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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 counterparts, emissions under incomplete regulation exceed the level of emissions that would have occurred under complete regulation. The reverse can be true when regulated firms are relatively dirty. 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 almost three times 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.[1]

Regulations that 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 two reasons for this. First, equity concerns make complete regulation broadly objectionable.[2] The second reason has more to do with the prevailing stalemate in climate policy negotiations. Regional policies, such as those recently instituted by the European Union, California, and a coalition of nine Northeastern US states, are emerging in response to policy inaction at higher levels of governance.

"Leakage" refers to increases in production and associated emissions among unregulated producers that occur as a direct consequence of incomplete environmental regulation (RGGI, 2007; CEC 2006c). Emissions leakage has become a defining issue in the design and implementation of regional climate policy. There is growing debate about the extent to which emissions leakage can undermine the effectiveness of incomplete environmental regulation in general, and regional climate policies in particular. This paper analyzes 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 affected industries most often targeted by incomplete environmental regulation. The majority of the industrial GHG emissions that are subject to regional, market-based regulations come from industries that are best characterized as imperfectly competitive (important examples include restructured electricity markets and cement).[3] In addition, wholesale forward commitments are common in many of these industries. Although these stylized facts play an important role in determining equilibrium 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.[4] This paper

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[1] This shift in production can also occur under complete regulation if the degree of regulatory stringency varies across sources.

[2] 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).

[3] GHG emissions from restructured electricity markets represent the majority of emissions currently targeted by regional cap-and-trade programs in the United States and Europe.

[4] See, for example, Bernstein et al. (2004), Breslow and Goodstein (2005), CEEEP (2005), ICF Consulting

demonstrates the importance of industry structure in determining both the extent to which leakage occurs and the welfare implications of incomplete regulation.[5]

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. Incomplete regulation affects producers' relative marginal operating costs. This has implications for aggregate production, relative market shares, and industry emissions. Assuming that the constraint imposed by the regulation binds, the introduction of incomplete regulation will result in emissions leakage. The amount of leakage that occurs is greater when emissions rates per unit of production are high and/or when demand is more elastic. In general, the more competitive the industry, the greater the emissions leakage.

The current policy debate presumes that incomplete participation and associated emissions leakage unambiguously reduces the welfare gains from environmental regulation (RGGI, 2007; CCAP, 2005). 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. Introducing incomplete environmental regulation can mitigate allocative production inefficiency if the firms that are exempt from environmental regulation are more efficient than their regulated counterparts. Under these circumstances, incomplete regulation can welfare dominate complete regulation. Conversely, if regulated firms are relatively more efficient than exempt producers, the introduction of incomplete regulation can exacerbate allocative production inefficiencies and the associated welfare costs can potentially overwhelm the welfare gains associated with reducing emissions at regulated firms.

In section 5, the analytical model is parameterized using detailed data from California's electricity industry. Equilibrium outcomes under a source-based cap-and-trade program limiting GHG emissions from electricity generation are simulated. Results indicate that, in the short run, a regulation that exempts out-of-state producers would reduce overall emissions by approximately 3 percent, as compared to the 9-10 percent reductions achieved under complete regulation. When participation is incomplete, between 62 and 65 percent of the emissions reductions achieved by regulated producers are offset by increased emissions among unregulated producers. The introduction of environmental regulation exacerbates pre-existing allocative production inefficiencies associated with the exercise of market power in the electricity market. These inefficiencies are fur-

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(2004), Petraglia and Breger (2005), Burtraw et al. (2005).

[5] Various interest groups have questioned how the estimated impacts of incomplete environmental regulation might change if modeling assumptions more closely represented the observed structural characteristics of affected industries. Questions about the relationship between permit market design and 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, 2005a) and working papers (Wilson et al. 2005).

ther intensified when participation is incomplete. The implied cost per ton of emissions reduced is almost three times as high when 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

The link between pollution regulation and comparative advantage has been an important theme in the international trade literature (Baumol, 1971; Siebert, 1977; Copeland, 1994). Copeland and Taylor (1994), among others, have hypothesized that an increase in the stringency of environmental regulation will, at the margin, affect plant location decisions and patterns of international trade.[6] Although this paper is similar to previous work investigating "pollution haven" effects in an international trade context, the application and emphasis are rather different. Researchers analyzing interactions between trade policies, environmental regulations, and the comparative advantages of different international trading partners have focused on identifying conditions under which reductions in trade barriers can alleviate or exacerbate problems caused by pre-existing, asymmetric environmental regulations. International and interindustry differences in pollution policies across industries and nations are motivated by income differences between trading partners. My analysis of emissions leakage within a single, incompletely regulated industry instead emphasizes specific structural characteristics of the market and the strategic interactions between asymmetric oligopolists. Intra-industry differences in regulatory stringency are assumed to result from some structural impediment (be it jurisdictional limitations, political constraints, or technical issues) that limits the reach of the regulator. 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.

This work is also preceded by several papers in the industrial organization literature that analyze *complete*, market-based environmental regulation of an imperfectly competitive industry. Levin(1985), Ebert (1991), Simpson (1995), and Van Long and Soubeyran (2005), among others, have investigated second-best Pigouvian taxes; Malueg (1990), Mansur (2007), and Sartzetakis(1997, 2004) analyze the interaction of complete, competitive permit markets and oligopolistic product markets. When producers in an imperfectly competitive industry generate a pollution ex-

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[6] See Copeland and Taylor (2004) for a recent summary of this literature.

ternality, firms' marginal abatement costs generally fall below the marginal damage from pollution at the second-best optimum.[7] Without exception, the prior literature assumes that all firms in an industry are subject to environmental regulation. This paper extends this work to the increasingly relevant case of incomplete regulation.

3 The Model

Using a partial equilibrium, asymmetric oligopoly model, this section investigates how the emissions and emissions leakage occurring under incomplete environmental regulation are affected by observable industry features: operating costs, emissions rates, participation requirements, and the degree of competitiveness. The emphasis here is on understanding how incomplete market-based regulation affects firm behavior in the short run.[8]

3.1 The basic framework

Recent empirical work suggests that firms in industries targeted by existing and planned incomplete environmental regulation can exercise market power by restricting supply (Borenstein, Bushnell and Wolak, 2002; Bushnell, Mansur, and Saravia, 2007). I assume Cournot non-cooperative behavior among N strategic firms.[9] 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. Producers vary both in terms of their production costs and emissions characteristics. Both kinds of asymmetry are important. A defining advantage of market-based environmental policy instruments (as compared to more traditional,

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[7] There are exceptions. 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.

[8] Admittedly, the most substantial reductions of industrial emissions will most likely be achieved via more long run investment decisions to replace older production assets with cleaner technology. However, 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.

[9] Much of the theoretical and empirical literature analyzing heavily polluting industries such as electricity and cement employs a static oligopoly framework in which firms are assumed to compete in quantities (Alba et al., 1999; Andersson and Bergman, 1995; Borenstein and Bushnell, 1999; Cardell et al, 1997; Chen and Hobbs, 2005; Bushnell et al. 2005 ; Demailly and Quirion, 2006; Ryan, 2007). Supply function equilibrium(SFE) models are another popular option when analyzing strategic behavior in restructured electricity markets (see, for example, Green and Newbery, 1992; Hortascu and Puller, 2006). The advantage of the SFE model is that it more closely resembles ths institutional realities of restructured electricity markets (i.e. firms bid supply curves versus single quantities). A disadvantage is that these models are computationally less tractable; variation in emissions rates, capacity constraints and operating costs are more difficult to incorporate into these models.

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 directly; she takes the structure of the product market as given. Following Malueg (1990) and Sartzetakis (1997; 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 being considered is one of several participating in the cap-and-trade (CAT) program (true for all cap and trade programs currently in place), or in the event that regional CAT initiatives are incorporated into a much larger international emissions permit market (true for planned regional programs capping greenhouse gas emissions).[10]

Firms' emissions rates per unit of production are exogenous to the model; 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).[11] 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.[12] 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. Several of these assumptions are relaxed in the simulation exercises.

