - e_i q_i) \right\}. \tag{7}$$

Assuming an interior solution ($i.e.$ $q_i > 0 \; \forall \; i$) implies the following first order conditions for an equilibrium:

$$p_s'(Q)(q_i - f_i) + p_s(Q) = c_i \; + \tau d_i e_i \; \forall \; i = 1, .., N. \tag{8}$$

For a given set of demand parameters a and b, cost vector and emissions rate vectors $\mathbf{c}$ and $\mathbf{e}$, and a permit price τ, the Nash-Cournot equilibrium for the spot market production stage game is characterized by:

$$q_i(\mathbf{f}) = \frac{a + \sum_{j \neq i} (c_j + \tau d_j e_j) - N(c_i + \tau d_i e_i - b f_i) - b \sum_{j \neq i}^{N} f_j}{(N+1)b} \tag{9}$$

$$Q(\mathbf{f}) = \frac{N}{(N+1)b} \left(a - \frac{1}{N} \sum_{n=1}^{N} c_i - \frac{\tau}{N} \sum_{n=1}^{N} d_i e_i + \frac{b}{N} \sum_{i=1}^{N} f_i \right) \tag{10}$$

Proof. See Appendix 3. ■

Note that the quantity supplied by firm i in the spot market is increasing in f_i and decreasing in f_j. If the firm has taken a more aggressive forward position, the returns to withholding production (and thus raising the equilibrium spot price) are reduced. This is the basic intuition behind the AV result that strategic firms' ability to sell forward (in the absence of any risk) has a pro-competitive effect on spot market outcomes.

3.3.2 The Forward Contract Market

Following AV, I assume that trading in a forward market occurs one period before production takes place. In this first stage, firms simultaneously choose their forward position f_i . Speculators take the opposite position, purchasing the aggregate forward quantity F. Assuming the forward positions of the other firms are fixed, the i^{th} producer chooses f_i to maximize:

$$\max_{f_i} \; \pi_i \left\{ \delta[(p_s(f_i, \bar{F}_{\_i}) - c_i - \tau d_i e_i) q_i(f_i, F_{\_i}) + \tau A_i] + [p_f - \delta p_s(f_i, F_{\_i})] \; f_i \right\}, \tag{11}$$

where δ is the rate at which spot market returns are discounted in the first stage. Rational expectations are assumed, which means that both firms and speculators correctly anticipate the effect of forward market contracting on the spot market equilibrium (*i.e.* $p_f = \delta p_s$). The vector of forward contract quantities $\mathbf{f}^* = (f_1^*, ..., f_n^*)$ is a Nash forward market equilibrium if for each $i = 1, .., N$, f_i^* solves:

$$\max_{q_i} \; \left\{ \delta[(p_s(f_i, F^*_{\_i}) - c_i - \tau d_i e_i) q_i(f_i, F^*_{\_i})] + \tau A_i \right\} \tag{12}$$

Allaz and Vila show how one can solve for a forward market Nash equilibrium in closed-form when demand and cost functions are affine and duopolists have identical cost functions. Su (2006) establishes an existence theorem for the forward market equilibrium when producers have non-identical cost functions by reformulating the forward market equilibrium problem as an equilibrium problem with equilibrium constraints. Building on this previous work, I solve for a forward market interior Nash equilibrium in closed form for a general number of oligopolists with non-identical cost functions.

For a given set of demand parameters a and b and cost vector $\mathbf{c}$, the Nash equilibrium outcome in the forward market can be characterized as follows:

$$f_i^* = \frac{(N-1)a}{(N^2+1)b} + \frac{(N^2-N+1)(1-N)}{(N^2+1)b}(c_i + \tau d_i e_i) + \frac{(N-1)N}{(N^2+1)b}\sum_{j \neq i}(c_j + \tau d_j e_j), \tag{13}$$

$$q_{*i2}(d_1, ..d_N) = \frac{Na + N^2 \sum_{j \neq i}(c_j + \tau d_j e_j) - N(N^2 - N + 1)(c_i + \tau d_i e_i)}{(N^2+1)b} \tag{14}$$

$$Q_2^*(d_1, ..d_N) = \frac{N}{(N^2+1)b}(Na - \sum_{n=1}^{N} c_i - \tau \sum_{n=1}^{N} d_i e_i) \tag{15}$$

These equilibrium conditions are derived in Appendix 4. The 2 subscript indicates that these prices and quantities correspond to the equilibrium in the two stage model where firms compete in both forward and spot markets.

3.3.3 Emissions and Emissions Leakage in the Two-Stage Game

The following expression defines emissions leakage in the two period model:

$$L_2 = \frac{N_1 N_0 N^2}{(N^2+1)b} \tau \, \overline{e^1} \quad \overline{e^0}. \tag{16}$$

It is straightforward to demonstrate that Propositions 1-4 hold qualitatively when firms compete in both spot and forward product markets. Appendix 5 proves these results for the two-stage model.[20] A comparison of [16] and [3] implies the following:

Proposition 5 *The existence of a forward market increases emissions leakage.*

Firm-level production and relative market shares are more responsive to relative changes in the marginal costs of production when firms can sell product forward. In this sense, the presence of forward contracts has the same effect on emissions leakage as a decrease in product market concentration. The presence of a forward market implies a more competitive product market and greater emissions leakage.

3.4 Perfectly competitive markets and corner solutions

In analyzing the effect of market structure on emissions leakage, it is instructive to consider a perfectly competitive industry as a reference case. If price-taking (versus strategic) behavior is assumed for all firms, and if the assumptions of constant marginal operating costs, heterogeneous operating costs, and non-binding capacity constraints are maintained, the competetive equilibrium will be a corner solution (*i.e.* the least cost firm(s) will supply the entire market and relatively high cost firms will produce nothing). Consequently, this informal investigation of the perfectly competitive case admits corner solutions.

[20] Some of these results do differ quantitatively across the one and two-stage models. For example, in the two stage model, a broader range of parameter values imply increasing emissions under incomplete participation.

Consider a perfectly competitive market supplied by the firm with the lowest production costs. Environmental regulation will have no impact on aggregate emissions if the identity of the least cost producer is unaffected by the introduction of the regulation. Similarly, there will be no emissions leakage if the identity of the least cost producer is unaffected by the degree of participation in the environmental regulation. Converseley, if the identity of the least cost producer changes with the introduction of environmental regulation, the effect on aggregate emissions can be dramatic as all production activity shifts from a firm with a relatively high emissions rate to a firm with relatively low emissions. Similarly, emissions leakage can be significant if the identity of the least cost producer depends on the degree of participation.

In summary, whereas an increase (decrease) in the level of industry competitiveness will increase (decrease) emissions leakage when only interior solutions are considered, the relationship between industry competitiveness and emissions leakage becomes more ambiguous when corner solutions are admitted.

4 A stylized example

I now consider the simple duopoly case in order to clarify the key results derived above and to illustrate the welfare implications of incomplete participation in market-based environmental regulation. Here I assume that the duopolists have emissions rates e_{high} and e_{low}, respectively (where emissions rates measure the quantity of pollution emitted per unit of output; $e_{low} < e_{high}$). The i^{th} firm's marginal cost of producing electricity is given by $C_i'(q_i) = c_i,\ i = low,\ high$. Firms face demand $P(q_{low} + q_{high}) = a - bq_{low} - bq_{high}$. Within this simple framework, equilibrium conditions are analyzed under four different regulatory regimes. In the benchmark case, emissions are unregulated. Under complete regulation, both firms are obliged to pay τ per unit of pollution they emit. Under incomplete regulation, only one of the firms is subject to the regulation.

4.1 Analysis of Emissions and Emissions Leakage

Figure 1 plots the best response functions of the duopolists in the single-stage game. The positive domain of the horizontal and vertical axes measure the production quantities of the *low* and *high* firms, respectively. The firms' emissions rates (e_{low} and e_{high}) are measured on these axes below and to the left of the origin, respectively.

The solid, downward sloping lines represent best response functions in the benchmark case. The intersection of these lines (point A) defines equilibrium production quantities when emissions are unregulated. The broken lines represent the best response functions under complete regulation. Complying with the environmental regulation increases the marginal production costs at both firms, shifting both best response functions towards the origin. Note that the best response function of the relatively dirty firm shifts towards the origin by relatively more. The intersection of these broken lines (point B) defines the equilibrium production quantities under complete environmental regulation.

With only two firms, there are two possible forms of incomplete environmental regulation. Point C defines equilibrium production levels when only the relatively clean firm is required to participate. Point D identifies the equilibrium quantities under the second scenario when only the firm with the relatively high emissions rate is subject to the regulation. Note that the best response function of the unregulated firm is unaffected by the introduction of incomplete regulation.

Emissions and emissions leakage can be measured in terms of the rectangular areas labeled F through L. Complete environmental regulation reduces emissions by $J - G$. If only the relatively clean firm is subject to the regulation, emissions leakage (equal to area I) exceeds the emissions reductions at the regulated firm (equal to area F). Figure 1 depicts a case where the introduction of incomplete environmental regulation results in a net *increase* in emissions relative to the benchmark case when the regulated firm is relatively clean. Note that, for this to occur, inequality [5] must be satisfied.

If only the relatively more polluting firm is subject to the regulation, emissions reductions at the regulated firm $(J + K)$ significantly exceed leakage $(G + H)$. Consistent with Proposition 4, aggregate emissions under complete participation *exceeds* incompletely regulated emissions. Note that this will only occur when the regulated firm is relatively clean and [6] holds.

Figure 2 plots the best response functions of the same duopolists competing in both spot and forward markets. Introducing a forward market to the model shifts the best response functions of both firms away from the origin. The intersection of the solid lines (point A) defines equilibrium production in the absence of environmental regulation.

The broken lines in Figure 2 define best response functions both duopolists under complete regulation. The introduction of the complete regulation affects the equilibrium forward positions of both firms. As a consequence, the best response function of the relatively less (more) polluting firm shifts in by relatively less (more) as compared to the previous example where firms compete in spot markets only. The effect of complete environmental regulation on aggregate emissions is amplified. Complete regulation reduces overall emissions by $P - M$.

The dotted lines in Figure 2 represent the best response functions under incomplete regulation that exempts the relatively more polluting firm. Contrary to the single-stage model, the best response function of the unregulated firm *is* affected by the introduction of the incomplete regulation. By [13], the increase in the regulated firm's marginal operating costs will induce the unregulated firm to increase its forward position, hereby shifting $q_{HIGH}(q_{LOW})$ away from the origin. The incomplete regulation affects the best response function of the regulated firm in two ways. First, the regulation-induced increase in marginal operating costs shifts the firm's best response function towards the origin. Second, by [13], the regulated firm will reduce its forward position, thus shifting its best response function further towards the origin. The combination of these effects results in more emissions leakage than would have occurred had firms competed in a spot market only. In Figure 2, leakage is represented by area O.

4.2 Welfare implications of incomplete regulation

Now consider the problem faced by a social welfare maximizing regulator. For expositional clarity, I adopt the simplest possible welfare measure. Welfare is defined to be the gross consumer benefit from consumption less production costs less monetized damages from emissions. This assumes that the regulator is indifferent to purely redistributional effects and weights all welfare impacts equally, regardless of the jurisdiction in which they accrue.[21] To further simplify, I assume that marginal damages are constant and equal to the prevailing permit price τ.[22]

The regulator's objective function can be written:

$$W(d_1, d_2) = \int_0^{Q(d_1,d_2)} D(s)ds - \sum_{i=1}^{2} c_i q_i(d_1, d_2) - \tau \sum_{i=1}^{2} e_i q_i(d_1.d_2).$$

Suppose that jurisdictional, political, or technical constraints limit the reach of this regulator such that firm 2 cannot be required to participate in the environmental regulation. The regulator will only want to introduce the incomplete regulation if doing so improves welfare. The net welfare effect of introducing incomplete regulation can be obtained by subtracting $W(0,0)$ from $W(1,0)$ and rearranging:

$$W(1,0) - W(0,0) = \int_{Q^B}^{Q^{COMP}} P(s)ds + \frac{\tau}{3b}\left(e_1(3c_1 - 2\bar{c})\right) + \frac{\tau^2}{3b}(3e_1^2 - 2e_1\bar{e}). \tag{17}$$

Requiring firm 1 to purchase permits to offset its emissions affects overall welfare via three different channels, each corresponding to one of the three arguments in [17]. The first argument measures the change in gross consumer benefit from consuming Q. The second measures the change in overall costs that results from both a change in industry production levels and a reallocation of production across duopolists. The final argument measures the change in monetized damages from emissions.

