Economic and Emissions Implications of Load-Based, Source-Based, and First-Seller Emissions Trading Programs Under California AB32

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In response to Assembly Bill 32, the state of California considered three types of carbon emissions trading programs for the electric power sector: load-based, source-based, and first-seller. They differed in terms of their point of regulation and in whether in-state-to-out-of-state and out-of-state-to-in-state electricity sales are regulated. In this paper, we formulate a market equilibrium model for each of the three approaches, considering power markets, transmission limitations, and emissions trading, and making the simplifying assumption of pure bilateral markets. We analyze the properties of their solutions and show the equivalence of load-based, first-seller, and source-based approaches when in-state-to-out-of-state sales are regulated under the cap. A numeric example illustrates the emissions and economic implications of the models. In the simulated cases, “leakage” eliminates most of the emissions reductions that the regulations attempt to impose. Furthermore, “contract reshuffling” occurs to such an extent that all the apparent emissions reductions resulting from changes in sources of imported power are illusory.

In reality, the three systems would not be equivalent because there will also be pool-type markets, and the three systems provide different incentives for participating in those markets. However, the equivalence results under our simplifying assumptions show that load-based trading has no inherent advantage compared to other systems in terms of costs to consumers, contrary to claims elsewhere.

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1. Introduction

Due to a lack of federal leadership, a number of states in the United States have taken actions to control greenhouse gas (GHG) emissions. The efforts by the western and the eastern states are called the Western Climate Initiative (WCI) and Regional Greenhouse Gas Initiative (RGGI), respectively. Among the WCI states, the State of California is the first to adopt legislation limiting GHGs. On September 27, 2006, California passed a comprehensive bill—AB32, the Global Warming Solutions Act—that aims at reducing in-state GHG emissions from various sectors to 1990 levels by 2020, a 25% reduction compared to the business-as-usual scenario. AB32 is the first climate change legislation in the United States that would regulate most polluting sectors in an economy. Led by the California Energy Commission (CEC) and the California Air Resources Board (CARB) in consultation with other agencies, a statewide emission cap is expected to be in effect by 2012. This is expected to be accomplished with a suite of instruments such as a low-carbon fuel standard for vehicles that would reduce GHGs of transportation fuels by at least 10% by 2020 (California Energy Commission 2007a).

California has historically been among the states with the lowest GHG emissions per capita in the United States, roughly 50% below the national average. If apportioned by sectors, approximately 40% of GHG emissions is from transportation, followed by 14% apiece from in-state electricity and imported electricity. Others include industrial and manufacturing for 10%; refining and other industries for 8%; and agriculture, forestry, and waste for 6%. The remaining 9% is attributed to commercial, residential, and other sources (California Energy Commission 2006b).

While imported electricity accounts for half of electric sector emissions, such imports represent only 22% of electricity demand in California in 2006 (California Energy
Commission 2006a). Thus, imported electricity is significantly dirtier than in-state generation because a significant portion is generated by coal plants located in Arizona, New Mexico, Montana, and other neighboring states (California Energy Commission 2007b).

While AB32 does not explicitly require the implementation of emissions trading programs, the CEC and CARB have been seriously considering using that approach for the electricity sector. A central issue in the recent debate over implementation of AB32 has been over the location along the electricity sector supply chain (i.e., fuel to generation to consumption) where limits should be imposed; this is the “point-of-regulation” issue. Currently, there are essentially three basic proposals on the table: source-based, load-based, and first-seller approaches.

Source-based systems are most popular elsewhere. The conventional point of regulation in an electric sector’s cap-and-trade system is at the generator (e.g., under the SO2 Acid Rain Program under the 1990 Clean Air Act Amendments and the USEPA NOx SIP Call). In source-based systems, a fixed number of emissions allowances are either distributed or sold to generators, who can then trade among themselves. Total emissions across all the regulated entities cannot exceed the number of allowances.