3.2 The one-stage game

This section introduces the one-stage model with N producers, one homogenous good Q , and one pollutant E. The i^{th} firm's constant marginal production cost is given by $C_i'(q_i) = c_i,\ i = 1..N$. Emissions at firm i are proportional to output; $E_i = e_i q_i$. Both marginal costs c_i and emissions

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[10] 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. Annual CO_2 emissions from electricity generation in California amount to 2.3 percent of the annual permit allocation under the EU ETS. Permits allocated annually under RGGI will likely amount to less than 8 percent of the annual EU ETS allocation.

[11] 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. For example, the bulk of greenhouse gas reductions from the electricity sector will be achieved by dispatching units in a way that favors 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.

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

rates e_i are allowed to vary across firms. Preferences on the part of consumers are represented by an inverse demand function $P = a - b\sum_{n=1}^{N} q_i, i = 1...N$.

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.[13] 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 $i = 1, .., N$ 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. With a perfectly competitive permit market, 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 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.

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[13] Because we assume that the permit price is independent of Q, the cap-and-trade program represented here is equivalent to a tax τ per unit of pollution.

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:[14]

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

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

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: $\sum_{n=1}^{N} d_i = N_1$;$\sum_{n=1}^{N}(1-d_i) = N_0$.

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 the b parameter, the greater the emissions leakage. Finally, note that an increase in industry concentration decreases emissions leakage, ceteris paribus. 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 (where $d_i = 0$ 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. In each case, strictly positive emissions rates and permit price are assumed. Proofs are presented in Appendix 2.

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

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

This follows directly from Equation [2]. Assuming that $\tau > 0$ and that $e_i > 0$ for at least one regulated firm, the introduction of 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):

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

Note that the numerator, the mean of the square of e_1 , cannot be less than the square of the mean of e_1. 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:

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

The somewhat counter-intuitive result will only be observed when regulated firms are relatively more polluting. The introduction of environmental regulation into a Cournot oligopoly 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, the reallocation of production induced by the introduction of environmental regulation 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.[15]

3.3 The Two-Stage Game

In this section, a forward product market is added to the model. This extension is warranted for two reasons. First, vertical arrangements are common in several of the major industries currently targeted by incomplete environmental regulation (including restructured electricity markets). Second, 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 period preceding the 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. Consequently, revenues from the sales of forward contracts are excluded from the spot market production stage profit function.[16]

The vector of production quantities $\mathbf{q}^* = (q_1^*, ..., q_n^*)$ is a Nash-Cournot equilibrium for the

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[15] Note that leakage will still occur. 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.

[16] Comparing the marginal revenue expression under forward contracting with the standard Cournot marginal revenue, it is clear that when the firm is short on the forward market ($f_i > 0$) it will be less sensitive to the price elasticity effect of increasing production. This is the driving force behind the result that forward contracting induces firms to produce more aggressively in the spot market.

spot market production game if for each $i = 1, .., N$, q_i^* solves:

$$\max_{q_i} \pi_i \left\{ p_s(q_i, \sum_{j \neq i}^{N} q_j^*)(q_i - f_i) - c_i q_i + d_i \tau (A_i - e_i q_i) \right\}. \tag{6}$$

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

$$p_s'(Q)(q_i - f_i) + p_s(Q) = c_i \ + \tau d_i e_i \ \forall \ i = 1, .., N. \tag{7}$$

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:

$$q_i(\mathbf{f}) = \frac{a + \sum_{j \neq i} (c_j + \tau d_j e_j) - N(c_i + \tau d_i e_i - b f_i) - b \sum_{j \neq i}^{N} f_j}{(N+1)b} \tag{8}$$

$$Q(\mathbf{f}) = \frac{N}{(N+1)b} \left(a - \frac{1}{N} \sum_{n=1}^{N} c_i - \frac{\tau}{N} \sum_{n=1}^{N} d_i e_i + \frac{b}{N} \sum_{i=1}^{N} f_i \right) \tag{9}$$

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. The forward price is set in a Bertrand auction where competitive speculators bid for the aggregate forward supply F. Speculators announce prices simultaneously; the lowest bidder purchases the entire market.

Assuming the forward positions of the other firms are fixed, the i^{th} producer chooses f_i to maximize:

$$\max_{f_i} \ \pi_i \left\{ \delta[(p_s(f_i, \bar{F}_{\_i}) - c_i) q_i(f_i, \bar{F}_{\_i}) + \tau A_i] + [p_f - \delta p_s(f_i, \bar{F}_{\_i})] \ f_i \right\} \tag{10}$$

Rational expectations are assumed, which means that 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:

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

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. Here, 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:

$$f_i^* = \frac{(N-1)a}{(N^2+1)b} + \frac{(N^2-N+1)(1-N)}{(N^2+1)b}(c_i + \tau d_i e_i) + \frac{(N-1)N}{(N^2+1)b}\sum_{j \neq i}(c_j + \tau d_j e_j), \tag{12}$$

$$q_{*i2}(d_1, ..d_N) = \frac{Na + N^2 \sum_{j \neq i}(c_j + \tau d_j e_j) - N(N^2-N+1)(c_i + \tau d_i e_i)}{(N^2+1)b} \tag{13}$$

$$Q_2^*(d_1, ..d_N) = \frac{N}{(N^2+1)b}(Na - \sum_{n=1}^{N} c_i - \tau \sum_{n=1}^{N} d_i e_i) \tag{14}$$

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:

$$L_2 = \frac{N_1 N_0 N^2}{(N^2+1)b} \tau \, \overline{e^1} \quad \overline{e^0}, \tag{15}$$

It is straightforward to demonstrate that Propositions 1-4 hold qualitatively when firms compete in both spot and forward markets. Appendix 5 proves these results for the two-stage model.[17] A comparison of this expression and equation [3] implies the following:

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

Proposition 5 *The existence of a forward market amplifies 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. Thus, as with a decrease in industry concentration, the presence of a forward market implies a more competitive product market and greater leakage.

3.4 Leakage in the limiting case: Perfectly competitive markets

Results presented thus far imply that emissions leakage increases with industry competitiveness. Although this is true in general, it is not necessarily true in the limiting case of perfectly competitive product markets.

Constant marginal costs and non-binding capacity constraints imply that the producer(s) with the lowest operating costs will supply the entire market if the industry is perfectly competitive. Under these assumptions, the emissions leakage that occurs when all producers behave competitively can exceed leakage under imperfect competition, all else equal. To see why this is so, suppose that a single, least cost producer supplies the market.[18] If the identity of the least cost producer is unaffected by the introduction of incomplete environmental regulation, there will be no leakage. In this case, emissions leakage under perfect competition is less than that which would occur under imperfect competition.[19]

4 A stylized example

I now turn to 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.

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[18] It is straightforward to generalize this to the case where multiple producers with equally low operating costs split the market.

[19] If the identity of the least cost producer is affected by the introduction of the regulation, and if this producer must purchase permits to offset uncontrolled emissions, "leakage" is now equal to industry emissions under incomplete 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 the 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). In this case, 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. Conversely, 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 *exceed* incompletely regulated emissions when the regulated firm is relatively clean.

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 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 [12], 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 [12], 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.[20]

4.2 Welfare implications of incomplete regulation

Now consider the problem faced by a welfare maximizing regulator. As a welfare measure, I adapt a standard approach: welfare is defined to be the gross consumer benefit from consumption less production costs less monetized damages from emissions. I assume that the regulator is indifferent to purely redistributional effects. To keep things simple, I assume that marginal damages are constant and equal to the prevailing permit price τ. 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:

$$W(1,0) - W(0,0) = \int_{Q^B}^{Q^{COMP}} P(s)ds + \frac{\tau}{3b}\left(e_1(3c_1 - 2\bar{c})\right) + \frac{\tau^2}{3b}(3e_1^2 - 2e_1\bar{e}). \qquad (16)$$

Requiring firm 1 to purchase permits to offset its emissions affects overall welfare via three different channels or sub-effects, each corresponding to one of the three arguments in [16]. 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

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[20] Note that, by Equations [3] and [15], $L_2 = \frac{4\tau}{5b} e_{LOW} e_{HIGH} > \frac{\tau}{2b} e_{LOW} e_{HIGH} = L_1$.

reallocation of production across duopolists. The final argument measures the regulation-induced 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 $e_1 > 0$). In the case of an asymmetric oligopoly, the regulation-induced reallocation of production can either positively or negatively affect overall production efficiency, and thus welfare. Note that the regulation-induced reduction in overall output can be associated with an *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 high cost firm, the introduction of incomplete regulation can exacerbate the allocative production inefficiencies resulting from the exercise of market power.