With regard to the first argument, aggregate production is unambiguously reduced under incomplete regulation (assuming that the permit price is strictly positive and $e_1 > 0$). This regulation-induced reduction in overall output can be associated with a decrease in average production costs (net of environmental compliance costs) if the unregulated firm has relatively low production costs. Conversely, if firm 2 is the relatively less productively efficient firm, the introduction of incomplete regulation can exacerbate the allocative production inefficiencies resulting

[21] An alternative approach could define welfare as a weighted sum of producers' and consumers' surplus, with less (or zero) weight ascribed to costs and benefits accruing to agents outside the jurisdiction imposing the regulation.

[22] In this example, all factor markets are assumed to be perfectly competitive. If inputs to production were taxed, this could introduce tax interaction effects with significant welfare implications. These are not considered here.

from the exercise of market power. Thus, the second argument can be either positive or negative, depending on the relative emissions rates and production costs of participating and exempt producers.

The effect of incomplete regulation on aggregate emissions (and thus damages) will depend on the relative emissions rates of the regulated and unregulated producers. Although the introduction of incomplete regulation will most likely reduce industry emissions in equilibrium, if the unregulated firm is more polluting than the regulated firm, it is possible that damages could increase under incomplete regulation.

Figure 3 illustrates how forward contracts, firms' emissions rates, and the degree of regulatory participation together determine net welfare impacts within this simple framework. To generate these figures, the emissions rate of the unregulated firm has been normalized to 1. The marginal production costs of firm 2 are assumed to be less than those of firm 1. This implies that the introduction of incomplete regulation will mitigate pre-existing allocative inefficiencies by raising the production costs of the relatively less efficient firm.[23]

The left panel plots environmental regulation induced welfare changes as a function of the emissions rate of firm 1 in the single-stage game. The solid line plots the welfare change induced by incomplete regulation (as defined by equation [16]). The broken line plots the welfare effects of complete regulation relative to the benchmark case (*i.e.* $W(1,1) - W(0,0)$). Note that the introduction of complete regulation decreases welfare over a large range of $e_1$values. The welfare costs induced by the regulation (*i.e.* further contraction of industry output and, when $e_1 < e_2$, an exacerbation of pre-existing allocative production inefficiency) overwhelm the benefits associated with a reduction in industry emissions. If the assumed damages per unit of emissions were to increase, welfare changes induced by complete regulation would be strictly positive over a larger range of e_1. For sufficiently large values of τ, the introduction of complete regulation will be welfare improving for all values of e_1 .

[23] Parameter values used to generate these figures are: $a = 80; c_1 = 1; c_2 = 3; e_2 = 1; b = 1; \tau = 10$.These parameter values are not meant to be representative of any particular policy scenario. This example is used to illustrate simple theoretical relationships between firms' relative emissions rates, the degree of regulatory participation, and welfare. A more realistic simulation model is introduced in section 5.

In the example depicted by Figure 3, incomplete regulation welfare dominates complete regulation over a wide range of values of e_1. Intuitively, incomplete regulation will welfare dominate complete regulation if the benefits of excluding firm 2 from the regulation (namely higher levels of industry production and more efficient allocation of production across firms) exceed the costs (namely, the damages associated with emissions leakage). The range of e_1 over which incomplete regulation welfare dominates would decrease (increase) if τ were to increase (decrease) because this increases (decreases) the costs of incomplete participation. An increase (decrease) in c_2 would increase (decrease) the benefits of incomplete participation vis a vis complete participation.

Welfare implications of introducing complete and incomplete regulation into the two-stage model are illustrated by the right panel. As compared to the one-stage model, complete regulation welfare dominates incomplete regulation over a broader range of e_1. Furthermore, the range of e_1 for which either regulation is welfare increasing has increased. Because of the pro-competitive effects of forward contracts, the pre-existing product market distortions are less severe in the two-stage model. Consequently, the potential gains from mitigating allocative production efficiencies through the introduction of incomplete regulation that exempts the relatively more efficient firm are reduced.

5 Assessing the potential for leakage in California

The theoretical framework developed in the previous sections provides some basic intuition about how observable features of an industry (such as emissions rates, operating costs, and industry structure) can affect both emissions leakage and overall welfare. However, these theoretical models are too abstract to be applied directly in an analysis of a particular policy. In this section, I demonstrate how the theoretical framework can modified so as to facilitate a more realistic and detailed policy analysis under alternative assumptions about firm conduct.

Leakage has become a defining issue in the debate over how California should curb GHG emissions from electricity generation (Climate Action Team, 2005; CCAP, 2005; CEC, 2005). Regulation passed in California in 2006 mandates a 25 percent reduction in state-wide GHG emissions by 2020. Ideally, California would regulate all electricity producers supplying the California market. Constitutional law and other jurisdictional limitations make this impossible. Legislators anticipate that the emissions leakage associated with an emissions trading program for only in-state producers would be substantial.[24]

In many respects, the theoretical framework developed in the previous section is particularly well suited to this application. Past research has demonstrated how the exercise of market power during peak hours has significantly affected outcomes in California's electricity industry (Borenstein, Bushnell and Wolak, 2002; Joskow and Kahn, 2001; Bushnell et al. 2007; Puller, 2007).[25] Moreover, theoretical and empirical analysis of restructured wholesale electricity markets indicates that the extent of forward contracting by suppliers has been an important determinant of equilibrium outcomes in restructured electricity markets (Bushnell et al., 2005; Chen and Hobbs, 2005; Wolak, 2000). Finally, the suite of generation technologies used to produce electricity market is very heterogeneous. This gives rise to significant variation in operating costs, operating constraints, and emissions rates across producers.

Detailed data from California and surrounding states (Arizona, Nevada, New Mexico, Oregon, Utah, Washington) are used to parameterize three numerical models based on the theoretical framework developed in the previous section: a one-stage model of oligopolists facing a competitive fringe, a two-stage model in which firms choose both spot market production and forward contract positions to maximize profit, and a model that assumes perfect competition. The one-stage Cournot model represents an upper bound on the extent to which market power could be exercised in this market, whereas the perfectly competitive case represents a lower bound. An investigation of outcomes under both extremes helps to define the range of possible emissions leakage outcomes, conditional on observed technology characteristics, ownership structure, demand patterns, etc. Conditional on firms being able to sell product forward, the two-stage model defines

[24] California is currently working with other states and Canadian provinces, under the auspices of the Western Climate Initiative (WCI) to develop a regional GHG emissions reduction strategy. However, California is the only state in the WCI that is actively developing a cap-and-trade system. (CARB, 2008; CCAP, 2005; CEC, 2005; CEC, 2008).

[25] Technical rigidities on the supply side (including transmission constraints and the prohibitively high costs of storing electricity) and a lack of short run demand response (due to limited real time metering and the nature of the commodity) make it impossible to rely exclusively on competitive markets to balance supply and demand. Designing perfectly competitive wholesale markets for electricity has proved difficult. Even where the market structure seems conducive to competition (i.e. ownership of generation assets is not concentrated and access to transmission capacity is not limited), market power can be exercised at particular locations or times.

the theoretical upper bound on the supply function equilibria.

Three regulatory scenarios are considered: (1) no regulation of GHG emissions (the baseline case); (2) a scenario in which all producers must purchase permits to offset uncontrolled emissions (*i.e.* complete market-based regulation); (3) market-based regulation of GHG emissions from California generators.[26] In these simulations, as in the theoretical model, the permit price is assumed (versus determined endogenously).

5.1 Modifying the model to reflect the realities of California's electricity market

To carry out the simulation exercises, the theoretical framework is modified in several important ways. First, some of the simplifying assumptions that were made to keep the theoretical analysis tractable cannot reasonably be maintained in this applied exercise. Constant marginal costs and interior solutions are no longer assumed. Equilibrium production quantities are those that maximize producer profits subject to unit-level capacity constraints, major transmission constraints, and assumed native load service obligations.

I assume perfectly inelastic demand in the short run. Electricity demand tends to be highly inelastic in the short run because few consumers have incentives to respond immediately to fluctuations in wholesale prices. Furthermore, the firms that procure customers' electricity in the wholesale market are mandated to provide the power at any cost. The simulation model can be modified to accomodate some demand response. Appendix 7 explores how simulation results change when demand elasticity is incorporated into hourly simulations.

Finally, a competitive fringe is added to the simulation model. In general, restructured

[26] Scenarios (2) and (3) encompass the range of possibilities under the "first-deliverer" program design that is being pursued in California. If all emissions from imports can be effectively traced back to sources located in non-participating jurisdictions, the first-deliverer design is equivalent to complete participation. The incomplete regulation scenario represents the other extreme: a scenario in which it is not possible to charge deliverers for the emissions associated with their imports. If California proceeds unilaterally with its proposed suite of state-level policies, the outcome would likely fall somewhere in between these two extremes. Regulations precluding long term contracts with relatively dirty out-of-state sources, protocols to measure out of state emissions, and other institutional factors would mitigate leakage to some extent. However, practical difficulties associated with accurately tracking and measuring emissions from imports makes complete elimination of the leakage problem unlikely.

wholesale electricity markets are served by a group of dominant firms and a fringe of smaller, price taking suppliers. If demand is perfectly inelastic, any production that is strategically withheld by dominant producers will be replaced with fringe production. The presence of the fringe has important implications for emissions leakage and overall efficiency.[27] To the extent that the introduction of environmental regulation increases the fringe market share, the regulation will exacerbate allocative production inefficiencies.

5.2 Data

The following sections describe the data used in the simulations. A detailed description of how the simulations were carried out is included in Appendix 6.

5.2.1 Generation Ownership

The analysis uses equity ownership as of January 2005. Plant ownership information from EIA Form 860 was checked against 2004 SEC 10K filings and a data set compiled by the Natural Resources Defence Council (2004).[28] Table 1 summarizes ownership of generation installed in the western states. Any generating capacity belonging to a parent company owning less than 2000 MW of fossil-fuelled generation is aggregated into a non-strategic, price-taking fringe. Ownership of the generating facilities operating in these states is shared by 341 firms. The eleven strategic firms own over half of the electricity generating capacity in California.

5.2.2 Imports and Load Serving Obligations

California control operators are required to report and classify metered electricity flows across California's borders. The California Energy Commission (CEC) assumes that all electricity generation that is owned or under contract by California utilities is used to meet California demand.[29] Pro-

[27] Mansur (2008) demonstrates how the exercise of market power in the PJM electricity market reduced overall emissions (relative to perfect competition) because fringe firms in PJM are relatively less polluting on the margin, as compared to dominant firms. In California, the reverse is more likely; the marginal fringe unit is more likely to be relatively more polluting.

[28] In cases where data was inconsistent across sources, the SEC filings were used.

[29] This approach may overestimate California imports. There may be hours when some of this out-of-state coal generation is used to serve native load.

duction at these facilities is classified as "firm imports". Appendix 8 lists the out-of-state capacity owned by California utilities. This generation plus known, long-standing contracts constitute firm imports.[30]

Total imports less firm imports are classified as "state" imports. State imports are grouped into two source regions: Pacific Northwest (PNW) and Southwest (SW). Electricity supply and demand in Washington and Oregon is used to represent PNW. Electricity supply and demand in Arizona, Nevada, New Mexico, and Utah is aggregated to represent the SW region. I assume that out-of-state generation not owned by California utilities is obliged to supply native load before it is made available to California. States surrounding California have not restructured their respective electricity industries. I assume that generation in these states is dispatched to minimize costs.

5.2.3 Load

All control areas must report hourly electrical load to the Federal Energy Regulatory Commission (FERC) as part of their Form No. 714 (FERC-714) reporting requirements.[31] Hourly loads reported by electric utility control and planning areas in California and surrounding states in 2004 (the most recent data available) are used in the simulations.[32]

5.2.4 Major Interstate Transmission Capacity Constraints

Transmission congestion limits the amount of electricity that can be imported into California in some hours. These constraints have implications for leakage. Transmission constraints limiting the flow of imports into California from neighboring states are represented crudely by the capacity constraints imposed by the two major interstate transmission paths. Path 66 connects northern California and Oregon. Upgrades in 2001 increased the transmission capacity of this path to 5,400 MW. Path 46 connects Southern Nevada and Arizona to Southern California. The total Path 46

[30] In 1985 SDG&E and PGE entered into an agreement for the purchase of 75 MW of capacity from PGE's Boardman Coal Plant from January 1989 through December 2013. SDG&E pays a monthly capacity charge plus a charge based upon the amount of energy received. California utilities also contract with the Western Area Power Administration for approximately 2000 GWh of hydro power annually.

[31] The FERC-714 is authorized by the Federal Power Act and is a regulatory support requirement as provided by 18 CFR § 141.51.