However, the alternative of load-based systems has received much attention in the California debate. Such systems can be viewed as being analogous to tradable renewable energy systems that have been used in other states and Europe, in which the seller of electricity to consumers is required to have a minimum portion of renewable electricity in its portfolio, either as contracts with renewable sources or unbundled “renewable energy credits.” The basic load-based program requires load-serving entities (LSEs) to track the emissions associated with the electricity they purchase from generators and third parties, and to ensure that the sales-weighted carbon emissions rate of its purchases does not exceed a target established by the regulator. Other variants that unbundle emissions certificates and power are represented by two proposals: the CO2RC (Michel and Nielsen 2008) and the Tradable Emission Attribute Certificates (TEAC) (Gillenwater and Breidenich 2009). Objectives of these proposals include the elimination of the need to track emissions associated with energy transactions, which lessens interfaces with pool-type energy markets, and the encouragement of clean out-of-state generators to participate voluntarily in emissions trading. Elsewhere, under a set of simplifying assumptions (including zero price elasticity, no transmission constraints, and no power imports), it is shown that the CO2RC and TEAC systems are economically equivalent to source-based systems in which allowances are freely allocated to generators in proportion to their sales (Hobbs 2007, Wolak et al. 2007).

The final of the three approaches is the first-seller proposal (Market Advisory Committee to the California Air Resources Board 2007). A first-seller is defined as the entity that first contracts to sell electricity in California. Consistent with this, we define generators as the point-of-regulation for in-state sources, while LSEs are designated as the first-seller for out-of-state to in-state sales. Although the first-seller proposal was not explicitly defined by CEC in 2008, the schedule coordinators (SCs) that contract with generators in other states to import electricity into California could be designated as the first-seller instead of the LSEs (Bushnell 2007). More recently, the California Public Utility Commission (CPUC) released a draft report and expressed their support of a “first-deliverer” approach. It is a variant of the first-seller system, and the entity that possesses the ownership of the electricity at the first point of delivery in California would be the point of regulation (California Public Utilities Commission 2008).

Table 1 summarizes the jurisdictional coverage of the programs analyzed in this paper. Two versions each of the source- and load-based programs are considered, differing in their treatment of power imports or exports. Together with the first-seller system, this means that we analyze five systems. We refer to the two source-based systems as the “pure” and “modified” systems. The pure source-based system is equivalent to traditional cap-and-trade programs and applies to only generation by California power plants. On the other hand, the modified source-based approach expands coverage to include imports (i.e., out-of-state-to-in-state sales). Similarly, the pure load-based approach imposes an emissions cap on California LSEs, including the emissions of power they import; whereas the modified load-based approach, in addition, regulates in-state-to-out-of-state electricity sales. The modified rather than pure approaches are of most interest here because they both attempt to account for emissions from out-of-state power production and are therefore the main focus of our analyses. Finally, the first-seller approach is a hybrid of source- and load-based approaches, where the emissions associated with the first-seller’s sales come under the cap, with California generators being responsible for their emissions and the LSEs being responsible for emissions associated with imports.

The biggest drawback of the pure source-based approach is its inability to count emissions from imported electricity (i.e., carbon leakage). A similar issue also arose in the context of international trade under the Kyoto Protocol. Kuik and Gerlagh (2003) examined the efficiency of Kyoto Protocol under the trade liberalization. They found that reduction in the import tariffs could substantially increase the