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. In this particular example, the emissions rate of the unregulated firm is normalized to 1. The marginal production costs of firm 1 are assumed to be less than those of firm 2.[21]

The left panel plots 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. $W(1,1) - W(0,0)$). First note that the introduction of complete regulation decreases welfare over a large range of values of e_1. This is because 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 welfare benefits associated with a reduction in industry emissions.[22] Also note that incomplete regulation welfare dominates complete regulation over a broad range of values of e_1. Intuitively, 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) Note that the net welfare impacts of introducing incomplete regulation become positive when the regulated firm is relatively dirty.

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

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[21] Parameter values used to generate these figures are: $a = 80; c_1 = 3; c_2 = 1; e_2 = 1; b = 1; \tau = 10$.

[22] In this simple duopoly example, given the assumed demand and cost parameters, regulation induced welfare changes will be strictly positive for all values of e_1 when τ gets large. When marginal damages from pollution are large, the benefits associated with pollution reductions outweigh the costs associated with a contraction of output.

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 systematically affect both emissions leakage and overall welfare. However, these theoretical models are too abstract to be applied directly in a practical analysis of incomplete regulation. In this section, the theoretical framework is modified so as to facilitate a more realistic and detailed analysis of leakage in a particular policy context: regulation of GHG emissions from electricity generators supplying California.

5.1 Leakage and regional climate change policy

Somewhat ironically, states are taking a leading role in responding to global climate change. Regional initiatives have had to emerge to fill the policy vacuum created by stalemate at higher levels of governance.[23] Concerns that incomplete industrial participation will undermine the effectiveness of these regional initiatives 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.[24] 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.[25] In a report issued by the

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[23] 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, nine 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. Whereas some states are pursuing policies to address global warming, several have taken an opposite tack and explicitly passed laws against any mandatory reductions in greenhouse gas emissions.These states are Alabama, Illinois,Kentucky, Oklahoma, West Virginia and Wyoming. (Senate Congressional Record, October 30, 2003: S13574).

[24] See, for example, Association Francaise des Enterprises pour l'Environnement. *EU-ETS REVIEW.* May 2005; Rinaud, J. Industrial Competitiveness under the European Union Emissions Trading Scheme. *IEA Information Paper*, February 2005.

[25] Preliminary modeling results presented to the Regional Greenhouse Gas Initiative (RGGI) stakeholder group predicts leakage rates of of 67% (EEI, 2005).

Australian Chamber of Commerce and Industry, an incomplete, state-based GHG trading system was dismissed as "completely unworkable" due to anticipated leakage problems.[26]

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, March 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. California policy analysts anticipate that the leakage associated with a conventional, generation-based emissions trading program for in-state producers would be substantial; regulators are thus pursuing more complicated policy approaches in an effort to circumvent the leakage problem (Bushnell et al. 2007; Climate Action Team, 2005; CCAP, 2005; CEC, 2005; CEC, 2006).[27] To my knowledge, no detailed analysis of the extent to which incomplete participation might compromise the effectiveness of a source-based trading program has been undertaken.

This section analyzes the potential for leakage in California's wholesale electricity market. 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).[28] 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).[29] 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.

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[26] "Emissions trading- Caution required." Australian Chamber of Commerce and Industry Issues Paper. June, 2006.

[27] More complicated "load-based" permit trading, together with performance standards for new baseload generation under contract, are being evaluated as potential ways around the leakage problem.

[28] 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.

[29] Electricity producers supplying the California market make wholesale price commitments for a significant portion of their capacity prior to committing to production in the spot market.

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

Detailed data from California and surrounding states 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. Hourly electricity production at generating units in California and six neighboring states (Arizona, Nevada, New Mexico, Oregon, Utah, Washington), hourly electricity imports to California, hourly wholesale electricity market prices, and hourly emissions are simulated under these three industry structures. Within each case, 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.

The theoretical framework is modified in several important ways in the interest of a more accurate representation of California's wholesale electricity industry. To begin with, 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.

Demand tends to be highly inelastic because few consumers have incentives to respond to short-run fluctuations in wholesale prices. Furthermore, the firms that procure customers' electricity in the wholesale market are mandated to provide the power at any cost. All simulations assume perfectly inelastic demand.[30]

Finally, a competitive fringe is added to the simulation model. In general, restructured wholesale electricity markets are served by a group of dominant firms and a fringe of smaller, price taking suppliers. Because demand is inelastic by assumption, any production that is strategically withheld by dominant producers is replaced with more expensive fringe production. The presence of the fringe has important implications for emissions leakage and overall efficiency.[31] To the extent that the introduction of environmental regulation increases the fringe market share, the regulation will exacerbate allocative production inefficiencies.

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[30] In fact, wholesale electricity demand in California is not *perfectly* inelastic in the short run. Some large customers are on interruptible rates or critical-peak pricing rates which can be triggered by either economic or reliability criteria.

[31] Mansur (2007) 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, this will not necessarily be the case; the marginal fringe unit may be relatively clean in some hours.

5.3 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.

5.3.1 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).[32]

Table 1 summarizes ownership of generation installed in California, Arizona, New Mexico, Nevada, Oregon, Utah, and Washington. 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.

5.3.2 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.[33] Generation at these facilities is classified as "firm imports". Table 2 lists the out-of-state capacity owned by California utilities. This generation plus known, long-standing contracts constitute firm imports.[34]

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.

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[32] In cases where data was inconsistent across sources, the SEC filings were assumed to be correct.

[33] 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.

[34] 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.

5.3.3 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.[35] 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.[36]

5.3.4 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 of 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 system has a maximum capacity of 10,118 MW.

5.3.5 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.[37] The North American Electric Reliability Council (NERC) tracks unit availability and outages at over 91% of installed capacity in North America.[38] These data are used to estimate unit-level forced outage factors f_i . For each unit, dependable capacity is calculated as $DMW_i = MW_i\ (1 - f_i)$.[39]

5.3.6 Hydro, Nuclear, and Renewable Generation

A significant share of California's gross system power is generated using large hydro, nuclear, and renewable generation assets.[40] Nuclear generation units are treated as must-run and must-take

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

[36] 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).

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

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

[39] Alternatively, Monte Carlo simulation methods could be used to simulate forced outages (see Borenstein, Bushnell and Wolak (2002), Mansur(2004)). 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(2006).

[40] 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).

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 the percentage of total hydro generation is accounted for by hourly ISO data in each month; hourly hydro generation data are scaled accordingly.[41] 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 load obligations.

5.3.7 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.[42] 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.[43] Hourly, boiler-level data are used to estimate CO_2 emissions rates when available. For smaller units that do not report CO_2 emissions, fuel-type specific estimates of emissions rates for California producers reported in CEC (2005a) are assumed.

5.3.8 Permit Price

Simulations are carried out for two permit prices: $10/ton CO_2 and $25/ton CO_2. These two values are within the range of damage estimates found in the literature. Tol (2005) reviews 103 estimates of monetized damages per ton of carbon dioxide. He reports median and mean damages of $4 and $25 per ton of carbon dioxide, respectively, although he argues that true damages are unlikely to exceed $14 per ton. These two values are also representative of observed prices in the EU ETS. In the first year of Phase I (2005), permit prices ranged from $9 to $37 per ton. In September 2007, the right to emit a short ton in 2008 and beyond was selling for $20-$25/ton.

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

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

[43] Under Part 75, Volume 40 of the Code of Federal Regulations.

5.4 A Preliminary look at the data

Figures 4, 5, and 6 summarize the emissions, marginal operating cost, 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).[44] 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.[45] For each region, a distribution of hourly loads 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 are capacity constrained.[46] California is the most capacity constrained of all three regions. The dirty out-of-state plants that provide the majority of firm imports are represented by the low cost, high polluting units to the left of the top panel in Figure 4. Note that these bars lie to the left of the distribution of load observations. This implies that there are rarely hours when these units are not running at capacity.

