The Impact of Imperfect Permit Market on Congested Electricity Market Equilibrium

Tanachai Limpaitoon[*], *Yihsu Chen*[†], *Shmuel S. Oren*[‡]

The impact and efficacy of a cap-and-trade regulation on electric power industry depend on interactions of demand elasticity, transmission network, market structure, and strategic behavior of generation firms. This paper develops an equilibrium model of an oligopoly electricity market in conjunction with a permit market to study such interactions. The concept of conjectural variations is proposed to account for imperfect competition in permit market. The model is then applied to a reduced WECC 225-bus system with a detailed representation of the California market. In particular, we examine the extent to which permit trading strategies affect the market outcome. We find that a firm with more efficient technologies can employ strategic withholding of permits, which allows for its increase in output share in the electricity market at the expense of other less efficient firms.

Keywords: Power market modeling, Cap-and-trade program, Market power, Conjectural variation

1 INTRODUCTION

In the recent years, growing concerns around the issue of climate change have led to numerous transformations in the electric power industry. These changes are partly driven by regulatory policies such as renewable portfolio standard and emission trading programs that rely on market-based mechanisms to mitigate emissions and/or promote renewable energy. One concern over the implications of these regulations is the possibility that some firms in the market posses market power in both electricity and permit markets. Such market power may manifest itself when a dominant firm can deliberately consume permits in order to raise other firms' production cost or it can withhold its capacity to drive up electricity prices. There is substantial empirical evidence that market power is a relevant issue in both permit and electricity markets (see e.g., Borenstein et al. 2002, Joskow and Kahn 2002, Mansur 2007, Puller 2007 on market power in electricity market; and Kolstad and Wolak 2003 on permit market).

Since the onset of California electricity crisis, the presence of market power, even within the electricity markets alone, has drawn considerable attention. This is mainly because the complexity of market rules and regulations in the electricity markets have made the markets fundamentally different from other commodity markets. In such a scenario, where the issue arises from the existence of market power, a Nash-Cournot game is commonly applied to model an electricity market. Such models can be justified by empirical evidence suggesting that the performance of several U.S. regional electricity markets, e.g., Pennsylvania, New Jersey, and Maryland (PJM), New England, and California, is consistent with Nash-Cournot market outcomes (see Bushnell et al. 2008).

[*]University of California, Berkeley, 4141 Etcheverry Hall, Berkeley, CA 94720, USA. E mail: limpaitoon@berkeley.edu

[†]University of California, Merced, 5200 N. Lake Rd., Merced, CA 95343, USA. yihsu.chen@ucmerced.edu

[‡]Corresponding author. University of California, Berkeley, 4141 Etcheverry Hall, Berkeley, CA 94720, USA. oren@ieor.berkeley.edu

Nevertheless, finding Nash-Cournot oligopoly equilibria could be complicated by the presence of a congestion-prone transmission network. For example, Neuhoff et al. (2005) showed that the inclusion of transmission constraints into the strategic models, used in the analysis of impacts of regulatory mechanisms, can result in unexpected equilibria. Cardell et al. (1997) and Borenstein et al. (2000) also demonstrated the effect of transmission congestion on firms' strategic behavior. The introduction of any emission regulation to a transmission-constrained electricity market can lead to some unintended consequences for market outcomes when transmission congestion occurs (see e.g., Downward 2010; Limpaitoon et al. 2011). These studies highlight the importance of incorporating transmission network into strategic models used in the analysis of market power in electricity markets.

As mentioned earlier, a market for trading emission permits has also faced concerns over potential market power. Studies have shown that dominant firms are able to employ manipulative strategies in order to move prices in their favor. For instance, Kolstad and Wolak (2003) provided empirical evidence that firms used permit prices to justify higher costs of electricity produced, and for raising electricity prices. The earliest work on market power in the permit markets was introduced by Hahn (1984). He considered one dominant polluting firm and other price-taking firms in a static model. Sartzetakis (1997) and Resende and Sanin (2009) studied two- and three-stage models, respectively. While the former assumed a perfectly competitive permit market, the latter examined a case in which a firm has first-mover advantage in the permit market. Montero (2009) extended Hahn's model to accommodate the more contemporary market settings such as permit auctions. Tanaka and Chen (2011) considered a model for electricity market in which permit prices can be manipulated through fringe producers.

Although existing models consider imperfect competition in permit markets, most have not taken into account neither transmission network nor realistic network scale. The exception is the work by Chen and Hobbs (2005) who considered electricity and permit markets with a realistic, yet coarse, scale of transmission network. Our work differs from those existing models in that we examine *simultaneous* interactions, instead of a multi-stage model, of oligopoly competition between multiple players of transmission-constrained electricity market participating in a carbon permit market at a more realistic scale. Our approach takes into account essential market characteristics such as electrical loopflow, resource ownership, and transmission constraints based on thermal ratings. To account for the transmission network, we employ a direct current (DC) approximation, which is a common approach to analyze the impact of market power because of its tractability (Wei and Smeers 1999; Pang et al. 2001).

In modeling market power in the permit market, we propose a conjectural variation approach, whereby the conjectural variation parameters are derived "empirically" through simulations.[1] The approach allows us to estimate conjectural variations under different permit endowments because our conjectural variation parameters are estimated endogenously, whereas the parameters derived in Chen and Hobbs (2005) are based on historical emissions. Our model is especially useful when a regulatory agency wants to examine the extent of market power, if exists, in *joint* electricity and permit markets. Furthermore, the proposed model is readily extended to account for other economy sectors participating in the permit market.

The model is applied to a reduced 225-bus representation of the Western Electricity Coordinating Council (WECC) 225-bus network system for two reasons.[2] First, evidence has shown that

[1]Conjectural variation approach generalizes Cournot model (Perry 1982) and is widely used in both empirical studies and modeling of imperfect output markets (see e.g., Mansur 2001; Ehrhart et al. 2008).

[2]The WECC 225-bus system was also implemented in Yu et al. (2010) under an agent-based framework.

the California market is among the least competitive restructured US electricity markets.[3] Second, California has recently implemented a cap-and-trade program under AB 32, where market power is a concern.[4] As for the issues of permit allocation[5], the paper is primarily focused on characterizing the equilibrium when emission permits are initially allocated for free to generation firms. This is because permits allocation in California under AB 32 is intended for various reasons other than efficiency and equity (e.g., mitigating price impact). Our main interest is to understand the potential strategies taken by firms, when they are given different permit endowments. A sensitivity analysis of permit endowments of firms may shed light on how firms strategically plan their permit positions. This is relevant to the issue of "holding limit" of emission permits that is currently under discussion by the California Air Resource Board in Resolution 11-32 (ARB 2011). We also look at various market scenario assumptions in attempt to investigate the extent to which simultaneous exercises of market power in both electricity and permit markets impact market outcomes.

Our analysis shows that when an efficient firm (less polluting and low production cost) is "grandfathered" a substantial number of permits, it tends to strategically withhold the "unused" permits in order to place upward pressure on permit price, hence driving up the electricity price. The degree to which firms strategically withhold permits may be lessened, when a stringent cap is imposed, a situation in which permit prices tend to be relatively expensive. Also, the effect of the degree of competition in the permit market on social welfare is ambiguous and depends on the cap level. Finally, patterns of transmission congestion can be influenced by trading activities in the permit market. However, given that the scope of a C&T policy covers more than one sector, the case study may underestimate the price elasticity of emission permits, therefore inflating permit prices. Along with the adoption of other complementary measures to mitigate potential for market power, the possible market outcomes, as we argue, are likely bounded by our simulation results.

This paper is organized as follows. Section 2 describes an equilibrium model that includes optimization problems and market equilibrium conditions. The concept of conjectural variation in the context of permit market is also introduced. Section 3 describes a case study of the California market through the WECC 225-bus network in conjunction with a C&T program. In this section we simulate various market scenarios, propose the estimation procedure for conjectural variations, and discuss the economic implications of a C&T program on the electricity market in the light of market power in the joint markets. Section 4 concludes.