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rate of leakage under the Kyoto framework. This “leakage” of emissions turns out to be crucial in regulating regional GHG emissions given that California is a net importer, and its generators are relatively clean compared with other western states. The first-seller and modified source-based approaches represent attempts to correct that problem. As our simulations show later in this paper, however, these approaches are not necessarily effective in preventing leakage. In contrast, while either the modified load-based or pure load-based approaches might address CO\textsubscript{2} leakage, other potential problems with load-based problems have been identified. One issue is whether implementation of a program that places responsibility for compliance upon LSEs would interfere with the operation of the day-ahead and real-time pool-based markets by providing incentives for clean generation to avoid those markets (Wolak et al. 2007). The other concern is whether such an approach would lead to so-called contract shuffling that would eventually result in little or no actual emissions reduction (Bushnell 2007). To the extent that there are large amounts of clean energy sources that could compete for contracts to sell into California, the likelihood of shuffling increases. On the other hand, an often cited advantage for load-based approach is that it might increase the incentive for LSEs to invest in demand-side management and improved energy efficiency (Bushnell 2007). Another claimed advantage is that by paying a premium only for clean power sources, consumer costs would be less than in a source-based system in which the opportunity cost of allowances for marginal power sources would raise the price of all power supply (Synapse Energy Economics 2007). As shown in the later sections, our findings directly refute such assertions, and we conclude that the load-based approach does not have such advantages over other approaches. Finally, whether any proposal that would regulate imported power (load-based, modified source-based, and first-seller) would survive a challenge based upon the Interstate Commerce Clause is an important question. (Further discussion of the three approaches in terms of potential legal challenges, ability to prevent leakage, and potential interference with electricity market operations can be found elsewhere; for example, in Bushnell 2007 and Van Horn and Remedios 2008.)

While there is no general consensus about which approach is most appropriate for California, a lack of careful analysis of economic implications makes the choice even harder. This paper focuses on analyzing the three proposed approaches that include power imports and exports (i.e., modified load-based, modified source-based, and first-seller programs) but also considers the pure load- and source-based approaches. We address the following questions assuming that emissions associated with California’s electricity consumption are required to meet the same CO\textsubscript{2} emission cap under three approaches. These questions are: First, do the approaches lead to different emissions allowances prices and electricity prices? The second question concerns income distribution—are profits and consumer costs the same among the proposals? Third, how do the proposals compare in terms of contract-shuffling and CO\textsubscript{2} leakage?

To answer these questions, we conduct a general theoretical analysis of the three approaches that regulate emissions of imports and exports and show their equivalence. (An earlier analysis that drew the same conclusion for load- and source-based programs, without considering imports, is Southern California Edison 2007.) We also conduct numerical simulations of six cases using a three-zone market, with one capped zone (representing California) and two zones that export to California. Cases 1–3 are the modified source-based, modified load-based, and first-seller approaches. Cases 4–6 correspond to pure source-based, pure load-based approaches and no cap (baseline), respectively. The pure cases show how emissions leakage and contract reshuffling can change relative to the modified cases. We report results concerning profits, consumer costs, social surplus, electricity and allowances prices, electricity sales, and CO\textsubscript{2} emissions.

The remainder of the paper is organized as follows. In §2, the mathematical formulations of the market equilibrium problems for the modified source-based, modified load-based, and first-seller approaches will be introduced. These are complementarity formulations in which each market participant solves an optimization problem (profit-maximization for generators, consumer net benefit maximization for LSEs, and maximization of transmission value for the Independent System Operator (ISO)), and market clearing conditions are imposed. In §3, the properties of the solutions of the three models will be discussed. In particular, we show equivalence of the three proposals. We discuss the results of the numerical example in §4, focusing on economic and emissions outcomes as well as the issues of CO\textsubscript{2} leakage and contract shuffling. Conclusions and policy implications are addressed in §5. An electronic companion to this paper is available as part of the online version that can be found at http://or.journal.informs.org/. The theoretical proofs are provided in the online e-companion, and the data used in the economic and emissions analysis are included in Appendix B.

2. Models

This section introduces the mathematical formulation of the three main proposals that regulate emissions of imports (modified load-based, modified source-based, and first-seller). Within each proposal, optimization problems faced by LSEs, power producers, and an ISO are presented. Market clearing conditions will also be specified. The formulations are a generalization of Hobbs (2001), accounting for allowances markets and differences in points of regulation among the proposals. Examples of previous studies that also analyze electricity markets using complementarity models include Adler et al. (2008), Bushnell (2003), and
Wei and Smeers (1999). Note that we also adopt the same hub-spoke type of modeling of a transmission network as in Hobbs (2001). This formulation is a standard one for pricing transmission transactions on this type of network. The linearity of the network means that the superposition principle applies: the expense of bringing power from \( i \) to \( j \) can be expressed as the sum of bringing power from \( i \) to any intermediate node \( k \) and then from \( k \) to \( j \). Thus, a generator generating at \( i \) and selling at \( j \) receives \( w_i \) (or pays \( w_j \)) per MW for providing power from its location \( i \) to the hub, and then pays \( w_j \) to deliver power for sale from the hub to customers at \( j \).