In hours when California demand for out-of-state imports is high, it is likely that demand in neighboring states will also be high. 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 dirtier than the marginal out-of-state unit.

5.5 Simulation results

Table 3 compares the observed outcomes in 2004 with the results from simulations that assume unregulated CO_2 emissions. Averaged over 8784 hours, wholesale electricity prices simulated using models that assume strategic behavior on the part of the dominant firms are both within 2 percent of observed prices when strategic behavior. As expected, slightly more competitive prices are associated with the two-stage model that incorporates forward contracts. Simulations that assume perfect competition yield electricity prices that are substantially lower than observed

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[44] Out-of-state units owned by California utilities are included in the California curve.

[45] 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.

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

prices.

Table 3 also summarizes simulated and observed emissions. Simulated emissions from generation located in California are within 1 percent and 2 percent of 2004 emissions (as estimated by the CEC) for the one-stage and two-stage Cournot models, respectively. The model that assumes price taking behavior on behalf of all firms does a much poorer job of replicating observed emissions; simulated emissions are more than 23 percent below observed emissions in California.

All three simulation models overpredict emissions of out-of-state producers. The model that assumes all producers act as price takers predicts aggregate emissions that are 12 percent above observed emissions. Models that assume dominant firms act strategically predict aggregate emissions that exceed observed emissions by 5-6 percent. Discrepancies between observed emissions and those predicted by the one-stage and two-stage modes are likely attributable to several factors. First, assumptions about unit availability, and emissions from small units that are not required to report emissions 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. This failure to represent intertemporal operating constraints can translate into inaccurate estimates of equilibrium spot prices. Finally, it is worth noting that the "observed" numbers reported by the EIA and CEC are by no means exact measures. Estimated emissions from imports into California are inaccurately measured.

Figure 7 plots the median of simulated emissions as a function of hourly electricity demand in California.[47] These spline functions summarize the results from simulations using the two-stage model (which performs the best in terms of replicating observed prices and emissions). The difference in aggregate emissions under complete and incomplete regulation varies significantly with load. Figures 3 and 4 indicate that, in hours when electricity demand is relatively low, the marginal plant in the Southwest is likely to be coal, whereas the marginal plant in California is likely to be relatively less polluting. Under these conditions we might expect emissions leakage to completely eliminate emissions reductions achieved by California producers under incomplete regulation. In Figure 7, we see that simulated emissions under incomplete regulation can exceed simulated, unregulated emissions in hours when electricity demand is low. Conversely, when electricity demand is high in California and surrounding states, the emissions rate of the marginal California producer can often exceed that of the marginal out-of-state generator. Under these conditions, we might expect emissions under complete regulation to exceed emissions under incomplete regulation. Figure 7 illustrates how simulated emissions under complete regulation do exceed incompletely regulated emissions when demand is high.

Figure 8 plots the median simulated hourly operating costs of supplying California load (not

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[47] Both figures 7 and 8 summarize data from the two-stage simulation model that assumes a permit price of \$10/ton CO_2.

including the costs of complying with the CO_2 regulation) as a function of California load. This figure illustrates how the introduction of environmental regulation unambiguously increases median operating costs. For most load levels, the median operating cost incurred to meet inelastic demand is higher under incomplete (versus complete) regulation, although there are some load levels for which the reverse is true. These results suggest that, overall, the marginal in-state producer has lower operating costs than the marginal out-of-state producer on average.

Results from these hourly simulations can be summed across hours to estimate total emissions leakage and associated costs over a year. Tables 4, 5, and 6 provide numerical summaries corresponding with the one-stage Cournot model, the two-stage Cournot model, and the model that assumes price taking behavior on behalf of all producers. Results are presented for two sets of simulations: one that assumes a permit price of \$10/ton CO_2, and one that assumes a price of \$25/ton CO_2. Overall, the models that assume that dominant firms behave strategically predict that incomplete regulation could achieve between 32 percent and 37 percent of the emissions reductions achieved by complete regulation. A permit price of \$10 is associated with emissions reductions on the order of 4 percent (1.5 percent) under complete (incomplete) regulation. If a permit price of \$25/ton CO_2 is assumed, complete regulation (incomplete regulation) delivers emissions reductions of roughly 9 percent (3 percent). The simulation model that assumes price taking behavior on behalf of all producers yields substantially different results. Emissions reductions are more moderate. When the permit price is assumed to be \$10/ton, emissions leakage entirely offsets emissions reductions achieved by in-state generators.[48]

Finally, simulated costs and emissions can be used to calculate the implicit cost per ton of CO_2 reduced. Variable operating costs are summed across producers, across hours under complete environmental regulation, incomplete environmental regulation, and in the absence of regulation. These costs include fuel costs and operations and maintenance costs, but do not include the costs of purchasing permits to offset CO_2 emissions. Aggregated variable operating costs accrued in the absence of regulation are subtracted from aggregated variable operating costs under regulation. This difference (measured in \$) is divided by the emissions reduction (measured in tons of CO_2). In the simulation models that assume strategic behavior, costs per ton of abatement under complete regulation are \$27 and \$28/ton (for the single-stage and two-stage models, respectively). Average costs per ton of abatement increase by almost three times under incomplete regulation. The average cost per ton of emissions reduced under perfect competition is \$14.35 when the permit price is \$25/ton . Because emissions leakage is so significant under perfect competition, this

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[48] Meaningful comparisons of the results from the simulations that assume perfect competition and those that assume strategic behavior in California's electricity market are somewhat confounded by methodological differences. Whereas linear approximations of the supply functions of the strategic firms and the fringe are used to determine equilibrium production quantities in the simulations based on the single-stage and two-stage models, no linear approximations are used in determining equilibrium outcomes under perfect competition. In order to make these results more directly comparable, marginal cost step functions (versus linear approximations) could be used in all simulations. This extension is beyond the scope of this paper.

average cost increases dramatically (to approximately \$370 per ton) under incomplete regulation.

6 Concluding remarks

Incomplete industrial participation in market-based environmental regulation has the potential to significantly (if not entirely) undermine policy effectiveness . This paper develops a theoretical framework for analyzing emissions leakage in an incompletely regulated, imperfectly competitive industry. Several key results emerge from a theoretical analysis of the partial equilibrium model. First, 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 more competitive the industry, the greater the effect of incomplete participation on industry emissions in equilibrium.

The net welfare effects of incomplete participation depend not only on the extent to which emissions leakage occurs, but also on how incomplete regulation reallocates 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. 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 state policies that aim to reduce greenhouse gas emissions from electricity consumption in the state. A numerical model that accounts for strategic behavior, 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, results indicate that complete regulation would reduce emissions associated with California electricity consumption by almost 11 percent in the short run. Incomplete regulation reduces emissions associated with California consumption by only 5.5 percent. The cost per ton of CO_2 emissions reduced is more than twice as high under incomplete regulation.

In this paper, the analysis is limited to simulating production and emissions at existing facilities. However, the most substantial reductions in industrial GHG emissions will likely be achieved through investing in new, cleaner technologies. Understanding how incomplete climate change mitigation policies will affect prices and asset utilization rates in the short run is an essential first step in understanding how regulatory incentives can affect investment patterns and accelerate asset replacement decisions in the longer term. For example, the model developed here could be used to evaluate returns to new investments in different types of generation. This would provide insights into the extent to which incomplete regulation of GHG emissions would discourage investment in cleaner, in-state generation.

Finally, this analysis is unique in its explicit consideration of the forward contracts which play an important role in determining equilibrium outcomes in many of the industries subject to market-based environmental regulation. It should be emphasized that I consider a very specific type of forward contracting here, namely contracts that emerge for strategic reasons. Other types of vertical arrangements (such as installed capacity requirements, the proposed performance standard for baseload generation under contract, or other regulatory interventions that affect firms' forward commitments) are not represented in the model. This framework could be modified to more accurately represent observed vertical arrangements. Such an extension would facilitate a more realistic analysis of the potential for leakage under incomplete environmental regulation.