[32] 2004 was described by the California Energy Commission and the California ISO as a year of "average weather conditions" in the state (CEC et al. 2005).

system has a maximum capacity of 10,118 MW.

5.2.5 Generation Capacity Constraints

Generation capacity constraints are imposed at the boiler level. Installed capacities of thermal and nuclear generating units (denoted MW_i) are adjusted to reflect seasonal changes in operating conditions and the probability that the unit will be unavailable in any given hour. Thermal unit capacity is derated to reflect summer operating conditions.[33] The North American Electric Reliability Council (NERC) tracks unit availability and outages at over 91% of installed capacity in North America.[34] These data are used to estimate unit-level forced outage factors f_i . For each unit, dependable capacity is calculated as $DMW_i = MW_i\ (1 - f_i)$.[35]

5.2.6 Hydro, Nuclear, and Renewable Generation

A significant share of California's gross system power is generated using large hydro, nuclear, and renewable generation assets.[36] Nuclear generation units are treated as must-run and must-take resources in the wholesale market simulations. Renewable generation capacity is discounted using GAR data and other available estimates of average resource availability.

Monthly hydro generation data are available for all hydro units in all states. Hourly hydro generation data for 2004 were obtained from the California Independent System Operator (ISO). The monthly data from California are used to calculate month-specific percentages measuring the share of total hydro generation accounted for by hourly ISO data. These percentages are used to scale up the hourly hydro generation data.[37] I assume that hydro generation dispatch will be unaffected by the introduction of a cap-and-trade program for GHG emissions. Hydro generation in surrounding states is only used to serve California demand if it is not required to meet native

[33] The summer derate capacity can range from 90 to 96 percent of nameplate capacity based on the type of unit and location.

[34] These data are compiled annually and reported in the Generating Availability Report (GAR).

[35] Alternatively, Monte Carlo simulation methods could be used to simulate forced outages (see Borenstein, Bushnell and Wolak, 2002). This approach is difficult to implement in this context, where equilibria of a two-stage game is solved for in each hour. The approach taken here is similar to that adopted by Bushnell, Mansur and Saravia(2008).

[36] It is estimated that in 2005, large hydro, nuclear and renewable generation accounted for 17 percent, 14 percent and 11 percent of gross system power, respectively (CEC, 2006).

[37] On average, the California ISO hourly data represents two thirds of state hydro generation.

load obligations.

5.2.7 Marginal Operating Costs

Unit-level marginal operating costs consist of three components: variable fuel costs, variable non-fuel operating and maintenance costs, and variable environmental compliance costs. Fuel costs (measured in \$/MWh) are calculated by multiplying a unit's reported heat rate by the corresponding fuel costs (reported in FERC form 423). I make the standard assumption that 20 percent of non-fuel, non-rent, non-compliance operating and maintenance costs are variable.[38] Finally, for thermal units subject to the Acid Rain Program and/or the RECLAIM Program, variable environmental compliance costs are calculated by multiplying a unit's reported emissions rate (measured in lbs/MWh) by the average pollution permit price in 2004.

CO_2 emission rates are estimated at the boiler level. All thermal electricity generating units over 25 megawatts must continuously monitor and report hourly CO_2 mass emissions, heat inputs, and steam and electricity outputs to the U.S. Environmental Protection Agency.[39] Hourly, boiler-level data are used to estimate CO_2 emissions rates when available. For smaller units that do not report hourly CO_2 emissions, technology specific estimates of emissions rates for California producers reported in CEC (2005a) are assumed.

5.2.8 Permit Price

Simulations assume a permit price of \$25/ton CO_2. Tol (2007) reviews 103 estimates of monetized damages per ton of carbon dioxide. He reports mean damages of \$25 per ton of carbon dioxide (although he argues that true damages are unlikely to exceed \$14 per ton). This value is also representative of observed prices in the largest operating carbon market (the EU ETS). The average price per ton of CO_2 in the EU market was \$24.30 in 2007.

[38] This is the assumption made by Platts and RDI.

[39] In a few instances, emissions reported in the hourly data were implausibly large or small. The CO2 emissions depends on the amount of carbon that the original fuel contains. When reported emissions deviated significantly from expected emissions (based on reported heat rates, output, and fuel btu content), emissions were imputed based on fuel-specific emissions rates.

5.3 A Preliminary look at the data

Figures 4, 5, and 6 summarize the emissions, marginal operating costs, and load data for California, the Pacific Northwest (Washington and Oregon) and Southwest (Arizona, Nevada, New Mexico, and Utah). To construct these figures, generating units within each region are arranged in ascending order of marginal operating cost (*i.e.* variable fuel costs, variable operating and maintenance costs, and variable costs of complying with SO_2 and NOx regulations where applicable).[40] The monotonic step function in the top panel of each figure traces out an aggregate marginal cost curve for each region. The bar graphs behind these marginal cost curves represent the emissions rates (measured in lbs of CO_2/MWh) corresponding to each unit.[41] For each region, a distribution of hourly load is also constructed using the 8784 realizations of hourly load in each region in 2004. These distributions are displayed in the lower panel of each figure.

Comparing the two panels helps to illustrate the extent to which the different regions rely on imports.[42] Of all three regions, supply is tightest in Californa. In hours when California's demand for out-of-state imports is high, it is likely that demand in neighboring states will also be high because hourly electricity demand in California is positively and significantly correlated with hourly demand in the Southwest and Northwest (correlation coefficients for 2004 hourly load are 0.89 and 0.58, respectively). Taken together, Figures 4, 5, and 6, and regional load correlations suggest that, in hours of high demand, the marginal unit in California hours could easily be more polluting than the marginal out-of-state unit.

5.4 Simulation results

Hourly electricity production at generating units in California and six neighboring states (Arizona, Nevada, New Mexico, Oregon, Utah, Washington), hourly imports, hourly wholesale electricity

[40] Data from out-of-state units owned by California utilities are used to generate the California figure.

[41] In California (figure 4), considerable hydro and renewable generation is represented by the zero or very low cost generation with zero CO_2 emissions. Out-of-state plants owned by California utilities are included in this figure. These coal units correspond to the low cost units with high emissions rates (to the left of the figure). Figures 5 and 6 represent the SW and PNW regions, respectively. The low cost units with high CO_2 emissions rates in the Southwest are all coal-fired. Figure 6 illustrates substantial hydro resources in the PNW region. Both figures illustrate that both regions have the capacity to export power to California in most hours.

[42] Installed capacity measures (versus dependable capacity) are used to generate these figures.

prices, and hourly emissions are simulated under all three policy scenarios, under all three sets of assumptions regarding firm conduct. This section discusses these results in detail.

5.4.1 The Benchmark Case

Before turning to the results from the counterfactual policy simulations, it is instructive to compare the outcomes we actually observed in 2004 (when no CO_2 regulation was in place) with the simulation results generated using models that assume no CO_2 emissions regulation. Over 8784 hours, the average wholesale electricity price associated with the two-stage simulation model is within one percent of the observed average price. As expected, prices simulated using the single-stage model (*i.e.*that assumes a less competitive spot market) are higher than observed prices (by approximately 3 percent on average). Simulations that assume a perfect competitive wholesale electricity market yield an average wholesale electricity price that is three percent below the observed average.

The last three rows of table 3 summarize simulated and observed emissions. Simulated emissions associated with California load (*i.e.* emissions from both in-state generation and imports) are within 1 percent of estimated emissions. The two-stage Cournot model performs the best in terms of predicting emissions that most closely approximate Caifornia Energy Commission's estimates. In these simulations, the average emissions rate of the marginal fringe firm is 1.08 lbs CO_2/kWh, exceeding the average emissions rate of the marginal unit operated by a strategic firm (0.91 lbs/kWh).

All three simulation models overpredict total emissions (summed across all Western states) by a considerable margin (i.e 12 percent). Discrepancies between simulated emissions and those estimated by the California Energy Commission or the Energy Information Administration are likely attributable to several factors. First, assumptions about emissions from small units and hourly hydro generation (particularly outside of California) may not reflect the realities in any given hour. These inaccuracies can result in inaccurate estimates of equilibrium prices and emissions. The simulation model also does not account for intertemporal operating constraints which can result in generators being willing to operate when prices are below marginal costs, or being unable to operate at full capacity when price exceeds marginal costs.[43] Finally, it is worth noting that the "observed" numbers reported by the EIA and CEC are by no means exact measures. In particular, emissions outside of California are somewhat crudely measured.

In summary, observed prices and emissions are most consistent with the two-stage model that assumes strategic behavior on the part of the largest producers. These findings are consistent with past empirical studies of California's wholesale electricity market which find that observed market prices exceed the competitive benchmark (Borenstein *et al.* 2002; Bushnell *et al.* 2008; Puller, 2007). Although the exercise of market power is one possible explanation, there are a number of institutional factors that could explain the relatively poor fit of the competitive model.[44] A more rigorous investigation of firm conduct in this electricity market is beyond the scope this analysis. In the interest of characterizing a range of possible outcomes, counterfactual policy simulations are conducted using all three simulation models.

5.4.2 Counterfactual Policy Scenarios

Results from the counterfactual policy simulations are summed across hours to estimate total emissions and production costs over a calendar year (2004). Table 3 provides a numerical summary of the results generated using the one-stage Cournot model, the two-stage Cournot model, and the model that assumes price taking behavior on behalf of all producers.

The introduction of environmental regulation (assuming a permit price of $25/ton) significantly impacts wholesale electricity prices. As expected, the resulting increase in wholesale electricity price is greater (in absolute and percentage terms) in simulations that assume a less competitive electricity market. In simulations that assume dominant firms behave strategically, complete regulation delivers an 8.5 percent reduction in total emissions. Incomplete regulation achieves 35 percent of these emissions reductions. The simulation model that assumes price taking behavior on behalf of all producers yields somewhat different results. The effect on wholesale electricity

[43] Mansur (2008) demonstrates how the competitive benchmark approach to measuring market power in electricity markets will overstate actual welfare losses if intertemporal operating constraints (and other non-convexities) are ignored.

[44] For example, intertemporal operating constraints are not represented in this model. Mansur (2008) demonstrates that ignoring production constraints that result in non-convex costs can lead to inflated estimates of the degree to which market power is being exercised.

prices is relatively small. Complete regulation delivers emissions reductions of over 11 percent. Incomplete regulation achieves only 25 percent of the emissions reductions achieved under complete regulation.

Recall that, in imperfectly competitive product markets, incomplete environmental regulation can potentially mitigate pre-existing allocative production inefficiencies if exempt facilities employ relatively more efficient (or less costly) production technologies. Figure 7 illustrates that, in this case, incomplete regulation leads to less efficient production. To construct this figure, the variable operating costs of meeting inelastic demand are computed in all hourly simulations. These costs include fuel costs and operations and maintenance costs, but do not include the costs of purchasing permits to offset CO_2 emissions. The hourly cost data generated using the two stage simulation model are plotted against hourly load. Flexible polynomial functions are fit to these data, summarizing how the average cost per MWh produced varies with load in the absence of regulation (the solid line), under complete regulation (the broken line), and under incomplete regulation (the dotted line). Intuitively, because the competitive fringe is disproportionately comprised of out-of-state producers, the fringe market share is greater under incomplete regulation. This implies higher average production costs under incomplete regulation.

Finally, simulated costs and emissions can be used to calculate the cost per ton of CO_2 reduced. To do this, operating costs (excluding the cost of complying with CO_2 regulation) are summed across producers, across hours under complete environmental regulation, incomplete environmental regulation, and in the absence of regulation. Aggregate variable operating costs in the absence of regulation are then subtracted from aggregate variable operating costs under environmental regulation. This difference represents the costs of dispatching more costly (but lower emitting) units in order to achieve emissions reductions. To compute the average abatement cost, I divide total abatement cost by the total emissions reductions. In the simulation models that assume strategic behavior, the average cost per ton of abatement under complete regulation is approximately \$31. This cost increases to \$78 under incomplete regulation. The average cost per ton of emissions reduced under perfect competition is below \$6. This average abatement cost increases to \$80 per ton under incomplete regulation.

6 Concluding remarks

Incomplete industrial participation in market-based environmental regulation has the potential to significantly undermine policy effectiveness. This paper develops a theoretical framework for analyzing emissions leakage, and associated welfare implications, in an incompletely regulated, imperfectly competitive industry.

Several key results emerge from a theoretical analysis of the partial equilibrium model. First, industry structure can play an important role in determining the extent to which emissions leakage occurs. The more competitive the industry, the greater the effect of incomplete participation on industry emissions (assuming interior equilibria). The relative emissions rates at regulated versus unregulated facilities also matters. If regulated firms are cleaner than their unregulated counterparts (and unregulated production can be easily substituted for regulated production), industry emissions will exceed the emissions that would have occurred under complete regulation. Conversely, if regulated firms are dirtier than their unregulated rivals, industry emissions under complete participation can exceed emissions under incomplete participation.