We first summarize the notation to be used in the models.

### Sets, Indices, and Dimensions

- \( N \): Set of zones in a network, including both power producers and LSEs; \( |N| = N \).
- \( NC \subset N \): Set of zones that are under the emissions cap.
- \( NC^c \subset N \): Set of zones that are not under the emissions cap; \( N_{NC} = N \setminus N_{c} \).
- \( F \): Set of electricity production zones that are under CO\(_2\) regulation; \( F \subset N \) and \( |F| = I \).
- \( D \): Set of demand zones that are under CO\(_2\) regulation; \( D \subset N \) and \( |D| = J \).
- \( A \): Set of (directional) transmission links in the network \( N \); \( |A| = 2J \).
- \( F \subset F \): Set of power producers; \( |F| = F \).
- \( i, j \in N \): Zones \( i \) and \( j \) are in the power generation network.
- \( f \in F \): Power producer \( f \).
- \( k \in A \): Transmission line \( k \).

### Parameters

- \( P_{ij} \): Price intercept of the inverse demand function at zone \( j \) [$/MW(h)]
- \( Q_{ij} \): Quantity intercept of the inverse demand function at zone \( j \) [$/MW(h)]
- \( K_f \): Initial free allocation of CO\(_2\) allowances to power producer \( f \) [tons]
- \( K_{SE} \): Initial free allocation of CO\(_2\) allowances to LSE \( j \) [tons]
- \( E_{fi} \): Emission rate of firm \( f \) in zone \( i \) [tons/MW(h)]
- \( E \): System-wide CO\(_2\) cap [tons]
- \( X_{fi} \): Capacity of firm \( f \) in zone \( i \) [MW]
- \( C_f(x) \): Firm \( f \)'s (convex) production cost function in zone \( i \) [$/MW(h)]
- \( PTDF_{ki} \): The \((k, i)\)-th element of the power transmission-distribution factor matrix
- \( T_k \): Transmission capacity bound on line \( k \)

### Variables

- \( z_{fij} \): LSE \( j \)'s purchase of power from firm \( f \) in zone \( i \) [MW(h)]. (Note that there is assumed to be just one LSE per zone; more general assumptions are possible, but would not change the conclusions of our analysis.)
- \( s_{fj} \): Power firm \( f \)'s sale of electricity to LSE \( j \) [MW(h)]
- \( x_{fij} \): Electricity sold to LSE \( j \), produced by firm \( f \) at zone \( i \) [MW(h)]
- \( y_i \): MWs transmitted from the hub to zone \( i \) [MW]
- \( w_i \): Fees charged for transmitting electricity from the hub to zone \( i \) [$/MW]
- \( p_j \): The price of electricity at zone \( j \) [$/MW(h)]
- \( p_{CO_2} \): CO\(_2\) price [$/ton]

#### 2.1. Modified Source-Based Emissions Trading Program

Under the modified source-based program, the compliance liability is with generators as long as a producer sells electricity to in-state consumers. In-state sources that export also must comply. This is in contrast to our pure source-based system, in which out-of-state sources are exempted from regulation when selling electricity to in-state customers. In what follows, we summarize the optimization problems faced by LSEs, producers and the ISO, followed by their optimality conditions and market clearing conditions.

Under a source-based approach within a perfectly competitive market, an LSE is simply a price taker. The LSE is assumed to act to maximize the net benefits received by its consumers; if demand was perfectly inelastic, this would be the same as minimizing consumer costs. The benefit function is the integral of the consumers’ demand curve, assumed to equal their willingness-to-pay for electricity. The demand curve is

\[
p_j = P_{ij} - \frac{P_{ij}}{Q_{ij}} \sum_f s_{fj}.
\]

In a source-based system, the LSE’s costs include only the expense of power, which is procured through bilateral contracts.