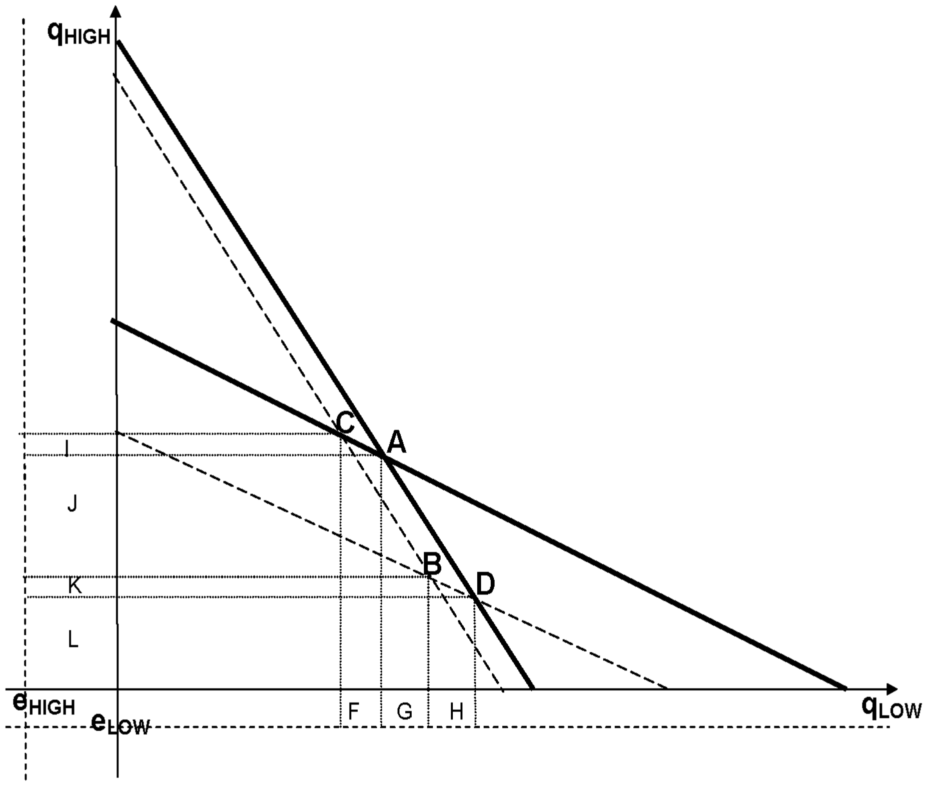

Figure 1 : The One-stage Duopoly Game

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.

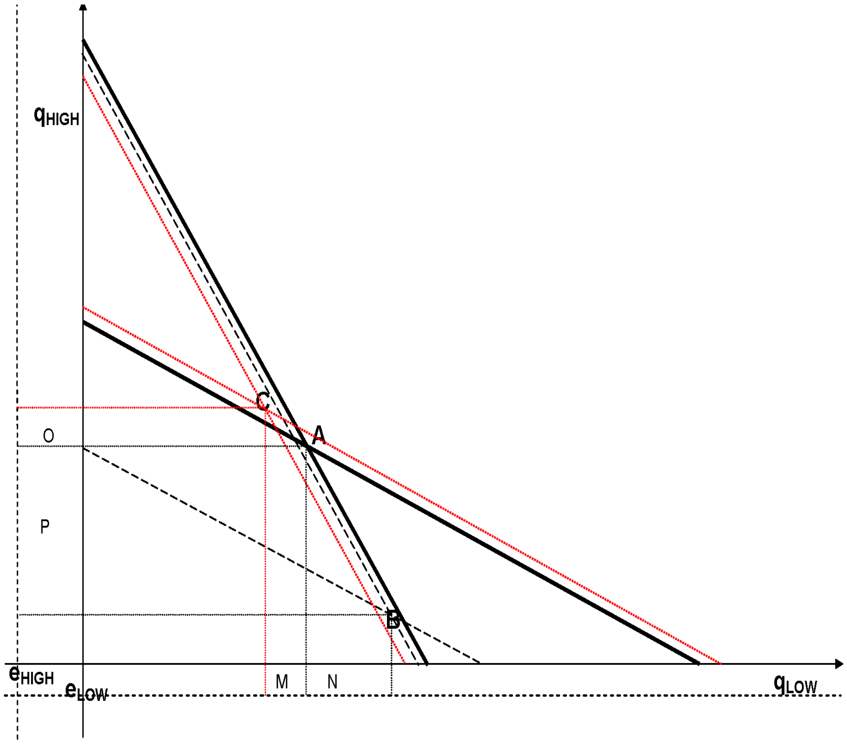

Figure 2 : The Two-Stage Duopoly Game

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.

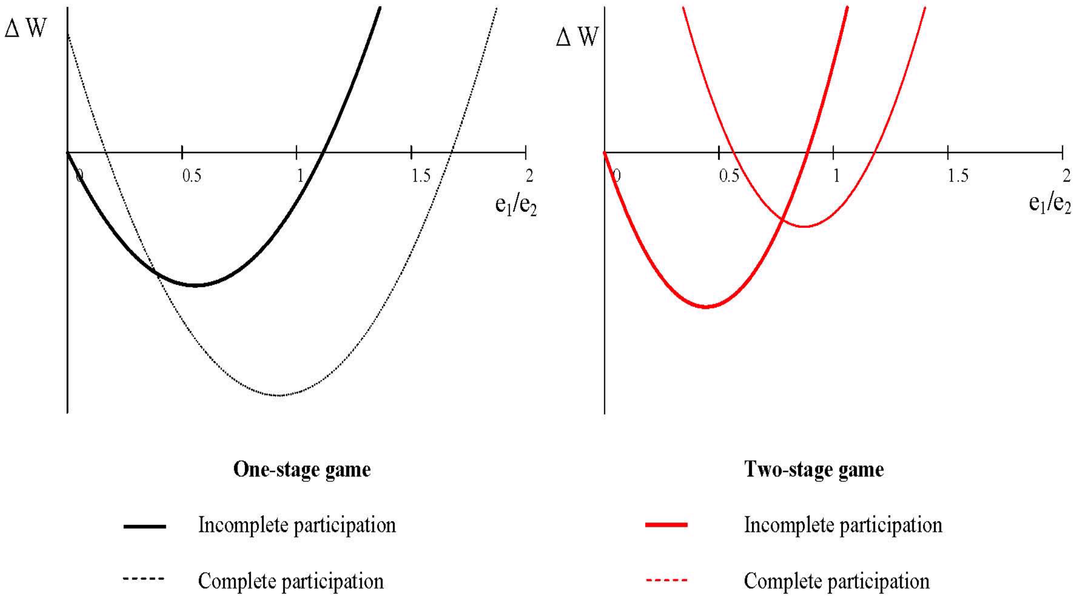

Figure 3 : Welfare Effects of Complete and Incomplete Regulation

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.