The net welfare effects of incomplete participation depend not only on the extent to which emissions leakage occurs, but also on how incomplete regulation affects industry production in aggregate, and the regulation-induced reallocation of production among heterogeneous producers. There are two potential sources of welfare gains from introducing environmental regulation into an imperfectly competitive market: those associated with reduced emissions, and those potentially achieved through a reallocation of production that favors more efficient producers. These are weighed against the welfare costs associated with reduced output and the potential to exacerbate pre-existing allocative inefficiencies. If exempt producers are more (less) efficient relative to their regulated rivals, the introduction of incomplete environmental regulation will mitigate (exacerbate) pre-existing allocative production inefficiencies.

Detailed data from California's electricity industry are used to analyze the implications of incomplete participation in a state-level, market-based regulation that aims to reduce greenhouse gas emissions from electricity consumption in the state. A numerical model that can accommodate strategic behavior in California's wholesale electricity market, forward contracts, and heterogeneous production technologies is used to simulate CO_2 emissions under a complete cap-and-trade program and a cap-and-trade program that only applies to in-state generators. Assuming a permit price of \$25/ton of CO_2, results indicate that complete regulation of an imperfectly competitive electricity sector would reduce total emissions by 8 percent in the short run . This number increases to 11 percent if the electricity market is assumed to be perfectly competitive. Simulation models that assume an imperfectly competitive electricity market predict that incomplete regulation would achieve 35 percent of the emissions reductions achieved under complete regulation. This number drops to 25 percent if competitive electricity markets are assumed. In all cases considered, costs per ton of CO_2 emissions reduced are significantly lower under complete regulation as compared to a regulation that exempts out-of-state producers.

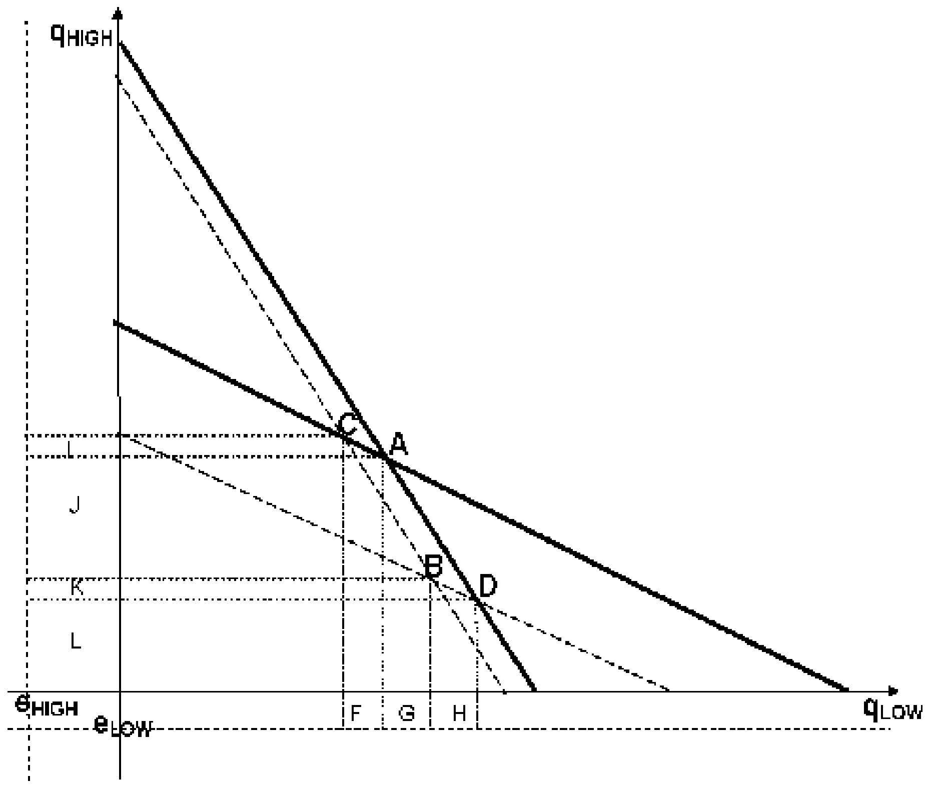

Figure 1 : The One-stage Duopoly Game

Notes: This figure plots the best response functions of duopolists competing in a spot market. The positive domain of the horizontal and vertical axes measures output at the relatively more polluting and less polluting firm, respectively. Emissions rates (measured in units of pollution per unit of output) are measured in the negative domain. The solid lines correspond to best response functions in the absence of environmental regulation. Broken lines represent best responses when environmental regulation is in place. Emissions leakage under incomplete regulation that exempts the relatively more polluting firm is represented by area I. Emissions leakage under incomplete regulation that exempts the relatively less polluting firm is equal to area G+H.

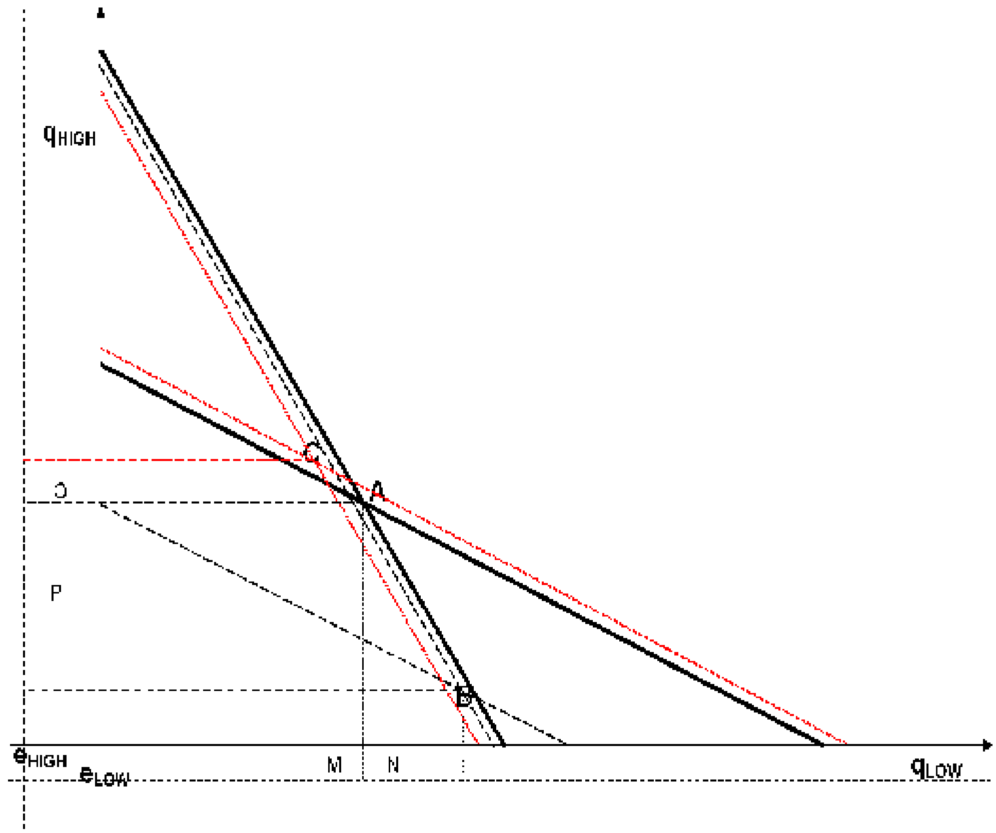

Figure 2 : The Two-Stage Duopoly Game

Notes: This figure plots the best response functions of duopolists competing in both spot and forward markets. The positive domain of the horizontal and vertical axes measures output at the relatively more polluting and less polluting firm, respectively. Emissions rates (measured in units of pollution per unit of output) are measured in the negative domain. The solid lines correspond to best response functions in the absence of environmental regulation. Broken lines represent best responses when complete environmental regulation is in place. Best response functions under environmental regulation that exempts the relatively dirty firm are represented by the dotted lines. Leakage is equal to area O.

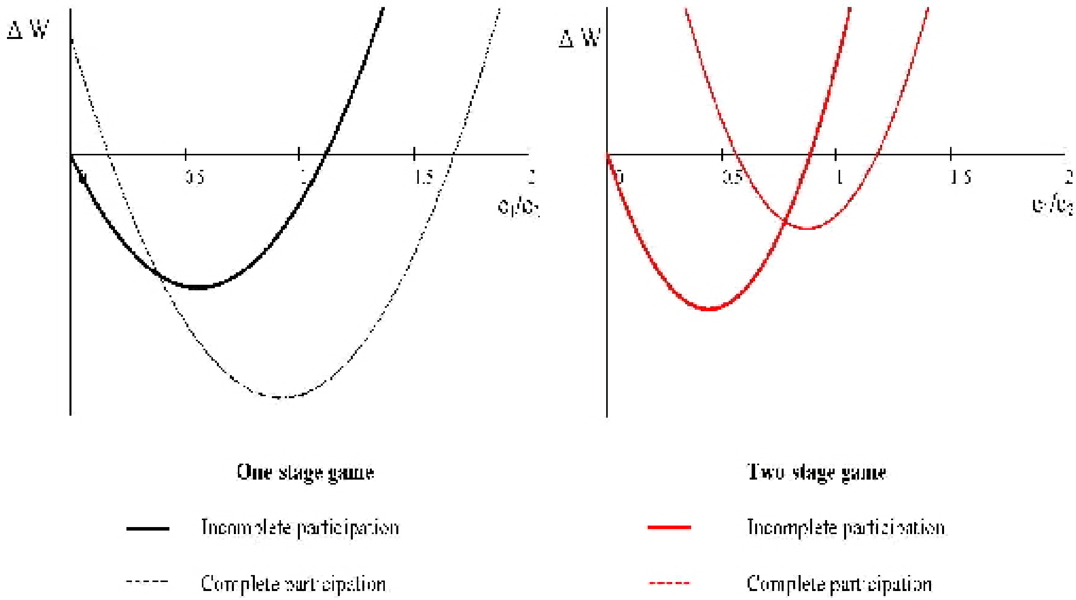

Figure 3 : Welfare Effects of Complete and Incomplete Regulation

Notes: This figure illustrates how welfare changes following the introduction of both complete and incomplete environmental regulation. The left panel plots welfare changes under the single-stage model. The right panel corresponds to the two-stage model. To generate these figures, parameter values are defined as follows: a=80; c1=3; c2=1; e2=1; b=1; t=10.

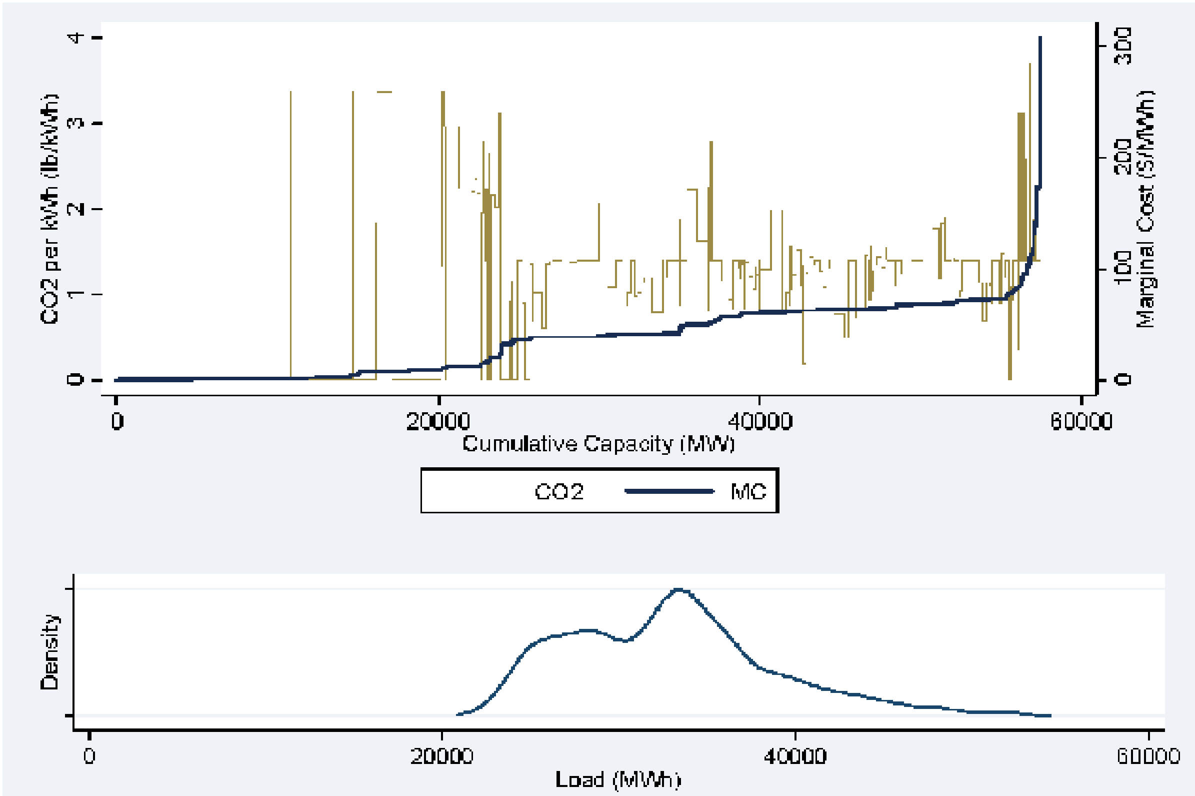

Figure 4 : Marginal Costs, CO_2 Emissions Rates, and Hourly Load in California

Notes: The monotonic step function in the upper figure traces out the marginal operating costs of generating units in California arranged in ascending order of operating cost per MWh. These costs include fuel, variable operating and maintenance costs, and marginal costs of complying with NOx and SO2 regulations in 2004. The bars in the upper panel represent the corresponding, unit-specific CO2 emissions rate (measured in lbs of CO2 per MWh). The bottom panel represents the distribution of hourly electricity demand in California in 2004.