2 MODEL

We extend the model proposed by Limpaitoon et al. (2011) to account for market power in an emission permits market via conjectural variations. In particular, instead of having the permit price being determined endogenously within a perfectly-competitive equilibrium framework using a complementarity constraint[6], imperfect competition in the permit market, herein, assumes that each firm makes a conjecture about other firms' demand for permits. Each firm's decision regarding the number of permits to hold at equilibrium is, therefore, based on its perceived residual supply

[3]See, for example, Mansur (2007), Puller (2007), and Bushnell et al. (2008).

[4]As directed by Resolution 11-32, the California Air Resource Board has established a market simulation group to identify situations that might lead to market disruptions. These include market power, market manipulation, and non-strategic market frictions.

[5]Issues such as allowance distribution can greatly influence market incentives. For example, Eshel (2005) studied how permits should be initially allocated in order for the efficiency of permit market to be maximized.

[6]A complementarity constraint is defined as follows: $x \geq 0$, $f(x) \geq 0$, and $f(x)^T x = 0$, where $x \in R^n$ and the function $f : R^n \to R^n$ are given (Cottle et al. 1992). In this paper, the orthogonality condition is denoted by $\perp$.

of permits. A firm's conjectured price response in the permit market—which relates the price and quantity of permits that the other firms are willing and able to purchase—is represented by a downward-sloping demand curve. These curves are constructed from the simulation results of a Nash-Cournot game of an electricity market and a perfectly-competitive permit market by varying levels of emission cap. The simulation of joint markets yields the demand for permits, resulting from electricity producers' unabated emissions as they behave à la Cournot in the electricity market but behave as price-takers in the permit market. This may introduce inconsistency concerning firms' behaviors in the permit market and the resulting residual permit supply function will be less price-responsive at equilibrium, thereby biasing the extent of market power upward.

In the proposed model, the electricity market consists of an Independent System Operator (ISO), producers, and consumers in an electricity market. The ISO maximizes social welfare. The producers are Cournot players who own multiple power plants (or electric power generation facilities) competing to sell energy at different locations in a locational marginal price (LMP)-based market[7], where prices are set by the ISO. As Cournot players in the electricity market, producers maximize their profits by adjusting production levels given their respective residual demand, while behaving as price takers with regard to locational congestion markups that are set by the ISO. Consumers at each location are assumed to be price-takers, and their demand is represented by a linear price-responsive demand function. To account for transmission constraints, the equilibrium model is based on a lossless DC load flow model where electric power flows on transmission lines are constrained by thermal capacities of the lines. The flows in the system are governed by the Kirchhoff's laws through the Power Transfer Distribution Factors (PTDFs).

In what follows, we first introduce notations used in the model and subsequently present the equilibrium model that consists of all Karush-Kuhn-Tucker (KKT) conditions of the optimization problems faced by all entities in both electricity and permit markets.

Let N denote the set of buses (or locations) and L be the set of transmission lines whose elements are ordered pairs of distinct buses. Let G be the set of firms, and $N_g \subset N$ be the set of buses where power plants owned by firm $g \in G$ are located. Let i and l be the elements in N and L, respectively. By construction, each i refers to bus i and also refers to the plant located at bus i, if a plant exists. The fuel cost of plant $C_i(q)$ is assumed to be a quadratic function of megawatt (MW) power output q defined as $C_i(q) = \frac{1}{2}s_i q^2 + c_i q$, $\forall i \in N$. The amount of emissions from power plants is given by $F_i(q) = e_i q$, $\forall i \in N$, where e_i is the emission rate of plant i.[8] Consumers in each location i are represented by the inverse demand function $P_i(q) = a_i - b_i q$, where a_i and b_i are location-specific constants, $\forall i \in N$.

2.1 ISO's problem

The welfare-maximizing problem faced by the ISO is described by the formulation in subsection 2.1.1. The variables in parentheses next to the constraints are the Lagrange multipliers corre-

[7]For computational ease, a virtual location (bus) is created for each additional power plant at those locations with multiple plants. These virtual locations are connected to their corresponding original location through a line with unlimited thermal capacities. Each location then has at most one plant.

[8] For greenhouse gas such as CO_2, the constant emission rate is commonly used in modeling energy policies, e.g., the Integrated Planning Model (IPM) used by U.S. Environmental Protection Agency ([EPA] 2012). In contrast, strong nonlinearity associated with output level for other air pollutants, e.g., NO_x (nitrogen oxides), is observed from a dataset provided by Continuous Emission Monitoring System (U.S. EPA 2007). If the CO_2 emission rate was modeled as proportional to the quadratic fuel cost, it would discourage power plants from producing at a higher level since they would incur higher carbon costs.

sponding to those constraints. The KKT conditions of optimization problem 2.1.1 is summarized in subsection 2.1.2.

2.1.1 ISO's optimization problem

$$\max_{r_i : i \in N} \quad \sum_{i \in N} \int_0^{r_i + q_i} P_i(q)dq - C_i(q_i) \tag{1}$$

$$\text{s.t.} \qquad \sum_{i \in N} r_i = 0 \qquad (p) \tag{2}$$

$$-K_l \leq \sum_{i \in N} D_{l,i} r_i \leq K_l, \qquad (\kappa_l^-, \kappa_l^+) \quad \forall l \in L \tag{3}$$

$$-\sum_{l \in L} h_{s,l} \sum_{i \in N} D_{l,i} r_i \leq T_s \qquad (\tau_s) \qquad \forall s \in S \tag{4}$$

$$r_i + q_i \geq 0, \qquad (\xi_i) \qquad \forall i \in N \tag{5}$$

The ISO is assumed to maximize welfare (1)—taking into account the MW output decisions of the firms—subject to the lossless energy-balance constraint in the network (2), transmission-related constraints (3,4), and the non-negativity constraint (5).

The ISO manages congestion by controlling electric power imports/exports r_i, which is positive for imports into location i. The Lagrange multiplier p of (2) is the system marginal energy cost or price at the reference location. Electric power flows on the transmission lines are simply a function of the import/export at all locations. That is, the MW flow on line l resulting from a MW transfer from location i to the reference location is measured by the PTDF, $D_{l,i}$. The flow on each transmission line l is constrained by its thermal limit K_l measured in MW in DC models, where κ_l^+ and κ_l^- correspond to the Lagrange multiplier of the upper and lower transmission limits in (3). The load, $q_i + r_i$, must be non-negative because electricity is non-storable, and ξ is the multiplier assigned to this non-negative constraint (5).

In addition to the thermal limits already accounted for by (3), the ISO may enforce a list of additional transmission constraints, often referred to as "bubble constraint", to ensure reliable operation in the case of unpredictable generation contingencies in so-called "load pockets." The purpose of such constraints is to enable emergency imports into the load pocket. The list includes several groups of transmission lines (branch groups). Let S be the set of branch groups and L_s be the set of lines included in group $s \in S$. The constraints for these branch groups are then accounted for by (4), where T_s is the power transfer limit of group s; τ_s is the corresponding Lagrange multiplier; and

$$h_{s,l} = \begin{cases} 1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the same direction,} \\ -1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the opposite direction,} \\ 0 & \text{if } l \notin L_s. \end{cases}$$

2.1.2 KKT conditions

$$\varphi_i = \sum_{l \in L}(\kappa_l^+ - \kappa_l^-)D_{l,i} - \xi_i - \sum_{s \in S}\sum_{l \in L}\tau_s h_{s,l} D_{l,i}, \qquad \forall i \in N \tag{6}$$

$$P_i(r_i + q_i) - p - \varphi_i = 0, \qquad \forall i \in N \tag{7}$$

$$\sum_{i \in N} r_i = 0, \tag{8}$$

$$0 \le \xi_i \perp r_i + q_i \ge 0, \qquad \forall i \in N \tag{9}$$

$$0 \le \kappa_l^- \perp \sum_{i \in N} D_{l,i} r_i + K_l \ge 0, \qquad \forall l \in L \tag{10}$$

$$0 \le \kappa_l^+ \perp K_l - \sum_{i \in N} D_{l,i} r_i \ge 0, \qquad \forall l \in L \tag{11}$$

$$0 \le \tau_s \perp T_s + \sum_{l \in L} h_{s,l} \sum_{i \in N} D_{l,i} r_i \ge 0, \qquad \forall s \in S \tag{12}$$

The above formulation is the KKT conditions for the ISO's optimization problem. φ_i in (6) is introduced to represent the sum of difference of κ_l^+ and κ_l^- over all the lines l weighted by the i-th row of the PTDF matrix minus ξ_i and $\sum_{s \in S}\sum_{l \in L}\tau_s h_{s,l} D_{l,i}$. In a sense, φ_i is the marginal congestion cost associated with bus i, which reflects the cost contributions of the various transmission elements experiencing congestion, measured between bus i and the reference bus. The last term of (6) reflects the additional cost of the branch groups experiencing congestion. The ISO uses congestion markup φ_i as a price signal corresponding to transmission congestion to control line flows. Reflected by (7), the market clearing LMP at bus i is then $p + \varphi_i$, where the demand at location i is equal to the MW power generated by plant i plus the MW import, expressed by $q_i + r_i$. (8) is the energy-balance constraint and (9)-(12) are the complementarity conditions.