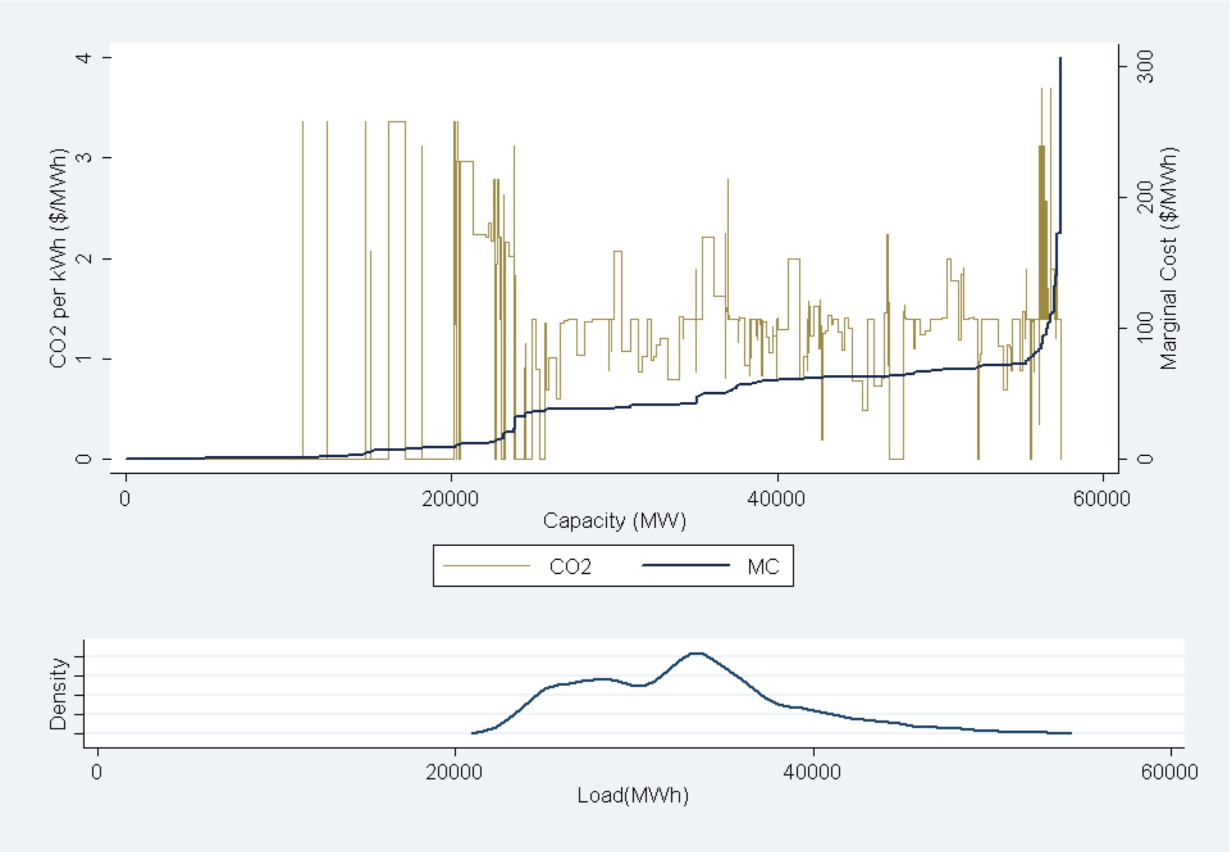

Figure 4 : Marginal Costs, CO_2 Emissions Rates and Hourly Load in California

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.

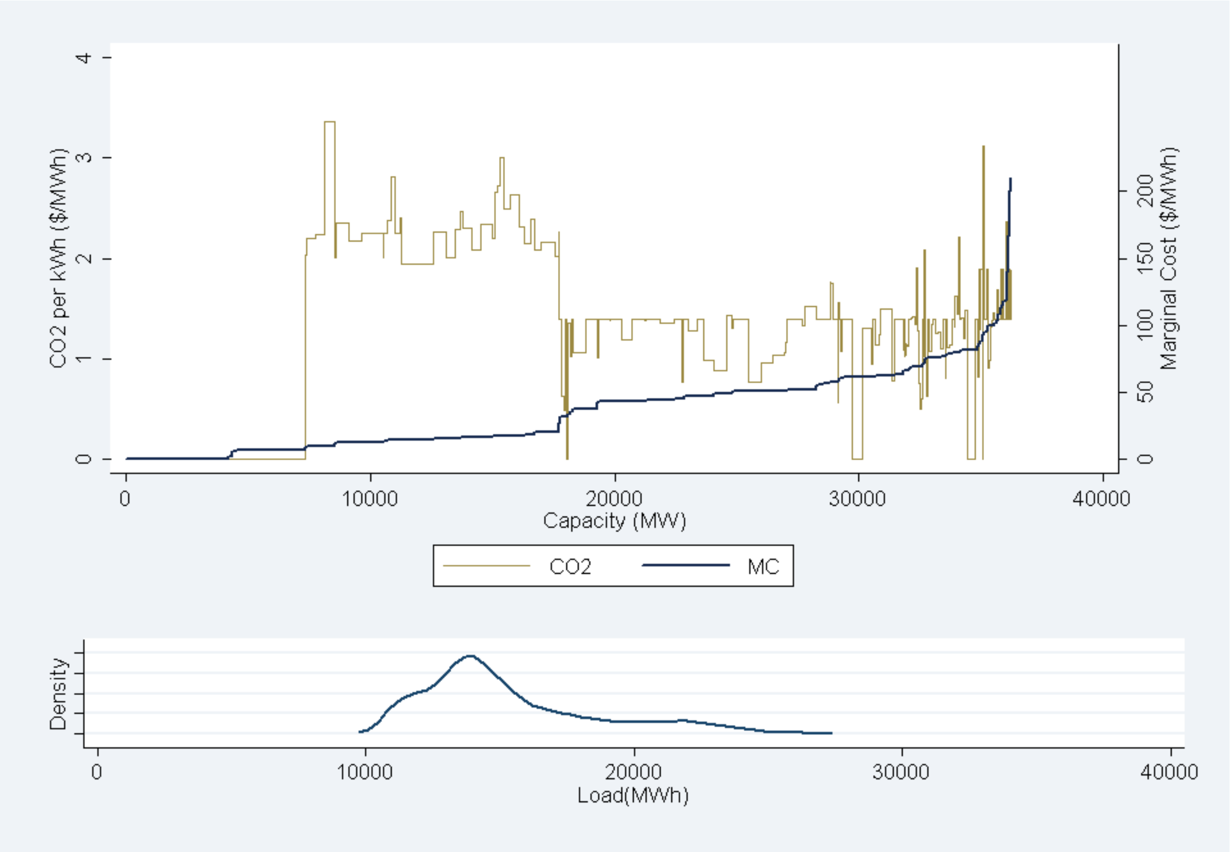

Figure 5 : Marginal Costs, CO_2 Emissions Rates, and Hourly Load in the Southwest

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.

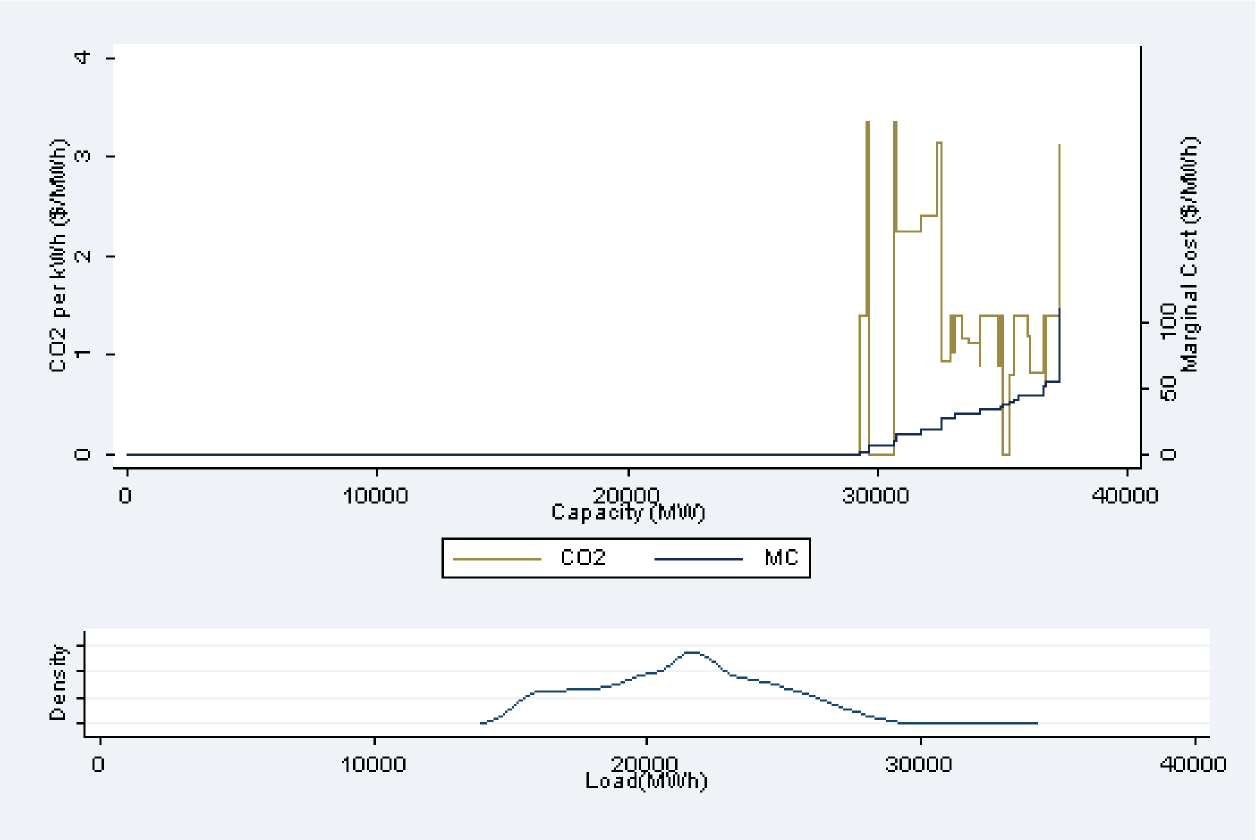

Figure 6 : Marginal Costs, CO_2 Emissions Rates, and Hourly Load in the Northwest

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.