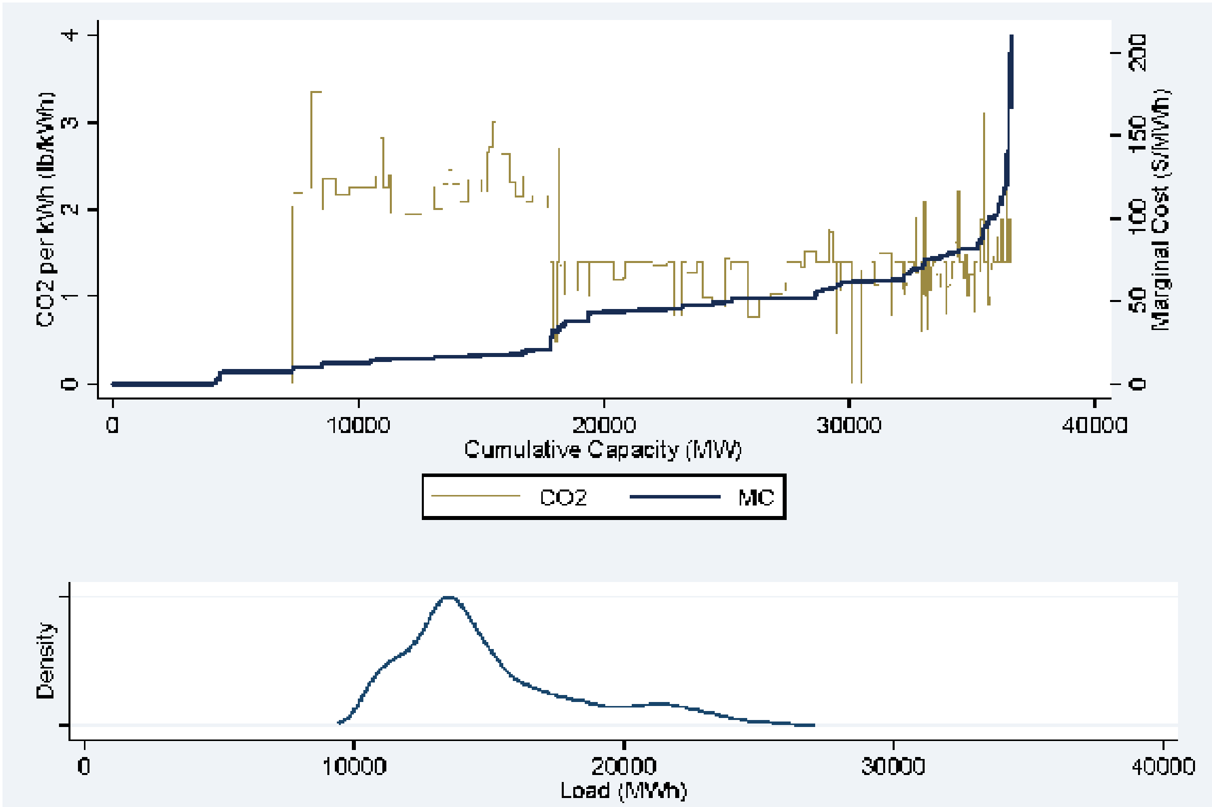

Figure 5 : Marginal Costs, CO_2 Emissions Rates, and Hourly Load in the Southwest

Notes: The monotonic step function in the upper figure traces out the marginal operating costs of generating units in the Southwest (AZ, NV, NM, UT) arranged in ascending order of operating cost per MWh. These costs include fuel, variable operating and maintenance costs, and marginal costs of complying with NOx and SO2 regulations in 2004. The bars in the upper panel represent the corresponding, unit-specific CO2 emissions rate (measured in lbs of CO2 per MWh). The bottom panel represents the distribution of hourly electricity demand in these four Southwesters states in 2004.

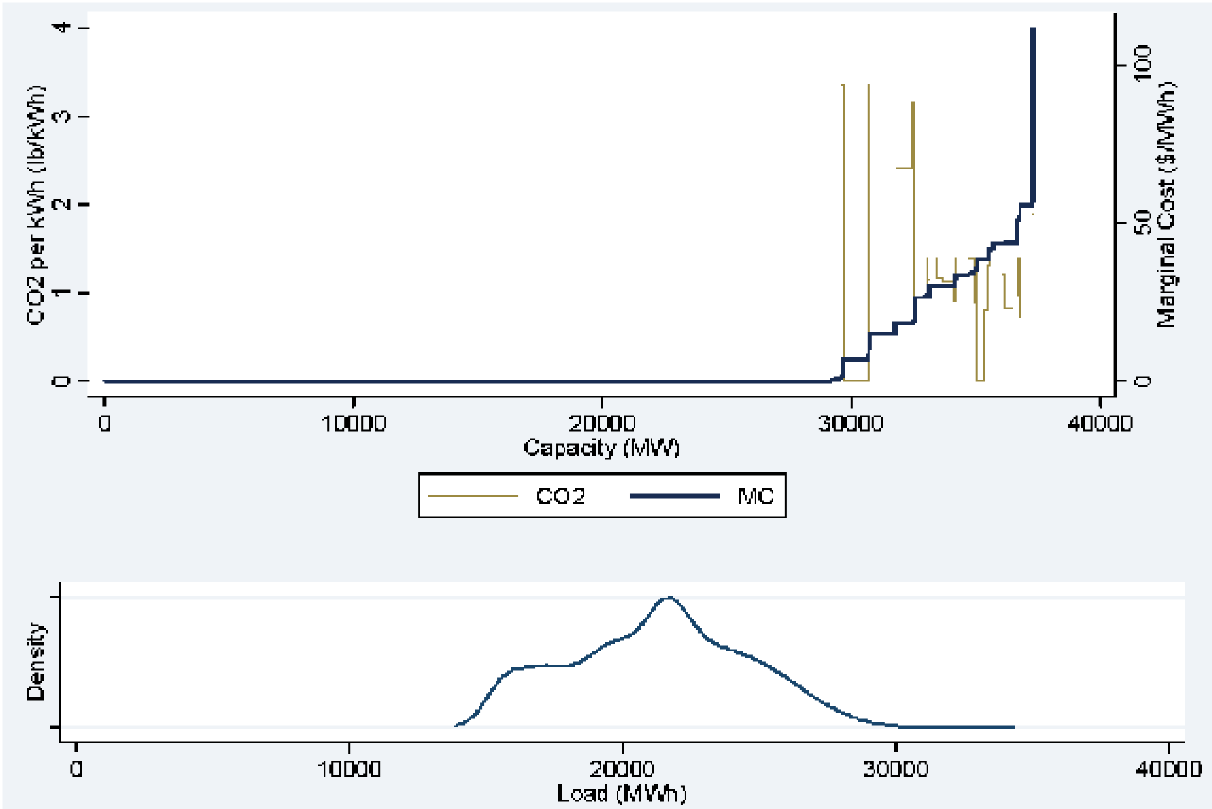

Figure 6 : Marginal Costs, CO_2 Emissions Rates, and Hourly Load in the Northwest

Notes: The monotonic step function in the upper figure traces out the marginal operating costs of generating units in the Pacific Northwest (WA and OR) arranged in ascending order of operating cost per MWh. These costs include fuel, variable operating and maintenance costs, and marginal costs of complying with NOx and SO2 regulations in 2004. The bars in the upper panel represent the corresponding, unit-specific CO2 emissions rate (measured in lbs of CO2 per MWh). The bottom panel represents the distribution of hourly electricity demand in these two Northwestern states in 2004.

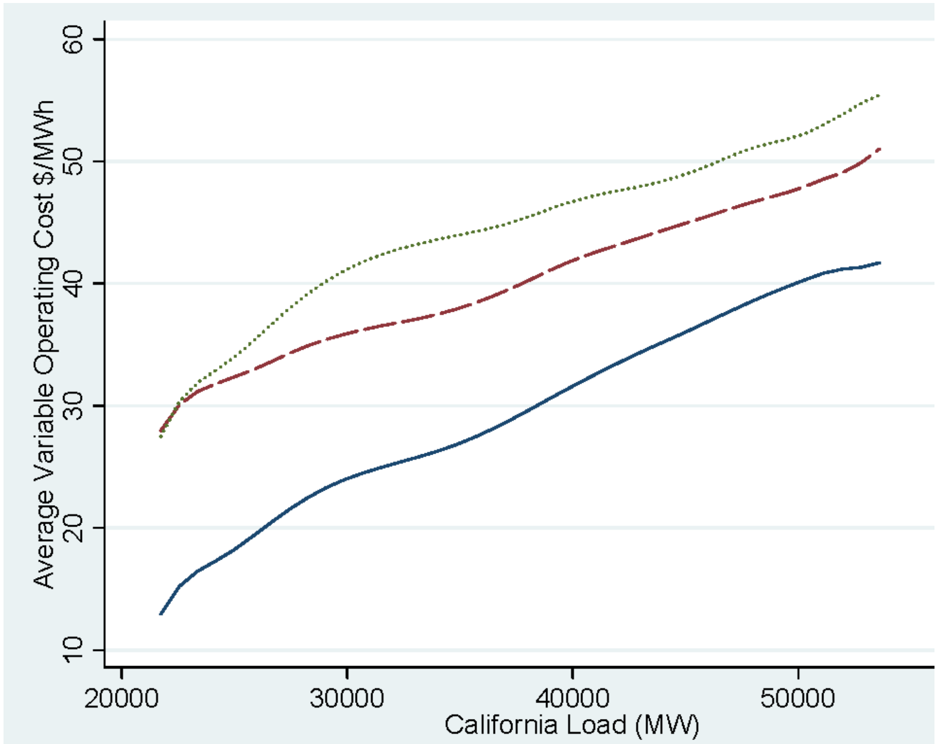

Figure 7 : Average Operating Costs per MWh under Factual and Counterfactual Policy Scenarios

Notes: These are flexible polynomial functions fit to simulated hourly operating costs (summed across all generators supplying California) plotted versus California load. These figures summarize results generated using the two-stage model. The solid line plots average costs in the absence of environmental regulation. The broken line represents average costs under complete regulation. The dotted line represents average costs under incomplete regulation. Note that the dotted line lies everywhere above the broken line. Production is allocated less efficiently under incomplete (versus complete) environmental regulation.

Table 1: Ownership of Generators in California and Surrounding States: January 2005

Parent Company	Total (exluding hydro) (MW)	%	Total Fossil (MW)	%	California total (MW)	%	Average emissions rate (exluding hydro) (lbs CO_2/kWh)
Calpine Corp.	7,700	5.0	6,210	6.8	6,181	9.5	0.85
Edison International	7,744	4.8	4,196	4.6	5,294	7.7	1.32
Pinnacle West	7,407	4.8	6,180	6.7	0	0	1.31
Pacific Gas & Electric	6,564	4.2	557	0.6	6,564	10.1	1.30
Duke Energy Corp.	5,493	3.5	5,493	6.0	4,293	6.6	1.32
Berkshire Hathaway	5,280	3.4	4,152	4.5	92	0.1	1.21
AES Corp.	4,650	3.0	4,437	4.8	4,631	7.1	0.83
Reliant Energy Inc.	4,187	2.7	4,187	4.6	3637	5.6	1.24
Sierra Pacific Resources	3,780	2.5	3,769	4.2	25	0.0	1.81
Mirant Corp.	2,875	1.9	2,875	3.1	2,300	3.5	1.06
UniSource Energy Corp.	2,310	1.5	2,306	2.5	0	0	1.11
Other	97,353	63	47,261	52	30,020	50	1.19
Total	155,168		91,747		65,134		1.21

Notes: This table summarizes electricity generating capacity ownership by parent company. A significant portion of the "other" capacity is comprised of public power, including generation owned by the Western Area Power Administration, Los Angeles Department of Water and Power, and the Salt River Project. Remaining generation is owned by "fringe" firms, defined here to be firms owning less than 2.5 percent of total fossil generation.