2.2 Firms' problem

The profit-maximization problem faced by each generation firm is described by the formulation in subsection 2.2.1. The KKT conditions in subsection 2.2.2 imply the set of equilibrium conditions for each firm g.

2.2.1 Firms' optimization problem

$$\max_{\substack{q_i : i \in N_g, p \\ x_g, \mu}} \quad \sum_{i \in N_g} \left\{(p + \varphi_i)q_i - C_i(q_i)\right\} - \mu(x_g - x_g^0) \tag{13}$$

$$\text{s.t.} \quad \sum_{i \in N_g} q_i = \sum_{i \in N}(P_i)^{-1}(p + \varphi_i) - \sum_{i \in N \setminus N_g} q_i \quad (\beta_g) \tag{14}$$

$$\underline{q}_i \le q_i \le \bar{q}_i, \qquad (\rho_i^-, \rho_i^+) \qquad \forall i \in N_g \tag{15}$$

$$x_g = M - y(\mu) - x_{-g}(\mu) \qquad (\alpha_g) \tag{16}$$

$$x_g - \sum_{i \in N_g} F_i(q_i) \ge 0 \qquad (\eta_g) \tag{17}$$

Each firm seeks to maximize profits (13)—in response to price signals φ_i from the ISO—subject to the firm's residual demand curve in the electricity market (14), the limits of electric power generation at plants owned by the firm (15), the firm's residual supply curve regarding the permit market (16), and the minimum permits constraint (17).

In the electricity market, each firm g considers the output of all other firms and optimally sets its own output q_i, $\forall i \in N_g$, so as to maximize its profits, expressed in (13). Firm g earns $p+\varphi_i$ for each unit of power output sold at location i as competing outputs from all firms simultaneously determine the reference-bus marginal energy cost p, while treating the locational congestion markup φ_i, determined by the ISO, as exogenous. This assumption implies bounded rationality of firms and is credible when the network is not radial (Neuhoff et al. 2005), as is the case for most LMP-based market such as the California market. Firm g incurs the fuel costs $\sum_{i \in N_g} C_i(q_i)$ as its power plants generate outputs. In order to comply with the cap-and-trade regulation, firm g may engage in permit trading. The firm optimally decides on the number of permits x_g it needs to acquire to cover its unabated emissions. Because firm g is initially allocated emission permits of x_g^0, $x_g > x_g^0$ implies that the firm purchases more permits (than initially allocated) from the permit market and incur the opportunity cost of permit price μ for each unit of emission. On the other hand, if $x_g < x_g^0$, firm g sells permits to the market and receives μ for each permit sold.

All firms exhibit a Cournot-like behavior by optimizing their profit with respect to their output level against their residual demand curve in the electricity market, expressed in (14), treating sales from other firms as fixed. Outputs from power plants are constrained by minimum operating limit ($\underline{q}_i$) and maximum operating limit ($\bar{q}_i$) in (15) so as to abstract from representing the startup, shut-down, ramping, and other non-convex costs that are typically considered in unit-commitment models.[9] The corresponding Lagrange multipliers ρ_l^- and ρ_l^+ reflect the shadow prices corresponding to the lower and upper limits in (15).

Our approach to modeling an imperfect permit market follows the notion of conjectural variations where strategic firms conjecture aggregate permits demanded by other firms. The approach is needed because the aggregate permit quantity is fixed (i.e., inelastic) and the supply elasticity for permits faced by any firm is endogenously determined by the price response of other firms participating in the permit market. The conjectural variation approach is incorporated into the model by (16). In response to changes in permit price μ, firm g conjectures changes in the aggregate number of permits demanded by all firms other than g that compete in the electricity market, denoted as x_{-g}, and the number of permits demanded by other sectors of economy, denoted as y. That is, x_{-g} and y are written as a function of μ in (16). Firm g optimally decides its own x_g—*concurrently* with making the output decisions—as if it is facing a residual supply curve (the right-hand side of (16)), which is equal to the total emission cap M less the sum of $y(\mu)$ and $x_{-g}(\mu)$. In addition, (17) requires that each firm is obligated to cover its unabated emissions $\sum_{i \in N_g} F_i(q_i)$ by holding corresponding number of permits. It is important to note here that the Lagrange multiplier of (17), η_g, reflects the marginal abatement cost of firm g for the emissions abated through changes in the firm's MW outputs. By means of the conjectural variation approach through (16), firms are no longer price-takers in the permit market as they anticipate changes in permits demanded as a result of changes in the permit price.

Modeling the firms' problem this way allows us to explore strategic interaction of firms as generation facilities of each firm are best responding to others throughout both electricity and permit markets simultaneously.

[9] This implies that our approach of modeling fixed minimum production limits without possibilities of decommitment may overestimate the emissions from these generation units for which such limits are imposed.

2.2.2 KKT conditions

$$p + \varphi_i - \beta_g + \rho_i^- - \rho_i^+ - \frac{dC_i(q_i)}{dq_i} - \eta_g \frac{dF_i(q_i)}{dq_i} = 0 \qquad \forall i \in N_g \tag{18}$$

$$\beta_g \sum_{i \in N} \frac{d}{dp}(P_i)^{-1}(p + \varphi_i) + \sum_{i \in N_g} q_i = 0 \tag{19}$$

$$-\mu - \alpha_g + \eta_g = 0 \tag{20}$$

$$-\alpha_g \left(\frac{dx_{-g}}{d\mu} + \frac{dy}{d\mu} \right) - (x_g - x_g^0) = 0 \tag{21}$$

$$\sum_{i \in N} q_i = \sum_{i \in N} (P_i)^{-1}(p + \varphi_i) \tag{22}$$

$$x_g + x_{-g} + y = M \tag{23}$$

$$0 \leq \eta_g \perp x_g - \sum_{i \in N_g} F_i(q_i) \geq 0 \tag{24}$$

$$0 \leq \rho_i^- \perp q_i - \underline{q}_i \geq 0, \qquad \forall i \in N_g \tag{25}$$

$$0 \leq \rho_i^+ \perp \bar{q}_i - q_i \geq 0, \qquad \forall i \in N_g \tag{26}$$

The preceding formulation is the KKT conditions for firm g's optimization problem. Equations (18)–(21) are the first-order conditions, (22) and (23) are equality constraints, and (24)–(26) are the complementarity constraints. Note that the residual demand curve in (14) can also be viewed as the market clearing condition for the electricity market (22) in which the reference price p is implied by the joint production decisions of all power plants in the same way as the price in a conventional Cournot model. Similarly, the residual supply curve in (16) implies the market clearing condition for the permit market (23)—or equivalently, by construction,

$$y + \sum_{g \in G} x_g = M, \tag{27}$$

where the total demand of permits equals the total supply of permits. At equilibrium, given the demand function y, the permit price μ is therefore determined by concurring decisions on x_g, $\forall g \in G$.