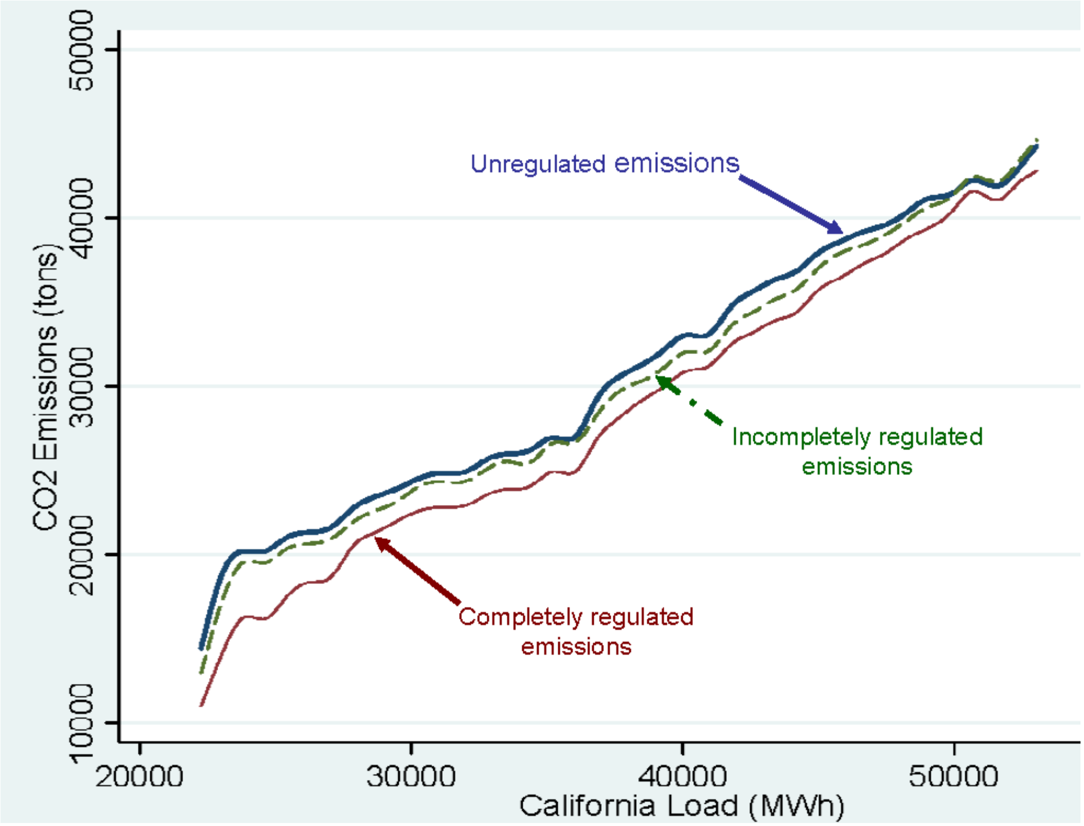

Figure 7 : Emissions as a Function of California Load

Notes: These three median spline functions plot hourly CO2 emissions in seven western states simulated using the two-stage model as a function of California load. The thick solid line plots unregulated emissions. The thin solid line traces out completely regulated emissions. The broken line represents incompletely regulated emissions. When incompletely regulated emissions equal unregulated emissions, emissions leakage exactly offsets emissions reductions at regulated firms. In hours when demand is high, completely regulated emissions can exceed incompletely regulated emissions.

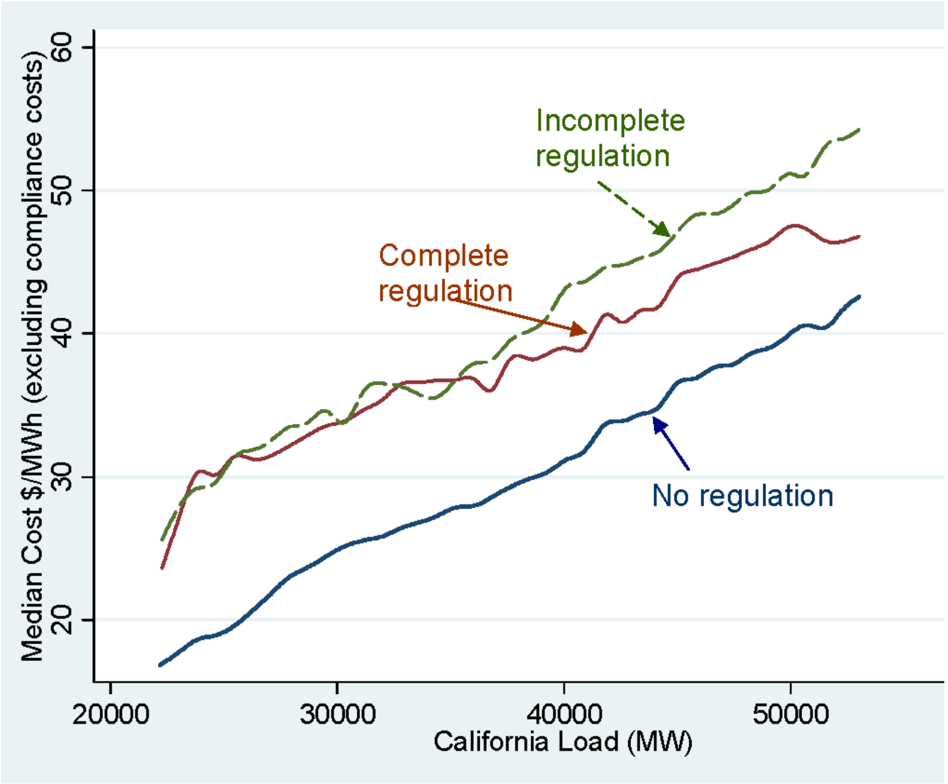

Figure 8 : Production Costs/MWh (Net of Compliance Costs) as a Function of California Load

Notes: These three median spline functions plot median hourly operating costs (not including the costs of complying with CO2 regulations) among strategic firms as a function of California load.

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

Parent Company	Total (exluding hydro) (MW)	%	Total Fossil (MW)	%	California total (excluding hydro) (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	7,441	4.8	3,893	4.2	4,991	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	4,693	7.2	1.32
Scottish Power	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	3,908	2.5	3,896	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	46	1.19
Total	155,168		91,447		65,134		1.21

Table 2: 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

*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.