Table 2: Summary of Equilibrium Prices and Emissions in the Absence of CO_2 Regulation

(standard deviations in parentheses)

	Observed (2004)	**One stage model**	**Two-stage model**	**Competitive model**
Average California electricity price (\$/MWh)	**\$46.71 (\$7.12)**	\$48.31 (\$8.73)	\$46.26 (\$8.34)	\$45.40 (\$8.29)
California emissions (million tons CO_2)	**55.2***	52.1	52.8	52.7
Emissions from generation supplying California (million tons CO_2)	**118.7****	119.4	118.7	118.1
Total emissions (million tons CO_2)	**206.4***	232.2	231.5	231.0

* These estimates are taken from the Energy Information Administration state profiles for 2004.

** This estimate is taken from the Inventory of California Greenhouse Gas Emission and Sinks: 1990 to 2004 (California Energy Commission, Oct. 2006). The report estimates that CO_2 emissions from instate generationin 2004 were 51.85 million tons. GHG emissions from electricity imports are estimated to be approximately 66.8 million tons. Note that the CEC estimate of California's emissions is substantially less than the EIA estimate.

Table 3: Summary of Equilibrium Permit Prices and Emissions Under Complete and Incomplete Regulation

(price standard deviations in parentheses)

	Single-stage model		Two stage model		Perfect Competition	
	Complete Regulation	Incomplete Regulation	Complete Regulation	Incomplete Regulation	Complete Regulation	Incomplete Regulation
Average California electricity price ($/MWh)	$74.76 ($11.94)	$71.45 ($10.35)	$69.58 ($11.06)	$66.47 ($10.57)	$64.10 ($15.38)	$63.96 ($10.89)
Emissions from generation located in California (millions of tons)	54.0	32.2	55.1	34.6	50.1	34..7
Emissions from generation serving California load (millions of tons)	109.2	112.4	108.6	111.9	101.3	111.4
Total emissions (million tons CO_2)	212.5	225.3	211.8	224.7	204.6	224.3
Total reduction (million tons CO_2)	19.7	7.0	19.7	6.8	26.4	6.7
Total reduction (%)	8.5%	3%	8.5%	2.9%	11.4%	2.9%

.

References

(n.d.).

Baumol, W. J. (1971), *Environmental Protection, International Spillovers and Trade*, Almquist and Wiksell.

Becker, R. A. & Henderson, J. V. (2000), 'Costs of air quality regulation', *Journal of Political Economy* **108**(2), 379–421.

Bergman, L. & Andersson, B. (1995), Market structure and the price of electricity: An ex ante analysis of the deregulated Swedish electricity market, Technical Report 47, Stockholm School of Economics.

Bernstein, P., Montgomery, W. D. & Tuladhar, S. (2004), Economic consequences of Northeastern state proposals to limit greenhouse gas emissions from the electricity sector, Technical report, Charles River Associates Incorporated.

Blaise, A. & Vila, J.-L. (1993), 'Cournot competition, forward markets and efficiency', *Journal of Economic Theory* **59**(1), 1–16.

Borenstein, S. & Bushnell, J. (1999), 'An empirical analysis of the potential for market power in California's electricity industry', *Journal of Industrial Economics* **47**(3), 285–323.

Borenstein, S., Bushnell, J. B. & Wolak, F. A. (2002), 'Measuring market inefficiencies in California's restructured wholesale electricity market', *American Economic Review* **92**(5), 1376–1405.

Breslow, E. & Goodstein, E. (2005), Impacts of the Regional Greenhouse Gas Initiative on overall business operating costs in Rhode Island, Technical report.

Brunnermeier, S. & Levinson, A. (2004), 'Examining the evidence on environmental regulations and industry location', *The Journal of Environment and Development* **13**(1), 6–41.

Burtraw, D., Palmer, K. & Krupnick, A. J. (1997), '"Second-best" adjustments to externality estimates in electricity planning with competition', *Land Economics* **73**(2), 224–239.

Bushnell, J. (2007), 'Oligopoly equilibria in electricity contract markets', *Journal of Regulatory Economics* **32**(3), 225–245.

Bushnell, J. B., Mansur, E. T. & Saravia, C. (2008), 'Vertical arrangements, market structure, and competition: An analysis of restructured US electricity markets', *American Economic Review* **98**(1), 237–66.

California Air Resources Board (2008), Climate change draft scoping plan: June 2008 discussion draft, Technical report.

California Climate Action Team (2006), Report to Governor Schwarzenegger and the California legislature, Technical report.

California Energy Commission (2005), Policy options for reducing greenhouse gas emissions from power imports, Technical report, CEC.

California Energy Commission (2006), Inventory of California greenhouse gas emissions and sinks: 1990 o 2004, Technical report, CEC.

California Energy Commission and California Public Utilities Commission (2008), Proposed final opinion on greenhouse gas regulatory strategies, Technical report.

Cardell, J. B., Hitt, C. C. & Hogan, W. W. (1997), 'Market power and strategic interaction in electricity networks', *Resource and Energy Economics* **19**(1-2), 109–137.

Center for Clean Air Policy (2005), Design of a cap on emissions from California power demand, Technical report, CCAP.

Center for Energy, Economic, and Environmental Policy (2005), Evaluation of CO2 emissions allocations as a part of the Regional Greenhouse Gas Inititative, Technical report, CEEEP.

Chen, Y. & Hobb, B. (2005), 'An oligopolistic electricity market model with tradable nox permits', *IEEE Trans. Power Systems* **2005**(1), 119–129.

Copeland, B. R. & Taylor, M. S. (1994), 'North-south trade and the environment', *The Quarterly Journal of Economics* **109**(3), 755–87.

Copeland, B. R. & Taylor, M. S. (2003), Trade, growth and the environment, NBER working papers, National Bureau of Economic Research, Inc.

Demailly, D. & Quirion, P. (2008), 'European emission trading scheme and competitiveness: A case study on the iron and steel industry', *Energy Economics* **30**(4), 2009–2027.

Dodds, D. E. & Lesser, J. A. (1994), 'Can utility commissions improve on environmental regulation', *Land Economics* **70**(1), 63–76.

Greenstone, M. (2002), 'The impacts of environmental regulations on industrial activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the census of manufactures', *Journal of Political Economy* **110**(6), 1175–1219.

Joskow, P. & Kahn, E. (2001), A quantitative analysis of pricing behavior in California's wholesale electricity market during summer 2000, NBER Working Papers 8157, National Bureau of Economic Research, Inc.

Katsoulacos, Y. & Xepapadeas, A. (1995), 'Environmental policy under oligopoly with endogenous market structure', *Scandinavian Journal of Economics* **97**(3), 411–20.

Kim, D.-W. & Knittel, C. R. (2006), 'Biases in static oligopoly models? evidence from the California electricity market', *Journal of Industrial Economics* **54**(4), 451–470.

Levin, D. (1985), 'Taxation within cournot oligopoly', *Journal of Public Economics* **27**(3), 281–290.

Malueg, D. A. (1990), 'Welfare consequences of emission credit trading programs', *Journal of Environmental Economics and Management* **18**(1), 66–77.

Mansur, E. T. (2007), 'Do oligopolists pollute less? evidence from a restructured electricity market', *Journal of Industrial Economics* **55**(4), 661–689.

Mansur, E. T. (2008), 'Measuring welfare in restructured electricity markets', *The Review of Economics and Statistics* **90**(2), 369–386.

Newcomer, A., Blumsack, S., Apt, J., Lave, L. B. & Morgan, M. G. (2008), 'Electricity load and carbon dioxide emissions: Effects of a carbon price in the short term', p. 179.

Oates, W. E. & Strassmann, D. L. (1984), 'Effluent fees and market structure', *Journal of Public Economics* **24**(1), 29–46.

Puller, S. L. (2007), 'Pricing and firm conduct in California's deregulated electricity market', *The Review of Economics and Statistics* **89**(1), 75–87.

Regional Greenhouse Gas Initiative Staff Working Group (2007), Potential emissions leakage and regional greenhouse gas initiative: Evaluating market dynamics, monitoring options, and possible mitigation options, Technical report.

Sartzetakis, E. (1997), 'Tradeable emission permits regulations in the presence of imperfectly competitive product markets: Welfare implications', *Environmental & Resource Economics* **9**(1), 65–81.

Sartzetakis, E. (2004), 'On the efficiency of competitive markets for emission permits', *Environmental & Resource Economics* **27**(1), 1–19.

Simpson, R. (1995), 'Optimal pollution taxation in a cournot duopoly', *Environmental & Resource Economics* **6**(4), 359–369.

Su, C.-L. (2007), 'Analysis on the forward market equilibrium model', *Oper. Res. Lett.* **35**(1), 74–82.

Sweeting, A. (2007), 'Market power in the england and wales wholesale electricity market 1995-2000', *Economic Journal* **117**(520), 654–685.

Tol, R. S. (2007), 'Carbon dioxide emission scenarios for the usa', *Energy Policy* **35**(11), 5310–5326.

VanLong, N. & Soubeyran, A. (2002), Selective penalization of polluters: An inf-convolution approach, CIRANO Working Papers 2002s-40, CIRANO.

Willems, B., Rumiantseva, I. & Weigt, H. (2007), Cournot versus supply functions: What does the data tell us?, Technical report.

Wilson, N., Palmer, K. & Burtraw, D. (2005), The effect of long-term generation contracts on valuation of electricity generating assets under the regional greenhouse gas initiative, Discussion paper, Resources for the Future.

Wolak, F. A. (2000), 'An empirical analysis of the impact of hedge contracts on bidding behavior in a competitive electricity market', *International Economic Journal* **14**, 1–40.

Wolfram, C. D. (1999), 'Measuring duopoly power in the british electricity spot market', *American Economic Review* **89**(4), 805–826.

Appendix 1: Deriving Equilibrium Conditions and Leakage in the One-Stage Game

The ith firm maximizes the profit function:

$$\pi_i = p_s(Q)q_i - c_i q_i + \tau(A_i - d_i e_i q_i).$$

First order conditions for a maximum are given by:

$$p_s(Q) + p_s'(Q)q_i - c_i - d_i\tau e_i = 0.$$

Summing across N yields:

$$Np_s(Q) - bQ - \sum_{i=1}^{N} c_i - \tau\sum_{i=1}^{N} d_i e_i = 0.$$

Dividing through by N yields:

$$p_s(Q) - \frac{b}{N}Q - \bar{c} - \tau\overline{de} = 0,$$

where $\bar{c} = \frac{1}{N}\sum_{i=1}^{N} c_i$; $\overline{de} = \frac{1}{N}\sum_{i=1}^{N} d_i e_i$.

Substituting for $p(Q)$ and simplifying yields and expression for Q^*:

$$Q_B^* = \frac{N}{(N+1)b}(a - \bar{c} - \tau\overline{de}).$$

First order conditions for a maximum can also be manipulated to derive q_i^*:

$$bq_i^* = p_s(Q*) - c_i - d_i\tau e_i$$

Substituting for Q^* we have:

$$bq_i^* = a - \left(\frac{N}{(N+1)}\left(a - \frac{\sum_{i=1}^{N} c_i}{N} - \tau\frac{\sum_{i=1}^{N} d_i e_i}{N}\right)\right) - c_i - d_i\tau e_i$$

$$q_{iB}^* = \frac{a + \sum_{j\neq i}^{N}(c_j + \tau d_j e_j) - N(c_i + \tau d_i e_i)}{(N+1)b}$$

Leakage in the single stage model is defined to be:

$$
\begin{aligned}
L &= \sum_{i=1}^{N}(1-d_i)e_i(q_i^{INC}-q_i^0) \\
&= \sum_{i=1}^{N}(1-d_i)e_i\left(\frac{\sum_{i=1}^{N}\tau d_i e_i-(N+1)\tau d_i e_i}{(N+1)b}\right) \\
&= \sum_{i=1}^{N}(1-d_i)e_i\left(\frac{\tau N_1\overline{e_1}}{(N+1)b}\right) \\
&= N_0\overline{e_0}\left(\frac{\tau N_1\overline{e_1}}{(N+1)b}\right)
\end{aligned}
$$

Appendix 2

Proof of proposition 2.1 : Complete regulation unambiguously reduces aggregate emissions

$$
\sum_{i=1}^{N}e_i\left(\frac{a+\sum_{i=1}^{N}(c_i+\tau e_i)-(N+1)(c_i+\tau e_i)}{(N+1)b}\right) < \sum_{i=1}^{N}e_i\left(\frac{a+\sum_{i=1}^{N}c_i-(N+1)c_i}{(N+1)b}\right).
$$

$$
\sum_{i=1}^{N}e_i\left(\sum_{i=1}^{N}\tau e_i-(N+1)\tau e_i\right) < 0
$$

$$
N^2(\overline{e})^2 < (N+1)N\overline{e^2}
$$

$$
-\overline{e^2} < N(var(e_i))
$$

This proves that aggregate emissions under complete regulation will be strictly less than unregulated emissions.