Plugging (20) into (21) and rearrange the terms, we obtain

$$-\left(\frac{dy}{d\mu} + \frac{dx_{-g}}{d\mu}\right)(\eta_g - \mu) = x_g - x_g^0. \tag{28}$$

This condition presents the relationship between marginal abatement cost η_g and permit quantity x_g, associating permit price μ with the firm's permit endowment x_g^0. In particular, firm g has an incentive to use the initially allocated permits to exert a favorable influence upon the permit price through its strategic decision on x_g. For instance, when more permits are demanded by other market participants as μ decreases, distributing *more* permits ex ante to firm g than it needs at equilibrium ($x_g - x_g^0 < 0$) will yield $\eta_g - \mu < 0$. In such a case, any further increase in x_g^0 would likely drive further the wedge between its marginal abatement cost η_g and permit price μ. The extent to which a strategic firm can manipulate the permit price, however, is influenced by several intricately intertwined forces. First, the extent of market power by firms in the electricity market is lessened by the extent of which other economy sectors participate in the permit market. Second, the strategic behavior is influenced directly by the firm's market power in the permit market. The model captures this aspect by means of conjectural variations. The third is the firm's ability to abate emissions at lower costs, i.e., whether or not the firm has lower marginal abatement cost curve compared to other firms, which is reflected by η_g in the model. Importantly, as the firm abates emissions through changes in outputs among its power plants, the abatement costs are further complicated by transmission congestion. Lastly, the firm's joint competitiveness in the electricity market, reflected by β_g, can largely affect outcomes in the permit market, as β_g is related to η_g in (18).

2.3 Equilibrium conditions

All KKT conditions for the ISO's and the firms' problems ($\forall g \in G$) represent the market equilibrium conditions that, in general, constitute a mixed nonlinear complementarity problem. When the presence of market power in the permit market is ignored, the complementarity problem (LCP) can be written in the form of a linear complementarity problem if the marginal cost functions and the inverse demand functions are linear (see Yao et al. 2008; Limpaitoon et al. 2011). By extending the model to account for the market power—of which the market clearing condition for the permit market is (27)—our market equilibrium conditions remain LCP given that the emission functions and the demand curves for permits are linear.

At equilibrium, the reference price p is determined simultaneously by all firms' decision on outputs. Equations (7) and (8) in the ISO's KKT conditions imply the market clearing conditions (14) and thereby (22). Nevertheless, including (14) in the firms' problem implies oligopoly behavior where the producers account for the effect of their joint decision on the reference price, as reflected by (19).

Similarly, condition (16) (thereby (23)) is simply the market clearing condition for the permit market (27). Including (16) in the firms' problem, however, allows firms to conjecture the effect of their permit demand on permit price. At equilibrium, permit price μ is therefore determined by concurring decisions on x_g, $\forall g \in G$, while taking y as exogenous. As incorporating other sectors into the permit market requires information concerning the residual permit demand curve y, we focus our attention on an isolated C&T market that targets the electricity market alone in the case study. That is, $y \equiv 0$ hereafter. In the case of perfect competition used in the simulation, the equilibrium conditions for both markets are modified as follows.

A perfectly competitive electricity market All firms behave as price takers with respect to both the reference price and the locational congestion markups; thus, (14) and thereby (22) are removed, while (19) is replaced with $\beta_g = 0$, $\forall g \in G$. This modification yields the same result as a cost-minimizing dispatch model with fixed demand when emission is not regulated.

A perfectly competitive permit market Firms are prevented from conjecturing about other firms' demand for permits and behave as price takers in the permit market. Therefore, (16) and thereby (23) are removed, while (21) is replaced with $\alpha_g = 0$, $\forall g \in G$. In effect, the firm-specific marginal abatement cost η_g equates across all firms and is equal to permit price μ, as implied by (20) when $\alpha_g = 0$.

Figure 1. A schematic diagram of the WECC 225-bus model

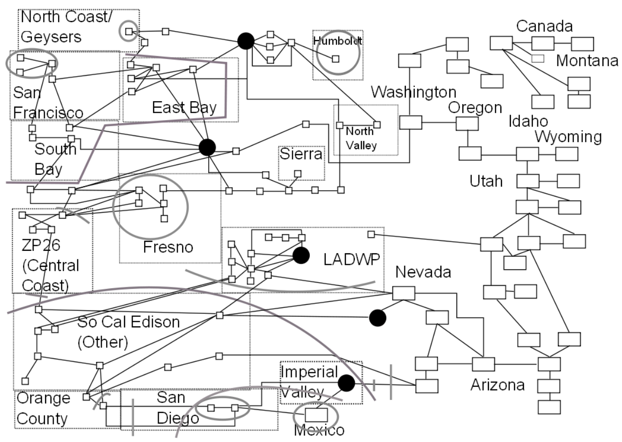


Table 1. Resource mix of the WECC 225-bus system

Fuel Type	Avg. MC ($/MWh)	Avg. CO_2 (lbs/MWh)	# of units	Total MW
Gas	70	1,281	23	26,979
Biomass	25	0	3	558
Nuclear	9	0	2	4,499
Hydro	7	0	6	10,842
Wind	0	0	3	2,256
Renewable	0	0	1	946
Geothermal	0	0	2	1,193

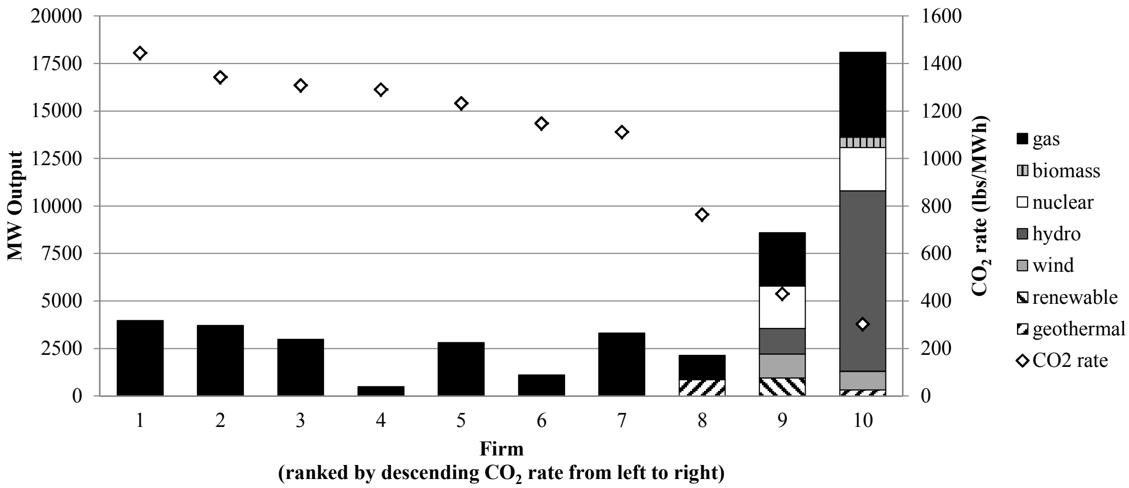
3 CASE STUDY

In this section, we perform an equilibrium simulation for a reduced 225-bus WECC network model with actual heat rate and load data, based on the equilibrium model introduced in Section 2. We aim to investigate the impact of market power on economic outcome and system operation. In the following subsections, we will first describe some important characteristics of the 225-bus system. Then, we discuss the assumption of market scenarios, elaborate on the estimation procedure of conjectural variation parameters, and subsequently proceed to the economic analysis.

3.1 Characteristics of the WECC 225-bus system

The WECC 225-bus system model represents the California ISO (CAISO) area and is composed of 293 transmission lines and 225 buses. Figure 1 depicts the network topology of the system. Bubble constraints are represented by the curved lines and circles, cutting across transmission lines. These bubble constraints help ensure reliable operation under system contingencies that may be caused by failures of generation or transmission. There are 23 aggregated thermal generators, 2 nuclear facilities, and a total of 15 aggregated hydroelectric and other renewable energy generators. Because gas is the predominant fuel, the aggregated thermal generators grouped as “gas” accounts for the largest share of total capacity of the WECC system. The gas technology has the highest average marginal cost, which is 70 $/MWh. All technologies, except for gas, have zero carbon emission. Table 1 summarizes the resource mix of this system.

Figure 2. Generation mix and average carbon emissions rate by firm



The net imports into the CAISO area are aggregated to several import points (dark circle nodes in Figure 1), i.e. Adelanto, El Dorado, Malin, Palo Verde, and Sylmar LA. To account for emissions, the state average CO_2 emission rates are used for imports (1,219 lbs/MWh for Arizona; 1,573 for Nevada; 456 for Oregon).[10] The net exports to the Sacramento Municipal Utility District (SMUD)—a separate control area surrounded by the CAISO control area—are assumed to be electrical loads (electricity consumers).