Table 3: 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)**	$47.82 ($8.99)	$45.79 ($8.61)	$41.46 ($8.34)
California emissions (million tons CO_2)	**55.2***	53.7	54.6	42.1
Emissions from generation supplying California (million tons CO_2)	**118.7****	124.5	123.5	128.2
Total emissions (million tons CO_2)	**206.4***	227.5	226.5	231.2

* 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 4: Summary of Equilibrium Prices and Emissions: Single-Stage Model

(price standard deviations in parentheses)

		Simulation Results		
	Observed	**No Regulation**	**Complete Regulation**	**Incomplete Regulation**
	PERMIT PRICE = $10/ton			
Average California electricity price ($/MWh)	**$46.71 ($7.12)**	$47.82 ($8.99)	$63.75 ($10.74)	$62.65 ($10.35)
Emissions from generation located in California (millions of tons)	**55.2**[*]	53.7	58.4	42.4
Emissions from generation serving California load (millions of tons)	**118.7**[**]	124.5	117.3	121.1
Total emissions (million tons CO_2)	**206.4**[*]	227.5	218.6	224.2
Leakage (million tons CO_2)				8
Leakage as a percentage of reductions at regulated facilities				71%
	PERMIT PRICE = $25/ton			
Average California electricity price ($/MWh)	**$46.71 ($7.12)**	$47.82 ($8.99)	$72.73 ($11.63)	$70.74 ($11.71)
Emissions from generation located in California (millions of tons)	**55.2**[*]	53.7	57.7	35.8
Emissions from generation serving California load (millions of tons)	**118.7**[**]	124.5	111.2	117.6
Total emissions (million tons CO_2)	**206.4**[*]	227.5	206.3	220.7
Leakage (million tons CO_2)				11.1
Leakage as a percentage of reductions at regulated facilities				62%

[*] 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 5: Summary of Equilibrium Prices and Emissions: Two-Stage Model

(price standard deviations in parentheses)

		Simulation Results		
	Observed	**No Regulation**	**Complete Regulation**	**Incomplete Regulation**
	PERMIT PRICE = \$10/ton			
Average California electricity price (\$/MWh)	**\$46.71** **(\$7.12)**	\$45.80 (\$8.61)	\$59.47 (\$10.05)	\$55.17 (\$11.18)
Emissions from generation located in California (millions of tons)	**55.2**[*]	54.6	59.2	43.4
Emissions from generation serving California load (millions of tons)	**118.7**[**]	123.5	116.9	120.7
Total emissions (million tons CO_2)	**206.4**[*]	226.5	218.2	223.7
Leakage (million tons CO_2)				8.4
Leakage as a percentage of reductions at regulated facilities				75%
	PERMIT PRICE = \$25/ton			
Average California electricity price (\$/MWh)	**\$46.71** **(\$7.12)**	\$45.80 (\$8.61)	\$68.11 (\$10.80)	\$65.78 (\$10.81)
Emissions from generation located in California (millions of tons)	**55.2**[*]	54.6	58.5	35.8
Emissions from generation serving California load (millions of tons)	**118.7**[**]	123.5	110.8	116.9
Total emissions (million tons CO_2)	**206.4**[*]	226.5	205.8	220.0
Leakage (million tons CO_2)				12.3
Leakage as a percentage of reductions at regulated facilities				65%

[*] 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 6: Summary of Equilibrium Prices and Emissions: Perfect Competition

(price standard deviations in parentheses)

		Simulation Results		
	Observed	**No Regulation**	**Complete Regulation**	**Incomplete Regulation**
PERMIT PRICE = $10/ton				
Average California electricity price ($/MWh)	**$46.71** **($7.12)**	$41.46 ($8.34)	$47.35 ($7.88)	$44.46 ($8.72)
Emissions from generation located in California (millions of tons)	**55.2**	42.1	40.3	29.7
Emissions from generation serving California load (millions of tons)	**118.7**[**]	128.2	125.8	128.6
Total Emissions (millions of tons)	**206.4**	231.3	227.2	231.7
Leakage (million tons CO_2)				12.9
Leakage as a percentage of reductions at regulated facilities				104%
PERMIT PRICE = $25/ton				
Average California electricity price ($/MWh)	**$46.71** **($7.12)**	$41.46 ($8.34)	$56.58 ($6.83)	$48.16 ($9.96)
Emissions from generation located in California (millions of tons)	**55.2**[*]	42.1	39.7	18.2
Emissions from generation serving California load (millions of tons)	**118.7**[**]	128.2	122.1	127.4
Total emissions (million tons CO_2)	**206.4**[*]	231.3	217.4	230.6
Leakage (million tons CO_2)				23.1
Leakage as a percentage of reductions at regulated facilities				97%

[*] 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 7: Costs per ton CO_2 Abated

	Permit Price	Complete Regulation	Incomplete Regulation
Single-stage Model	\$10/ton	\$42.08	\$101.44
	\$25/ton	\$27.95	\$77.90
Two-stage model	\$10/ton	\$36.77	\$100.05
	\$25/ton	\$27.08	\$80.85
Perfect Competition	\$10/ton	\$4.46	–
	\$25/ton	\$14.58	\$361.32

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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:

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

Appendix 2

Proof of proposition 2.1 : Complete regulation unambiguously reduces aggregate emissions

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

$$
\begin{aligned}
\sum_{i=1}^{N}e_i\left(\sum_{i=1}^{N}\tau e_i-(N+1)\tau e_i\right) &< 0 \\
N^2(\overline{e})^2 &< (N+1)N\overline{e^2} \\
-\overline{e^2} &< N(var(e_i))
\end{aligned}
$$

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.

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

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

$$N\overline{ee_1} > (N+1)\overline{e_1^2}$$

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

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:

$$\pi_i^s = p_s(Q)(q_i - f_i) - c_i q_i + \tau(A_i - d_i e_i q_i). \tag{17}$$

First order conditions for a maximum are given by:

$$p_s'(Q)(q_i - f_i) + p_s(Q) - c_i - \tau d_i e_i = 0. \tag{18}$$

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:

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

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 :

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

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:

$$
\begin{aligned}
\begin{bmatrix} 1 & .. & .. & \frac{N-1}{2N} \\ : & 1 & & : \\ : & & 1 & : \\ \frac{N-1}{2N} & .. & .. & 1 \end{bmatrix} &= \frac{N+1}{2N}I + \begin{bmatrix} \frac{N-1}{2N} & .. & .. & \frac{N-1}{2N} \\ : & & & : \\ : & & & : \\ \frac{N-1}{2N} & .. & .. & \frac{N-1}{2N} \end{bmatrix} \\
&= \frac{N+1}{2N}I + \frac{N-1}{2N}\iota\iota^T \\
&= \frac{N+1}{2N}\left(I + \frac{N-1}{N+1}\iota\iota^T\right)
\end{aligned}
$$

Substituting back into our original system, we have:

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

From Henderson and Searle(1981) we have:

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

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

$$\begin{aligned}
\left(I + \frac{N-1}{N+1} \iota\iota^T \right)^{-1} &= I - \frac{\frac{N-1}{N+1}}{1 + N(\frac{N-1}{N+1})} \iota i' \\
&= \left(I - \left[\frac{N-1}{N^2+1} \right] \iota i' \right) \\
&= \begin{bmatrix} \frac{N^2-N+2}{N^2+1} & .. & .. & -\frac{(N-1)}{N^2+1} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ -\frac{(N-1)}{N^2+1} & .. & .. & \frac{N^2-N+2}{N^2+1} \end{bmatrix}.
\end{aligned}$$

Substituting this matrix into our original system of equations:

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

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:

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

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

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:

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

$$E_F = \sum_{i=1}^{N}e_iq_i = \frac{N^2\overline{e}(a + N^2\overline{c} + N^2\tau\overline{de}) - N(N^2+1)\sum_{i=1}^{N}\left(e_ic_i + \tau d_ie_i^2\right)}{(N^2+1)b}$$

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

Proof of proposition 2.2 : Complete regulation unambiguously reduces aggregate emissions

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

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

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

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

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.

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

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

$$N^2\overline{ee_1} > (N^2+1)\overline{e_1^2}$$

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

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 developed in the previous section 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.[49] 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 demand curve faced by the strategic firms is constructed by subtracting fringe supply from California demand in that hour.

For each of three scenarios (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

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[49] 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.

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.[50] 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 [10]. 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 equilibrium can be rewritten:

$$p_{st}(Q_t)\frac{\partial q_{it}}{\partial f_{it}} + q_{it}\frac{\partial p_{st}}{\partial f_{it}} - c_{it} - \tau d_i e_i \frac{\partial q_{it}}{\partial f_{it}} = 0 \tag{19}$$

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 (19).

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 [19]. 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 also carried out. Wholesale electricity market outcomes in the Southwest and Pacific Northwest are simulated in

---

[50] 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.

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). Hourly California supply curves are constructed using all in-state generation, out-of-state generation owned by California utilities, and out-of-state export supply curves. Hourly least-cost dispatch is simulated. For each hour, equilibrium emissions and electricity prices are recorded for each region.