Proof of Proposition 3.1 :If $\overline{e_0} > \overline{e_1}$, the introduction of incomplete environmental regulation can result in a net increase in overal emissions.

$$\sum_{i=1}^{N} e_i \left(\frac{a + \sum_{i=1}^{N} (c_i + \tau d_i e_i) - (N+1)(c_i + \tau d_i e_i)}{(N+1)b} \right) > \sum_{i=1}^{N} e_i \left(\frac{a + \sum_{i+1}^{N} c_i - (N+1)c_i}{(N+1)b} \right)$$

$$\sum_{i=1}^{N} e_i \left(\sum_{i=1}^{N} \tau d_i e_i - (N+1)(\tau d_i e_i) \right) > 0$$

$$N\overline{e e_1} > (N+1)\overline{e_1^2}$$

$$\frac{N}{N+1} > \frac{\overline{e_1^2}}{\overline{e}\ \overline{e_1}}$$

If the exempt firms are sufficiently more polluting, this inequality can be satisfied.

Proof of Proposition 4.1: If $\overline{e^1} > \overline{e^0}$, aggregate emissions under complete environmental regulation can exceed aggregate emissions under incomplete regulation.

This proposition implies:

$$\sum_{i=1}^{N} e_i \sum_{i=1}^{N} d_i e_i - \sum_{i=1}^{N} e_i \sum_{i=1}^{N} e_i < (N+1) \left(\sum_{i=1}^{N} e_i d_i e_i - \sum_{i=1}^{N} e_i e_i \right)$$

$$\frac{\overline{e_0^2}}{\overline{e}\ \overline{e_0}} < \frac{N}{N+1}$$

In order for this inequality to hold, it must be that $\overline{e_0} > \overline{e}$, (*i.e.* regulated firms are relatively more polluting).

Appendix 3: Equilibrium Conditions in the Spot Market Production Stage

Given the vector f, the firm maximizes the spot market production game profit function:

$$\pi_i^s = p_s(Q)(q_i - f_i) - c_i q_i + \tau(A_i - d_i e_i q_i). \tag{18}$$

First order conditions for a maximum are given by:

$$p_s'(Q)(q_i - f_i) + p_s(Q) - c_i - \tau d_i e_i = 0. \tag{19}$$

Summing across N firms yields:

$$Np_s(Q) - bQ + b\sum_{i=1}^{N} f_i - \sum_{i=1}^{N} c_i - \tau\sum_{i=1}^{N} d_i e_i = 0.$$

Dividing through by N yields:

$$p_s(Q) - \frac{b}{N}Q + \frac{b}{N}\sum_{i=1}^{N} f_i - \bar{c} - \tau\overline{de} = 0,$$

where $\bar{c} = \frac{1}{N}\sum_{i=1}^{N} c_i;\,;\ \overline{de} = \frac{1}{N}\sum_{i=1}^{N} d_i e_i.$
Substituting for $p(Q)$ and simplifying yields and expression for $Q(F)$:

$$Q(F) = \frac{N}{(N+1)b}\left(a - \bar{c} - \tau\overline{de} + \frac{b}{N}\sum_{i=1}^{N} f_i\right)$$

First order conditions for a maximum can also be manipulated to derive $q_i(f_i, F\_i)$:

$$bq_i = (a + bf_i - bQ(F) - c_i)$$

Substituting for $Q(F)$:

N

$$bq_i = a + bf_i - c_i - \frac{N}{(N+1)}\left(a - \bar{c} - \tau\overline{de} + \frac{b}{N}\sum_{i=1}^{N} f_i\right)$$

$$q_i(f_i, F\_i) = \frac{a + \sum_{j\neq i}(c_j + \tau d_j e_j) - N(c_i + \tau d_i e_i - bf_i) - b\sum_{j\neq i}^{N} f_j}{(N+1)b}$$

Appendix 4: Deriving Equilibrium Conditions in the Forward Market

In order to choose a forward contract level, firm i evaluates:

$$\begin{aligned}\pi_i &= \delta[(p_s(f_i, F_{-i}) - c_i - \tau d_i e_i)q_i(f_i, F_{-i}) + \tau A_i] \\ &= \frac{\delta}{(N+1)^2 b}\left(a - c_i - Nc_i + N\bar{c} - \tau d_i e_i - N\tau d_i e_i + N\tau\overline{de} - b\sum_i f_i\right) \\ &\left(a - c_i + N\bar{c} - Nc_i - \tau d_i e_i + N\tau\overline{de} - b\sum_{j\neq i} f_j + Nbf_i\right)\end{aligned}$$

First order conditions for a maximum imply:

$$\frac{\delta}{(N+1)^2 b}\left(\begin{array}{c} Nb(a-c_i-\tau d_i e_i - N(c_i+\tau d_i e_i)+\sum_i (c_i+\tau d_i e_i) - b\sum_i f_i) - \\ b(a-c_i-\tau d_i e_i + \sum_i (c_i+\tau d_i e_i) - N(c_i+\tau d_i e) - b\sum_{j\neq i} f_j + Nbf_i) \end{array}\right) = 0$$

Solving for f_i :

$$f_i = \frac{(N-1)\left(a+\sum_{i=1}^{N}(c_i+\tau d_i e_i) - b\sum_{j\neq i} f_j\right) + (1-N^2)(c_i+\tau d_i e_i)}{2Nb}$$

In the symmetric cost case, this system can be easily solved for an arbitrary N :

$$f = \frac{(N-1)(a-c-\tau de - b(N-1)f)}{2Nb}$$
$$f_i^* = \frac{(N-1)(a-c-\tau de)}{(N^2+1)b}$$

Solving the system of N equations implied by the nonidentical marginal cost case is more difficult.The system can be rewritten as:

$$f_i + \frac{N-1}{2N}\sum_{j\neq i} f_j = \frac{N-1}{2Nb}\left(a+\sum_{i=1}^{N}(c_i+\tau d_i e_i)\right) + \frac{(1-N^2)(c_i+\tau d_i e_i)}{2Nb},$$

which can in turn be rewritten as follows:

$$\begin{bmatrix} 1 & .. & .. & \frac{N-1}{2N} \\ : & 1 & & : \\ : & & 1 & : \\ \frac{N-1}{2N} & .. & .. & 1 \end{bmatrix} f = \frac{N-1}{2Nb}\left(a+\sum_{i=1}^{N}(c_i+\tau d_i e_i)\right)\iota + \frac{(1-N^2)}{2Nb}mc,$$

where f is the vector $[f_1....f_n]^T$, mc is the vector of marginal costs $[c_1+\tau d_1 e_1, ..., c_N+\tau d_N e_N]$ and ι is the vector $[1....1]^T$.

This implies:

$$f = \begin{bmatrix} 1 & .. & .. & \frac{N-1}{2N} \\ : & 1 & & : \\ : & & 1 & : \\ \frac{N-1}{2N} & .. & .. & 1 \end{bmatrix}^{-1} * \left(\frac{N-1}{2Nb}\left(a+\sum_{i=1}^{N}(c_i+\tau d_i e_i)\right)\iota + \frac{(1-N^2)}{2Nb}mc\right).$$

Note:

$$\begin{bmatrix} 1 & .. & .. & \frac{N-1}{2N} \\ : & 1 & & : \\ : & & 1 & : \\ \frac{N-1}{2N} & .. & .. & 1 \end{bmatrix} = \frac{N+1}{2N} I + \begin{bmatrix} \frac{N-1}{2N} & .. & .. & \frac{N-1}{2N} \\ : & & & : \\ : & & & : \\ \frac{N-1}{2N} & .. & .. & \frac{N-1}{2N} \end{bmatrix}$$

$$= \frac{N+1}{2N} I + \frac{N-1}{2N} \iota\iota^T$$

$$= \frac{N+1}{2N} \left(I + \frac{N-1}{N+1} \iota\iota^T \right)$$

Substituting back into our original system, we have:

$$\left(I + \frac{N-1}{N+1} \iota\iota^T \right) f = \frac{2N}{N+1} \left(\frac{N-1}{2Nb} \left(a + \sum_{i=1}^{N} (c_i + \tau d_i e_i) \right) \iota + \frac{1-N^2}{2Nb} mc \right)$$

$$\left(I + \frac{N-1}{N+1} \iota\iota^T \right) f = \frac{N-1}{(N+1)b} \left(a + \sum_{i=1}^{N} (c_i + \tau d_i e_i) \right) \iota + \frac{1-N^2}{(N+1)b} mc$$

From Henderson and Searle(1981) we have:

$$(A + buv')^{-1} = A^{-1} - \frac{b}{1 + bv'A^{-1}u} A^{-1} u v^{-1} A^{-1},$$

where u is a column vector and v is a row vector. This implies:

$$\left(I + \frac{N-1}{N+1} \iota\iota^T \right)^{-1} = I - \frac{\frac{N-1}{N+1}}{1 + N(\frac{N-1}{N+1})} \iota i'$$

$$= \left(I - \left[\frac{N-1}{N^2+1} \right] \iota i' \right)$$

$$= \begin{bmatrix} \frac{N^2-N+2}{N^2+1} & .. & .. & -\frac{(N-1)}{N^2+1} \\ : & & & : \\ : & & & : \\ -\frac{(N-1)}{N^2+1} & .. & .. & \frac{N^2-N+2}{N^2+1} \end{bmatrix}.$$

Substituting this matrix into our original system of equations:

$$f = \begin{bmatrix} \frac{N^2-N+2}{N^2+1} & .. & .. & -\frac{(N-1)}{N^2+1} \\ : & & & : \\ : & & & : \\ -\frac{(N-1)}{N^2+1} & .. & .. & \frac{N^2-N+2}{N^2+1} \end{bmatrix} \left(\frac{N-1}{(N+1)b} \left(a + \sum_{i=1}^{N} (c_i + \tau d_i e_i) \right) \iota + \frac{1-N^2}{(N+1)b} mc \right).$$

This implies:

$$f_i = \frac{(N-1)a + (N^2-N+1)(1-N)(c_i+\tau d_i e_i) + (N-1)N\sum_{j\neq i}(c_j+\tau d_j e_j)}{(N^2+1)b}$$

Having solved for f_i in terms of the parameters N, a, b and the vector mc we can now solve for q_i by substituting this expression into the to the equation defining equilibrium quantity from the production stage game:

$$q_i = \frac{a - N(c_i+\tau d_i e_i) + \sum_{j\neq i}(c_j+\tau d_j e_j) - b\sum_i f_i + (N+1)bf_i}{(N+1)b}$$

$$q_i = \frac{Na - N(N^2-N+1)(c_i+\tau d_i e_i) + N^2\sum_{j\neq i}(c_j+\tau d_j e_j)}{(N^2+1)b}$$

To solve for Q_i^*, we sum across q_i^* :

$$Q^* = \frac{N^2(a-\overline{c}-\tau\overline{de})}{(N^2+1)b}$$

$$p^* = \frac{a + N^2\left(\overline{c}+\tau\overline{de}\right)}{(N^2+1)}$$

Finally, firm-level and aggregate emissions in equilibrium are:

$$e_i q_{iF} = \frac{Nae_i - N(N^2+1)(c_i e_i + \tau d_i e_i^2) + N^2\sum_{i=1}^{N} e_i(c_i+\tau d_i e_i)}{(N^2+1)b}$$

$$E_F = \sum_{i=1}^{N} e_i q_i = \frac{N^2\overline{e}(a+N^2\overline{c}+N^2\tau\overline{de}) - N(N^2+1)\sum_{i=1}^{N}\left(e_i c_i + \tau d_i e_i^2\right)}{(N^2+1)b}$$

Appendix 5: Proof of propositions 1- 4 when firms trade forward

Proof of proposition 2.2 : Complete regulation unambiguously reduces aggregate emissions

$$\sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i=1}^{N} (c_i + \tau e_i) - N(N^2+1)(c_i + \tau e_i)}{(N^2+1)b} \right) < \sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i=1}^{N} c_i - N(N^2+1)c_i}{(N+1)b} \right).$$

$$\sum_{i=1}^{N} e_i \left(N \sum_{i=1}^{N} e_i - (N^2+1)e_i \right) < 0$$

$$N^2(\overline{e})^2 < (N^2+1)\overline{e^2}$$

$$-\overline{e^2} < N^2 var(e_i)$$

This proves that aggregate emissions under complete regulation will be strictly less than unregulated emissions.