The owners and fuel types include aggregations of some owners and fuel types within each zone. The biggest non-investor-owned utility (non-IOU) owners are retained, while the others are grouped into the IOUs' portfolio since many of them would actually be under contracts with the IOUs. In total, there are 10 aggregated owners (firms) and a competitive fringe that represents imports into the CAISO. As shown in Figure 2, there is a great disparity of resource mix between the firms. Clearly, not only firms 9 and 10 dominate the market with their greater shares of generation capacity, but both firms also possess technologies that are much less polluting on average, depicted by their lower capacity-weighted average emission rate (CO_2 rate).

3.2 Scenario assumptions

Three market scenarios are considered. The first scenario, denoted by OG, is oligopoly equilibria in the electricity market with perfectly competitive permit market. The second scenario, denoted by OG-MP, is oligopoly equilibria in the electricity market with market power in the permit market. The third scenario, denoted by PC-MP, is perfectly competitive equilibria in the electricity market with market power in the permit market. Although PC-MP scenario is less likely in the real world, this scenario will be used for the purpose of comparison. All these scenarios are the same as the ones used in Montero (2009), whose work analyzes theoretically the impact of market power in permit market under a Stackelberg setting. The OG scenario, while being "socially efficient" in the permit market, is not so in the electricity marketand, therefore, serves as a benchmark for the comparison with OG-MP scenarios.

Our simulated hour is the median of the total hourly system load to represent the typical

[10]Source: eGRID2006 V2.1, April 2007

Table 2. Base allocation scheme: proportions for initial permit allocation

Firm	1	2	3	4	5	6	7	8	9	10	import fringe
Emission (tons)	874	951	1157	48	995	245	862	821	0	0	3814
Percent share	9%	10%	12%	0%	10%	3%	9%	8%	0%	0%	39%

system condition. In the real setting, the permit price is determined by the supply and demand conditions over an extended time period, typically a one-year compliance period. Nevertheless, by focusing on the median-hour analysis, it allows us to explore the market outcomes when producers respond to the C&T more aggressively.[11] The emissions target is set at 15% (the cap of 8,301 tons) and 30% (the cap of 6,836 tons) reduction from the oligopoly equilibrium of electricity market without any emissions trading. The 15% and 30% targets, hereafter, are referred to as a loose cap and a tight cap, respectively. For scenarios where the electricity market structure is oligopoly, an emission target at a level greater than the tight cap would simply result in a number of firms being outcompeted because the carbon costs are too high. With these emission targets, we can compare economic outcomes meaningfully across all market scenarios.

Unless noted otherwise, permits are freely allocated to firms in proportion to their emissions resulted from a scenario in which these firms were to compete in an oligopolistic electricity market in the absence of C&T. Such initial allocations henceforth are referred to as the "baseline" scheme. Table 2 reports emission results used as the basis for the baseline allocation scheme. A notable observation is that firms 4, 9, and 10 emit no carbon pollution under such a circumstance for different reasons. Firms 9 and 10 do so as they withhold their thermal generators at equilibrium to place an upward pressure on LMPs. On the other hand, firm 4 is an exception as it is outcompeted at equilibrium. As a result, firms 4, 9 and 10 are not allocated any free permit ex ante, whereas firms 2, 3 and 5 each receive at least 10 percent of the total permits.

The inverse demand function at each location is assumed to be linear with a price elasticity of -0.1, sloping through its corresponding competitive equilibrium solution of an electricity market without any permit trading. Although short-run elasticities are nearly zero, this level of elasticity is consistent with empirical studies (Azevedo et al. 2011). For computational purposes, we assume the existence of price-responsive demand at all locations, and hence the demand curve at a location with no load is set as almost vertical with the intercept on the x-axis being a very small positive number.

The import supplies are assumed to represent a competitive fringe with a price-responsive supply curve, which can be constructed using the same approach that generates the demand curves. The price-responsive supply functions for imports into California are assumed to be linear with supply elasticity of 0.005 (Tsao et al. 2010). The import supplies are also assumed to be a competitive fringe with regard to the permit market.

[11] Had the model been extended to an annual simulation, the permit price would be more elastic as producers are capable of coordinating their production decisions over extended periods. In fact, the model can be modified to account for annual simulations. For example, Chen and Hobbs (2005) presented a similar framework that allows the price of NO_x emission permits to be determined endogenously. However, coupling multiple periods would likely complicate our analyses with limited additional insights unless permit banking and borrowing are also taken into account.

3.3 Estimating conjectural variation and its consistency

Because oligopoly equilibria empirically describe electricity markets (Bushnell et al. 2008), OG scenario is used as the benchmark for comparing market outcomes that may deviate from a perfectly competitive permit market if market power exists in the permit market. Such market power, as noted earlier, is captured by conjectural variations. As our study is confined to the permit market in which only electricity sector is included, $y \equiv 0$. The procedure in which conjectural variations are estimated is illustrated in Figure 3. The conjectural variation of firm g is derived from a linearized relationship, in a small neighborhood ϵ of an emission cap M, between the equilibrium permit price and the number of permits held at equilibrium by all other firms. At cap level M, for instance, we initially simulate the OG scenario with the cap set at $M - \epsilon$ and obtain x_{-g} and μ at equilibrium. This is point A in Figure 3. We then change the cap level to $M + \epsilon$ and obtain the corresponding equilibrium point B. The inverted slope of the line passing through both A and B, equal to $\triangle x_{-g}/\triangle\mu$, is served as an initial estimate of $dx_{-g}/d\mu$ in (28).[12] In order to obtain "consistent" conjectural variations that are equivalent to what is defined by Perry (1982), we re-evaluate $\triangle x_{-g}/\triangle\mu$ through repeated simulations of the OGMP scenario, using the same procedure at the cap M, until the sequence $[\triangle x_{-g}/\triangle\mu]_n$ converges.[13] Finally, the converged parameter estimates are used to produce further results in all market scenarios. In particular, the sensitivity analyses that follow apply the same converged estimates obtained from the baseline allocation scheme across all different endowments.

3.4 Economic analysis

This subsection is divided into two parts: a sensitivity analysis of permit endowments and a comparative analysis of market scenarios. The sensitivity analysis allows us to examine strategies

[12] Our approach can be related to the definition commonly used in the standard literature on industrial organization theory (Tirole 1988) as follows. Let us define the conjectural variation parameters commonly used as

$$\delta_g \equiv \frac{dx_{-g}}{dx_g},$$

reflecting firm g's conjectured change in the number of permits demanded by other firms in response to its demand for permits. Since it is convenient for our model to work with $dx_{-g}/d\mu$ in (28), the following derivation will relate the derivative term with δ_g. We approximate a linear relationship between permit price and quantity locally at the emission cap of interest. Formally, let the price function of permit quantities in small neighborhood ϵ of cap level M be approximated linearly by $\mu \equiv P^M(Q) = a^M - b^M Q$, where $Q \in (M - \epsilon, M + \epsilon)$ and $Q = x_g + x_{-g}$. a^M and b^M are positive constants. Rewrite $\mu = a^M - b^M(x_g + x_{-g})$ and take the derivative with respect to μ on both sides to obtain

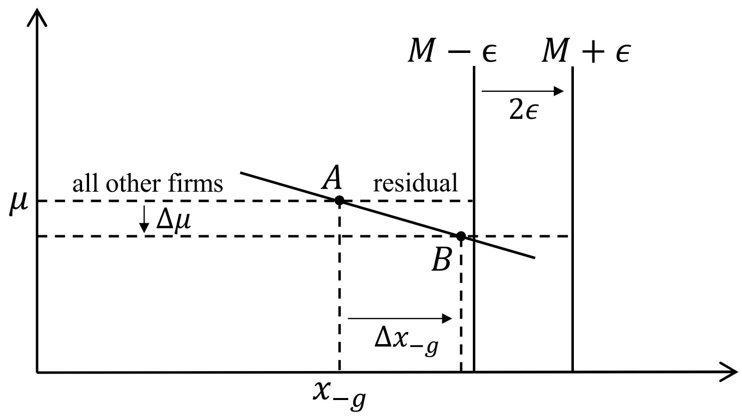
$$1 \quad = \quad -b^M\left(\frac{dx_g}{dx_{-g}} \cdot \frac{dx_{-g}}{d\mu} + \frac{dx_{-g}}{d\mu}\right)$$

Under the assumption that firm g is not a price taker ($\delta_g > -1$), we can rearrange the preceding equation and obtain the relation between $dx_{-g}/d\mu$ and δ_g as follows:

$$\frac{dx_{-g}}{d\mu} = -\left(\frac{\delta_g}{\delta_g + 1}\right) \cdot \frac{1}{b^M}$$

[13] Perry (1982) defined "a conjectural variation is consistent if it is equivalent to the optimal response of the other firms at equilibrium defined by that conjecture." If sequence $[\triangle x_{-g}/\triangle\mu]_n$ converges for all $g \in G$, each firm is best responding to the other firms at equilibrium. Therefore, all conjectural variations are consistent when the sequence converges. To deconstruct δ_g from the relation derived above, we use the convergence limit of $[\triangle x_{-g}/\triangle\mu]_n$, and b^M is equal to $|\triangle\mu/2\epsilon|$ as sequence $\left|\triangle P^M(Q)/\triangle Q\right|_n$ converges. The sequences may not necessarily converge, however.

Figure 3. Estimation procedure of conjectural variations



in which firms of different technologies exercise market power, while the comparative analysis provides insights into the extent of market power as well as the impact on social welfare under different assumptions on market competition in the joint markets.

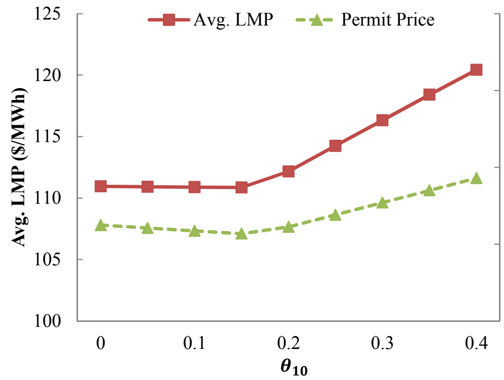
3.4.1 A sensitivity analysis of permit endowments

Figures 4 and 5 show the sensitivity analysis under the tight- and the loose-cap cases, respectively. Panels (a) and (b) plot the average sale-weighted LMP and permit price under varying initial allocations. Panels (c) and (d) plot the number of permits held by firms at equilibrium (x_g) and marginal abatement costs (n_g) under varying initial allocations. The parameter θ_g is defined as a fraction of the total number of permits that is first allocated to firm g, while allocating the remaining permits (1-θ_g) to the rest of the market, based on the proportions shown in Table 2. For example, $\theta_3 = 0.2$ means that 20 percent of the total number of permits is allocated to firm 3 and then the remaining 80 percent is allocated to the rest of the market in proportions according to the recalculated percent shares that discard firm 3 from the table.

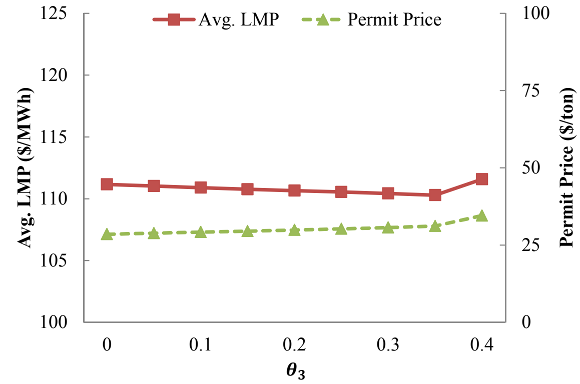
Firms 3 and 10 are chosen to perform the sensitivity analysis of permit endowments for two reasons. First, a "dirty" firm can be characterized by firm 3 as it has on average high emission intensity of available resources; a "clean" firm can be characterized by firm 10 as it has on average low emission intensity (see Figure 2). Second, among firms with relatively high emission rate, firm 3 produces relatively more outputs in OG scenario. Under the baseline allocation scheme, firm 3 therefore receives the highest number of the permits allocated, whereas firm 10 receives none. Since it is of our particular interest in this paper to investigate strategies taken by firms with different technologies, and these two firms offer such contrast in technologies, firms 3 and 10 are chosen as examples to illustrate possible strategies taken by other firms of similar characteristics.

LMP and permit price Figures 4 and 5 suggest that firms' optimal strategies for permit trading can be greatly influenced by permit endowments. We summarize three main observations as follows. First, whether a firm is more or less polluting, once it is granted substantial permit endowments above and beyond its ex post needs, it can potentially exert unilateral market power to increase prices. In such a case, a firm tends to place upward pressure on the permit price, thereby driving up the average LMP. This is implied by a sharp kink that bends the price curves upward for both

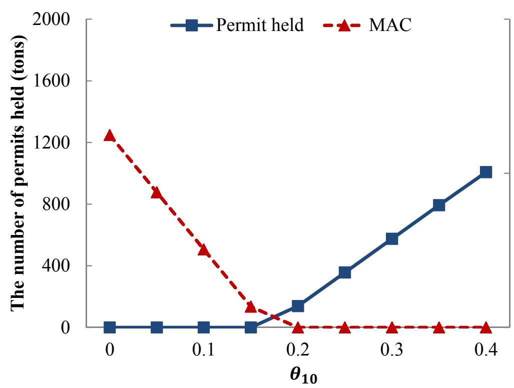
Figure 4. Sensitivity results for loose cap



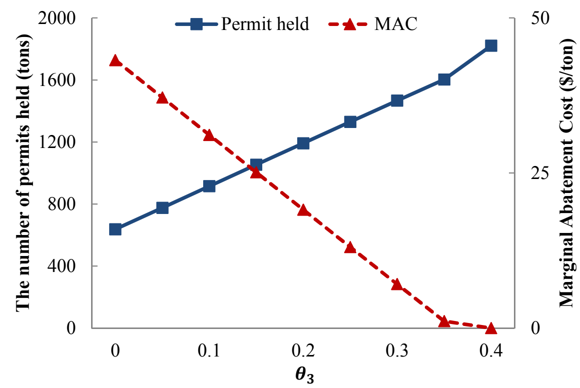
(a) Electricity price and permit price under varying share of firm 10's permit endowment



(b) Electricity price and permit price under varying share of firm 3's permit endowment



(c) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 10's permit endowment

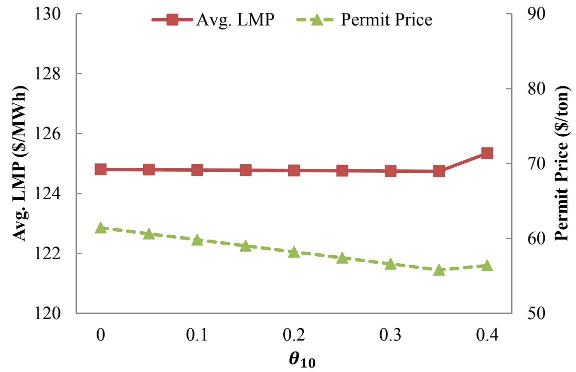


(d) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 3's permit endowment

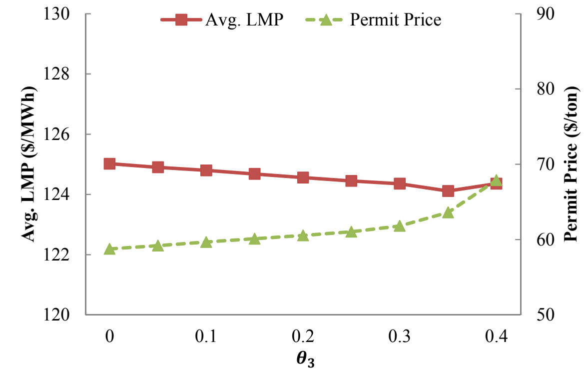
LMP and permits, plotted in (a) and (b) of Figures 4 and 5. This kink is indeed found to occur at a threshold in which a firm's marginal abatement cost reaches zero.[14] At this point, any marginal increase in emissions by such firm, as a result of changes in outputs, is fully subsidized ex ante, thereby leaving to the firm an excess number of permits. One can refer to the complementarity condition (24) in the firms' problem. As they are given more endowment, both firms 3 and 10 increasingly withhold the "unused" permits—except for firm 3 under the tight-cap case—because its private marginal abatement cost remains zero after the threshold, a point at which any further withholding of permits would increase the permit price and the LMP. But the extent to which they withhold the number of unused permits is clearly much greater in the case of firm 10, as depicted by steeper bends when comparing (c) and (d) of Figures 4 and 5. For firm 3, any increase in permit allocations would rather be used in order to expand its share of output in the electricity market. Nonetheless, when further allocations to the firm render zero marginal abatement cost, it

[14]We assume all firms are not able to modify their technologies in the short term; therefore, firms can only abate their emissions through a change in outputs and/or the use of permits. What the zero marginal abatement cost means, within the caveat of this assumption, is that firms do not incur any incremental cost for their marginal change in emissions at equilibrium when they ex ante receive substantial allocations for free.