Proposition 3.2 :If $\overline{e_0} > \overline{e_1}$, the introduction of incomplete environmental regulation can result in a net increase in overall emissions.

$$\sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i=1}^{N} (c_i + \tau d_i e_i) - N(N^2+1)(c_i + \tau d_i e_i)}{(N^2+1)b} \right) > \sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i+1}^{N} c_i - N(N^2+1)c_i}{(N^2+1)b} \right)$$

$$\sum_{i=1}^{N} e_i \left(N \sum_{i=1}^{N} d_i e_i - (N^2+1)(d_i e_i) \right) > 0$$

$$N^2 \overline{e e_1} > (N^2+1)\overline{e_1^2}$$

$$\frac{N^2}{N^2+1} > \frac{\overline{e_1^2}}{\overline{e}\ \overline{e_1}}$$

If the exempt firms are sufficiently more polluting, this inequality can be satisfied.

Proof of Proposition 4.2: If $\overline{e^1} > \overline{e^0}$, aggregate emissions under complete environmental regulation can exceed aggregate emissions under incomplete regulation.

This proposition implies the following inequality can hold:

$$\sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i=1}^{N} (c_i + \tau d_i e_i) - N(N^2+1)(c_i + \tau d_i e_i)}{(N^2+1)b} \right) < \sum_{i=1}^{N} e_i \left(\frac{Na + N^2 \sum_{i+1}^{N} (c_i + \tau e_i) - N(N^2+1)(c_i + \tau e_i)}{(N^2+1)b} \right)$$

$$N^2 \sum_{i=1}^{N} e_i \sum_{i=1}^{N} d_i e_i - N^2 \sum_{i=1}^{N} e_i \sum_{i=1}^{N} e_i < N(N^2+1) \left(\sum_{i=1}^{N} e_i d_i e_i - \sum_{i=1}^{N} e_i e_i \right)$$

$$\frac{\overline{e_0^2}}{\overline{e}\ \overline{e_0}} < \frac{N^2}{N^2+1}$$

In order for this inequality to hold, it must be that exempt firms are relatively less polluting. Again, note that there are situations in which incomplete regu

Appendix 6 : Simulation Methods

The single-stage game

The single-stage Cournot model is modified to reflect the realities of the California market. Firms' marginal costs are now assumed to be increasing with production (versus constant). Unit-level capacity constraints and transmission constraints are explicitly represented.

Supply curves for the Pacific Northwest (*i.e.* Washington and Oregon) and Southwest (*i.e.* Arizona, Nevada, New Mexico, and Utah) are constructed using dependable capacity measures and marginal costs of all generation located in these states that is not owned by California utilities. Least cost dispatch is assumed in the PNW and SW regions.[45] Generation not required to serve native load is assumed to be available for export to California, subject to transmission constraints. Transmission capacity is allocated first to firm imports, and then to the least costly out-of-state generation that is not needed to serve native load.

The competitive fringe includes all non-strategic instate generation and all non-strategic, out-of-state generation that can be accommodated by existing transmission capacity. The out-of-state units that help comprise this fringe vary from hour to hour with loads in neighboring states. In each hour, the residual

[45] With the exception of Oregon (where the vast majority of generating capacity is hydro), all of the states surrounding California have elected not to restructure their electricity industries. Consequently, least cost dispatch in these states is a reasonable assumption.

demand curve faced by the strategic firms is constructed by subtracting fringe supply from California demand in that hour.

For each of three policy regimes (*i.e.* no environmental regulation, complete regulation, and incomplete regulation) 8784 hourly supply curves are constructed for each of the eleven strategic firms supplying the California market. The total capacity that the i^{th} firm has available in hour t is comprised of the in-state generation and firm imports owned by the firm, plus any out-of-state generation owned by the firm that is not required to supply native load. These generating units are arranged in order of ascending marginal operating cost to yield a firm-specific, hour-specific step function. For simulations that assume GHG regulations (complete and incomplete), marginal costs reflect the cost of complying with the environmental regulation.

A linear function $c_{it}(q_{it})$ is fit to these firm-specific, hour-specific step functions. The vector of equilibrium production quantities $\mathbf{q}_t^* = \{q_{1t}....q_{11t}\}$ solves:

$$\max_{q_{it}} \left\{ p_{st}(q_{it}, \sum_{j \neq i}^{N} q_{jt}^*) q_{it} - c_{it}(q_{it}) - d_i \tau e_i q_{it} \right\}, i = 1..11,$$

subject to unit-level non-negativity constraints, unit-level capacity constraints and transmission constraints.

In each hour, I solve iteratively for the Cournot equilibrium. Using the GAUSS eqsolve procedure, the profit-maximizing output for the i^{th} Cournot supplier is determined conditional on the production of the other Cournot suppliers.[46] For each hour, equilibrium quantities, equilibrium emissions and electricity prices are recorded for the three regions.

The two-stage game with forward contracts

In the theoretical analysis of the two period model, it was possible to solve for $\mathbf{q}^*$ by substituting $\mathbf{q}(\mathbf{f})$ directly into [11]. In order to make the model more realistic, the simplifying assumption of constant marginal costs is released. Consequently, it becomes prohibitively difficult to solve explicitly for spot market production quantities $\mathbf{q}$ in terms of the forward positions $\mathbf{f}$.

Fortunately, the explicit function $\mathbf{q}(\mathbf{f})$ is not essential to solving the system of first order conditions that define the spot market equilibrium. Note that the system of equations that define the spot market

[46] The algorithm begins by solving for the profit-maximizing output of the first supplier assuming that the other strategic suppliers do not produce. In the next step, the level of output at the second firm is solved for conditional on the q_1 calculated in the previous step, and assuming that $q_i = 0$ for all $i \neq 1, 2$. The algorithm proceeds, looping repeatedly through suppliers and solving for profit-maximizing output conditional on the output levels of other producers calculated in previous iterations. The process continues until no supplier can profit from changing its output levels given the output of the other strategic producers. Once equilibrium levels of output among the strategic suppliers have been identified, the corresponding equilibrium prices and emissions for the hour can be calculated.

equilibrium can be rewritten:

$$p_{st}(Q_t)\frac{\partial q_{it}}{\partial f_{it}} + q_{it}\frac{\partial p_{st}}{\partial f_{it}} - c_{it} - \tau d_i e_i \frac{\partial q_{it}}{\partial f_{it}} = 0 \tag{20}$$

The multivariate implicit function theorem allows us to solve for the matrix of partial derivatives $\mathbf{q}'_t(\mathbf{f}_t)$ without having to explicitly solve for $\mathbf{q}(\mathbf{f})$. These partial derivatives can then be substituted into the system of equations defined by (20).

The hour-specific, firm-specific marginal cost functions $C_{it}(q_{it})$ and the residual demand equation $a_t - b_t(\sum_{i=1}^{11} q_{it})$ discussed in the previous section are also used to parameterize the system of first order equations defined by [20]. The same iterative algorithm described in the previous section is used to solve this system. Equilibrium production at strategic firms $\mathbf{q}_t^*$, fringe firms, aggregate emissions $\mathbf{E}_t^*$ and electricity price p_{st}^* are computed for each hour.

Perfectly Competitive Spot Markets

Simulations that assume price taking behavior on the part of all electricity producers are carried out using a very similar approach. Wholesale electricity market outcomes in the Southwest and Pacific Northwest are simulated in precisely the same way as in the simulations based on the single-stage and two-stage models (*i.e.* generation not required to serve native load is assumed to be available for export to California, subject to transmission constraints). The same hourly supply curves used in the simulations that assume price taking behavior are used to simulate outcomes in a perfectly competitive California market. All firms are assumed to produce up to the point where marginal cost equals the wholesale electricity price. In each hour, I iteravely increase the wholesale price until supply equals demand in that hour.

Appendix 7 : Releasing the Assumption of Perfectly Inelastic Demand

The simulation models used to generate results presented in the paper assume perfectly inelastic demand. This assumption is fairly standard in electricity market simulations (Puller, 2007; Kim and Knittel, 2006). Few customers are exposed to time-varying pricing; empirically estimated own-price elasticities in electricity markets tend to be quite small. However, inasmuch as consumers do exhibit some demand elasticity, these results will under-estimate the effects of the policy on industry emissions (because demand reduction is not accomodated as a possible emissions abatement option).

Newcomer et al., 2008 consider U.S. electricity consumers' short run response to the introduction of a tax (or fixed permit price). They assume that consumers are exposed to real time electricity price fluctuations. Holding the level of the carbon tax fixed, they simulate emissions reductions for assumed price elasticities of demand in the range of -0.1 to -0.2. The more elastic demand, the greater the emissions reductions. In order to investigate how sensitive the simulation results presented in this paper are affected when the assumption of perfectly inelastic demand is released, some simulations are conducted that assume a downward sloping (versus vertical) demand curve. An elasticity of- 0.3 is assumed.

Tables A1 and A2 summarize results for a representative hour in which observed electricity demand was at average levels in California and surrounding states..California load, net of hydro supply, is 26,675 in this hour. To run these simulations, California electricity demand is represented by a downward sloping, linear inverse demand function. The intercept and slope parameters are those which are consistent with an own-price elasticity of -0.3 at the observed level of electricity consumption and the competitive equilibrium price under assumptions of inelastic demand ($41.97). Emissions reductions are greater when demand response is built into the simulation model. Intuitively, this is because emissions reductions can be achieved through both a re-ordering of the dispatch and demand reductions. Incomplete regulation achieves a larger percentage of the emissions reductions achieved under complete regulation. Note that the regulation-induced increase in wholesale electricity price is similar under complete and incomplete participation. Thus, a significant fraction of the demand (and associated emissions) reductions induced by complete regulation is also observed under incomplete regulation.

Table A1: Summary of Equilibrium Permit Prices and Emissions Under Complete and Incomplete Regulation for a Representative Hour (One-stage Model)

	Complete Regulation		Incomplete Regulation	
	Perfectly inelastic demand	**Elastic Demand**	**Perfectly inelastic demand**	**Elastic Demand**
Average California electricity price ($/MWh)	$70.20	$61.40	$68.89	$59.91
Net California load (MWh)	26,675	23,588	26,675	23,825
Emissions from generation located in California (tons)	4,562	3,543	2331	1,658
Emissions from generation serving California load (tons)	12,882	11,114	13,230	11,898
Total emissions (million tons CO_2)	21,884	20,116	23,465	22,133
Total reduction (million tons CO_2)	2,459	4046	878	2,029
Total reduction (%)	10%	17%	4%	8%

Table A2: Summary of Equilibrium Permit Prices and Emissions Under Complete and Incomplete Regulation for a Representative Hour : Competitive Model

	Complete Regulation		Incomplete Regulation	
	Perfectly inelastic demand	**Elastic demand**	**Perfectly inelastic demand**	**Elastic demand**
Average California electricity price ($/MWh)	$64.58	$58.73	$60.90	$56.14
Net California load	26,675	24,008	26,676	24,420
Emissions from generation located in California (tons)	4,985	3,731	2,488	1,965
Emissions from generation serving California load (tons)	12,746	11,319	13,350	12,247
Total emissions (million tons CO_2)	21,745	20,321	23,585	22,482
Total reduction (million tons CO_2)	2,558	3,982	718	1,821
Total reduction (%)	11%	16%	3%	7%

Appendix 8

Table A3 : Out-of-state Generation owned by California entities

Plant name	**State**	**Fuel Type**	**Capacity (MW)**	**CA Share Percent**	**MW**
Four Corners	NM	Coal	2,140	34.6%	740
Intermountain	UT	Coal	1,810	96%	1,738
Navajo	AZ	Coal	2,250	21.2%	477
Palo Verde		Nuclear	3,867	27.4%	1,060
Reid Gardner	NV	Coal	595	29.9%	178
San Juan	NV	Coal	1,647	24.2%	399

Notes : In 2004, California utilities also owned 66% of the Mohave coal plant in Nevada. This plant was closed in 2005 due to air quality permit compliance issues. This plant is not included in simulation exercises.