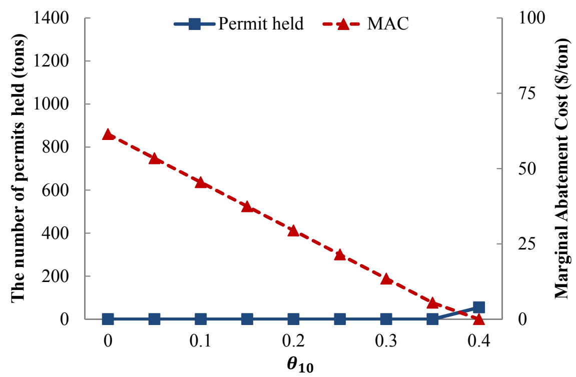
Figure 5. Sensitivity results for tight cap



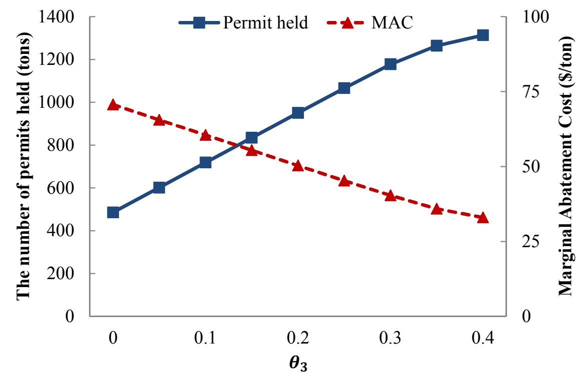
(a) Electricity price and permit price under varying share of firm 10's permit endowment



(b) Electricity price and permit price under varying share of firm 3's permit endowment



(c) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 10's permit endowment



(d) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 3's permit endowment

will employ the same strategic withholding as firm 10 does.

Although this result does not depend on the cap level, such a threshold is relatively higher (in absolute value) for the tight-cap case. For instance, the threshold for firm 10 under the loose cap is approximately 1,660 (=0.2 × 8,301) tons of permit allowances, which is much lower than the threshold of 2,734 (=0.4 × 6,836) tons under the tight cap. This is simply because marginal abatement costs are significantly higher in the tight-cap case, implying that permit prices are at least 20% higher. At such prices, firm 10 would be better off selling its permits, rather than withholding them. Similarly, firm 3 would likely use all the permits for its unabated outputs, instead of holding some of them unused, unless they are allocated an enormous number of permits.

Therefore, a substantial subsidy for emission costs, in terms of permit allocation that far exceeds such a threshold described previously, would potentially lead to a situation in which firms substantially withhold unused permits. The degree of such withholding at equilibrium is negatively correlated to the permits supply in the market; firms tend to withhold fewer unused permits because they can significantly profit from selling permits at high prices when the permits are scarce. In general, where permit banking is allowed, this situation could be thought of as a dominant firm purchasing a lot of permits at low prices within one compliance period in attempt to place an upward pressure on prices in both permit and electricity markets in the subsequent period.

Second, the strategic withholding of unused permits pursued by firm 10 can exert a higher upward pressure on LMPs than the strategy of firm 3 does. That is, the effect of market power in terms of LMP tends to be greater in the case of firm 10. In the loose-cap case (referring to (a)-(b) in Figure 4), the slope of the LMP curve (after the kink) of firm 10 (0.005 \$/MWh-ton in 4(a)) is steeper than that of firm 3 (0.003 \$/MWh-ton in 4(b)). By employing the strategic withholding, firm 10 can effectively create shortage in permits supply, thereby raising its rivals' abatement costs. Such scenario can potentially force some polluting units to be outcompeted in the electricity market and raise the LMPs, while leaving firm 10's non-polluting inframarginal outputs largely unaffected. While firm 3 can also induce a short supply of permits, if granted substantial permits initially, it does so at a lesser extent because of its need for permits.

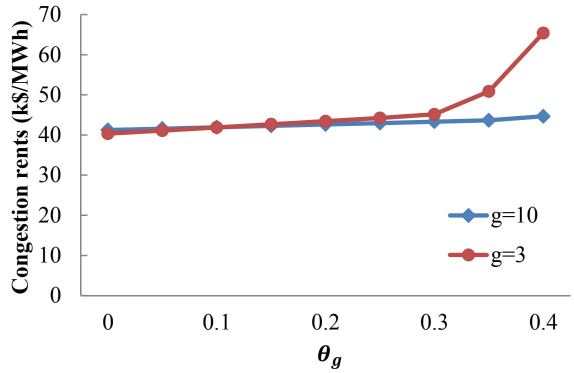
Third, although LMPs and permit prices are often thought to be positively correlated in light of cost-raising strategies, as illustrated in the first two observations, we found that 1) the increase in permit prices does not necessarily give rise to the increase in LMPs; and 2) the LMP may remain unchanged even when there is a decline in permit price. The first result involves the situation where a relatively polluting firm receives disproportionately higher endowment for its emissions. Figure 4(b) shows a slight decline in LMP with increasing permit price as a result of more permits, of up to 35 percent of total permits, being allocated to firm 3. When firm 3 is increasingly being subsidized for its emissions, it can increase its output, thereby lowering LMP as shown in Figure 4(d). Despite being more polluting, the firm's generation units with lower marginal cost can become more competitive in the electricity market, resulting in the lower LMPs. The same result holds in the case of tight cap shown in Figure 5(b).

The latter result occurs in our analysis when a greater permit endowment is given to a less-polluting firm 10. In particular, as the share of initial allocation increases from zero to the thresholds (in Figures 4(a) and 5(a)), firm 10 is a net seller as it sells of all permit endowment, which can be seen from Figures 4(c) and 5(c) where the firm's equilibrium number of permits is zero. When firm 10's permit endowment is less than those at thresholds, the firm would become better off if it sells all of its permits. Not only can the firm sustain the level of LMP that allows itself to maintain the profit from inframarginal units, but the firm can also retrieve similar profit from selling all permits, even at slightly lower permit prices.

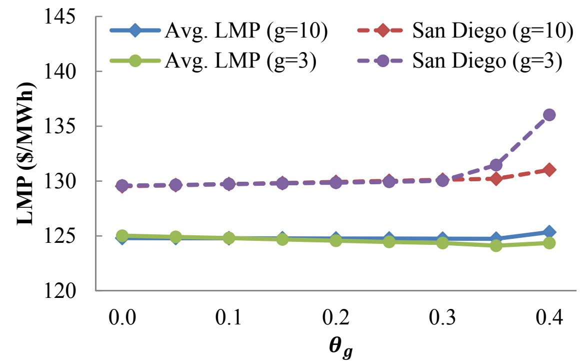
Network congestion Figure 6 shows the impact of initial allocations on the system network under the tight-cap scenarios. We omit the results of loose-cap scenarios because the same general conclusion can be drawn. Figure 6(a) shows congestion rents (i.e., ISO revenues) which indicate the overall congestion level under varying initial allocations of both firms 3 and 10, whereas Figure 6(b) shows average LMPs and zonal prices. We conclude that market power in the permit market can influence system operation as follows.

We observe that more permits allocated to a specific firm can induce a higher level of transmission congestion, especially in the case of firm 3. The increase in congestion, shown in Figure 6(a), mainly arises from the increased power import into the San Diego area. Such increase in congestion is relatively higher in the case of firm 3. The Miguel transmission corridor connecting Miguel, which is located in the San Diego area, to Imperial Valley (referred to Figure 1) experiences higher level of congestion because gas-fired generation units in San Diego area, owned by firms 5 and 7, become less competitive and lower their outputs when permit price rises. This situation increases energy imports from Imperial Valley which further draws more energy imports from Palo Verde, causing congestion on the Arizona-to-Imperial Valley corridor. As a result, the zonal LMP

Figure 6. Congestion rents and zonal prices



(a) Congestion rents under varying share of firm g's permit endowment



(b) Avg. LMPs and zonal prices (San Diego) under varying share of firm g's permit endowment

of the San Diego area rises in both cases—as shown in Figure 6(b)—but higher in the case of firm 3. Since this phenomenon results from an aggregate effect of interactions in the network, it is difficult to trace its root cause or deduce any specific conclusion as to whether market power induces higher congestion level or not. Rather, this highlights the interaction of market power in the permits market and system operations that can alter the level and pattern of transmission congestion.

3.4.2 Comparative analysis of market scenarios

Table 3 reports the total CO_2 emission, total energy consumption, average sale-weighted LMP, permit price, average output-weighted emission rate, social welfare, consumer surplus, producer surplus, and congestion rents for all market scenarios. In the table, we present the results of $\theta_g = 0.4$ in order to make distinct comparison with the baseline allocation scheme.

The impact on oligopoly equilibria Table 3 shows that there is no difference in LMP between OG and OG-MP (baseline). In contrast, there is a noticeable increase in LMPs between OG and the other OG-MP scenarios where firm 3 is given a significant permit endowment that places an upward pressure on permit price. This is evidenced by at least 20 percent higher permit prices in the θ_3 scenarios, i.e., from 29 $/ton to 35 $/ton in the loose-cap case, and from 55 $/ton to 68 $/ton in the tight-cap case. The average emission rates tend to be lowest when firm 10 is granted a substantial number of permits. In the loose-cap case, the emission rate of OG-MP (when $\theta_{10} = 0.4$) is 0.272 tons/MWh, which is much lower than 0.304 of OG; in the tight-cap case, the emission rate of OG-MP is 0.255, which is slightly lower than 0.257 of OG. Firm 10 can increase its less-polluting outputs at the expense of other firms' polluting outputs when the permit price rises partly due to the strategic withholding of permits. As a result, the actual emission of 7,293 tons in the OG-MP is approximately 12% lower than the cap of 8,301 tons under the loose cap. The firm can do so to a lesser extent when the cap is more stringent.

Economic surpluses When permits are allocated highly disproportionately to a few firms, such firms can reap the economic benefits, as is this case for firm 3 or firm 10. The cost of permits would rise because of the strategic withholding of unused permits. In addition, the overall producer

Table 3. Economic results

	Loose Cap (15%)					Tight Cap (30%)				
	OG	OG-MP			PC-MP	OG	OG-MP			PC-MP
		baseline	θ_{10}=0.4	θ_3=0.4			baseline	θ_{10}=0.4	θ_3=0.4	
Total CO_2 emission [tons]	8301	8301	7293	8155	6075	6836	6836	6782	6836	6086
Energy consumption [MWh]	27343	27324	26819	27292	30275	26615	26584	26556	26619	30269
Avg. LMP [$/MWh]	111	111	120	112	61	124	125	125	124	61
Permit price [$/ton]	29	31	46	35	3	55	61	56	68	7
Emission rate [ton/MWh]	0.304	0.304	0.272	0.299	0.201	0.257	0.257	0.255	0.257	0.201
Social welfare [K$]	9957	9957	9985	9963	10385	9997	9996	9997	10000	10383
Consumer surplus [K$]	7467	7457	7201	7440	8896	7099	7084	7069	7096	8893
Producer surplus [K$]	2462	2471	2745	2489	1275	2857	2871	2883	2839	1277
Congestion rents [K$]	28	28	39	34	214	42	41	45	65	213

surplus may rise at the expense of consumers as the LMP is higher. Although lessened competition in the permit market can lead to the decrease in energy consumption, its effect on social welfare is ambiguous. Table 3 illustrates that the loose cap results in a slightly improved welfare in OG-MP relative to OG, due largely to skewed allocations of permits. In contrast, the social welfare is slightly lower for OG-MP (baseline) relative to OG in the tight-cap case.

Despite the decrease in energy consumption under the loose-cap case (from $27,343k to $26,819k), efficient firms (e.g., firms 9 and 10) can increase their outputs at the expense of the other less-efficient firms, leading to a slight increase in the social welfare (from $9,957k to $9,985k). This is consistent with the conclusion by Sartzetakis (1997). Nonetheless, under the tight-cap case, the welfare remains unchanged even with decreased outputs when the permit market is no longer perfectly competitive. In particular, "grandfathering" more permits to an efficient firm than to a less efficient firm may result in higher welfare when the permit market is relatively less stringent. This highlights that the cap level (or the availability of permits) may also play a role in the welfare effect in the presence of market power in joint permit and electricity markets.

The PC-MP scenario, where the electricity market is assumed to be perfectly competitive, results in a drop in the average LMP from 111 $/MWh to 61 $/MWh under the loose-cap case and from 124 $/MWh to 61 $/MWh under the tight-cap case, as shown in Table 3. Consequently, the drop in prices leads to the increase in energy consumption. If firm 10 were to compete in PC-MP, its equilibrium output would have been higher than in OG and in OG-MP. The sharp output differentials are mainly caused by the strategic withholding of outputs by firm 10. This leads to a significant drop in the permit prices because the demand for permits falls when non-polluting resources do not pursue strategic withholding in the electricity market and increase their outputs. This result implies that the permit price can be greatly influenced by the level of competition in electricity market. Furthermore, the highest social welfare and the highest consumer surplus in PC-MP imply that the degree of competition in the electricity market itself can affect economic outcomes of the market to a greater extent than the presence of market power in the permit market.

4 CONCLUSION

In this paper, we propose a model to analyze the joint interaction between electricity and permit markets. The proposed approach is proven useful as a tool for market monitoring purposes in the short run from the perspective of a system operator, whose responsibility has become indirectly intertwined with emission trading regulation. This paper examines strategic interactions among firms in a transmission-constrained network that can closely represent the California's electricity market and an imperfect market for trading carbon permits. A short-term equilibrium analysis of the joint markets in the presence of market power reveals that strategic permit trading can play a vital role in determining economic outcomes in the electricity market. Following is the summary of our main findings.

First, when less polluting electricity supplies are allocated a "substantial" number of permits, these supplies are more likely than the more polluting ones to strategically withhold of permits in order to place upward pressure on permit price and to drive up the electricity price. The extent to which firms employ such strategic withholding to influence the electricity price is likely to be diminished with a stringent emission target. To mitigate the excessive accumulation of permits, one possible modification to the C&T policy is to limit the number of permits a firm is allowed to hold. Alternatively, firms may be required to surrender some portion of permits on a regulated time basis. Second, the effect of the degree of competition in the permit market on social welfare is ambiguous and may depend on the cap level. Third, strategic permit trading can influence patterns of transmission congestion. This might create a potential gaming opportunity in congestion revenue rights (CRR) market, where a firm may participate in a strategic permit trading in order to induce a certain pattern of congestion that is favorable to their CRR positions.

Our approach, however, is subject to limitations. Our model does not take into consideration neither permit banking and borrowing nor intertemporal demands. The permit price should be determined by the supply and demand conditions over an extended time period, such as a typical compliance period of one year, or over a longer period if banking and borrowing over multiple periods are considered. One possible remedy is to extend the model to a multi-period setting in which firms take into account seasonal electricity demand in making the decision on permits banking and borrowing under the cap that declines over time. Such modeling can further investigate potential market issues associated with holding limits as well as timing and compliance. We leave these considerations to future research.

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