Under the modified source-based program, all producers selling in the regulated zones have to buy allowances. Because importers are also subject to the emissions cap, out-of-state imports need to buy CO\(_2\) allowances from the allowances market to cover the electricity they deliver to California. (An important policy issue under this approach would be whether the CO\(_2\) allowances for in-state sources should be auctioned.) It is likely to be argued on discrimination grounds that if allowances are allocated for free to in-state sources, then imports should also receive allowances. A system that allocates allowances for free only to in-state generation would be subject to a commerce clause-based challenge. Avoiding this by allocating allowances to imports, however, would be difficult because...
CO₂ emissions associated with imports cannot be unambiguously determined. (How to allocate allowances and how to distribute economic rents associated with those allowances are issues that are beyond the scope of this paper.) Here, we consider only a scenario in which in-state power producers have an initial fixed endowment of allowances (obtained through either auctions or other means), while imports have to purchase allowances. It turns out that the initial fixed endowments do not affect power producers’ decisions, given that the producers behave competitively in both the electricity and allowances markets.

Producer \( f \) solves the following optimization problem.

\[
\text{maximize} \quad \sum_{j \in S} p_{ij} s_{ij} - \sum_{i \in N} C_i \left( \sum_{j \in S} x_{ij} \right) - \sum_{i \in S} \left[ w_i s_{ij} - \left( \sum_{j \in S} w_j x_{ij} \right) \right] - p^{\text{CO}_2} \left( \sum_{i \in S, i \in NC} x_{fi} E_i^f + \sum_{i \in S, i \in EC} x_{fi} E_i^f - K_i^f \right),
\]

subject to

\[
\begin{align*}
\sum_{j \in S} x_{ij} & \leq X_i, \quad \forall i \in N, \quad (p_{ij}), \\
\sum_{j \in S} x_{fi} & = s_{fi}, \quad \forall j \in N, \quad (\theta_{fi}), \\
x_{ij} & \geq 0, \quad \forall i \in N.
\end{align*}
\]

The first term within the last parenthesis (i.e., \( \sum_{i \in S, i \in NC, j \in S} x_{ij} E_i^f \)) is the emissions associated with in-state sources, no matter where the electricity is sold; whereas the second term (i.e., \( \sum_{i \in S, i \in EC, j \in S} x_{ij} E_i^f \)) is the emissions of imported electricity. The transmission charge \( w_i \) is defined as the per MW price of delivering power from the hub to location \( i \). This can be positive or negative; it is positive if moving 1 MW from the hub to \( i \) worsens congestion, while it is negative if moving power in that direction instead relieves congestion (so-called counterflow). A negative flow from the hub to \( i \) (that is, a delivery in the opposite direction) instead is paid that amount by the grid, as economically and physically it has precisely the opposite effect on system costs. This would not be the situation, for instance, in the case of transshipment networks.

The two constraints are capacity and sales balance constraints. Within this paper, we make the blanket assumption that the cost function \( C_i \) is convex and differentiable for each \( f \in T \) and \( i \in N \). It follows that Problem (2) is convex in its own variables \((s, x)\) for each \( f \in T \) (that is, any local optimum to the problem is also a global optimum). (Here we assume that producers absorb all costs incurred by transmission congestion and add the costs to the market price of electricity. Alternative assumptions could be made, but would not affect our fundamental equivalence results.) In addition, because the constraints in a firm’s profit optimization problem are all linear, the linear constraint qualification holds at any feasible point. Hence, a necessary and sufficient condition for an optimal solution to satisfy is given by the following first-order conditions:

\[
\begin{align*}
0 \leq x_{ij} - \nabla_x C_i \left( \sum_{j \in S} x_{ij} \right) + p^{\text{CO}_2} E_i^f - w_i + \rho_{fi} - \theta_{fi} & \geq 0, \\
\forall i \in N, j \in N^C, \\
0 \leq x_{ij} - \nabla_x C_i \left( \sum_{j \in S} x_{ij} \right) - w_i + \rho_{fi} - \theta_{fi} & \geq 0, \\
\forall i \in N, j \in N^C, \\
0 \leq s_{ij} - w_j + \theta_{fi} & \geq 0, \quad \forall j \in N, \\
0 \leq \rho_{fi} - \sum_j x_{ij} & \geq 0, \quad \forall i \in N, \\
\theta_{fi} & \text{ free, } \quad \sum_i x_{ij} - s_{ij} = 0, \quad \forall j \in N.
\end{align*}
\]

If \( x_{ij} \) is greater than zero (therefore, \( s_{ij} > 0 \)) and subject to an emissions cap, the above conditions indicate that the power price in a \( \text{CO}_2 \)-capped region is equal to the sum of marginal cost (\( \nabla C_i (\sum_{i \in S} x_{ij}) \)), the transmission charge (\( w_i \)), the \( \text{CO}_2 \) cost (\( p^{\text{CO}_2} E_i^f \)) and a scarcity rent if the output is at its upper bound (\( \rho_{fi} \)). The term \( p^{\text{CO}_2} E_i^f \) is omitted when \( x_{ij} \) is not subject to the emissions cap. Notice that the allowance position (i.e., \( K_i^f \)), a firm’s initial possession of allowances, does not enter into the optimality conditions. Hence, as long as firms treat their grant of allowances as exogenous and their allocations are not linked to firms’ future generation, how allowances are allocated does not affect the firms’ behavior. That said, allocation of the allowances does affect the distribution of economic rents.

The system operator is assumed to maximize the value of the transmission network, without strategically manipulating power flows to earn profits. We use the same formulation as in Metzler et al. (2003):

\[
\text{maximize} \quad \sum_{i \in A} w_i y_i,
\]

subject to

\[
\begin{align*}
\sum_{i \in A} y_i & = 0, \quad (\eta) \\
\sum_{i \in A} PTDF_{ki} y_i & \leq T_k, \quad \forall k \in S, \quad (\lambda_k).
\end{align*}
\]

ISO’s first-order conditions are formulated below:

\[
\begin{align*}
y_i & \text{ free, } \quad w_i - \sum_{k \in S} PTDF_{ki} \lambda_k + \eta = 0, \quad \forall i \in N, \\
\eta & \text{ free, } \quad \sum_{i \in S} y_i \leq 0, \\
0 & \leq \lambda_k - \sum_i PTDF_{ki} y_i \geq 0, \quad \forall k \in S.
\end{align*}
\]

Two sets of market clearing conditions are associated with this problem. Respectively, they determine the charges for transmission by acting as a central auctioneer to auction
off scarce transmission capacity and CO₂ allowance prices. Note that \( \bar{E} \) could be equal to \( \sum_j K^j_f \), but in general they could differ if some of the allowances are retained by the government for other purposes, such as price control or reservation for new entrants.

\[
w_i = \sum_j s_{ji} - \sum_{f, i \in N} x_{fji}, \quad \forall i \in N, \\
0 \leq p^{CO₂} + \bar{E} - \sum_{f, j, i \in NC} x_{fji} \bar{E}_{ji} - \sum_{f, j, i \in NC} x_{fji} \bar{E}_{ji} \geq 0. \tag{6}
\]

The first line in (6) is an energy balance that defines the nodal withdrawal or injection. A set of network injections or withdrawals \( y_i \), along with the PTDF matrix associated with the network, can yield the actual flows along each transmission line in the network. Note that the first equation in (6) together with the second constraint in (2) implies that \( \sum_{i \in N} y_i = 0 \). Hence, the corresponding equation in formulation (5) is redundant. We refer to the system consisting of formulations (1), (3), (5), and (6) as the modified source-based model, or Model SB.

### 2.2. Modified Load-Based Emissions Trading Program

A pure load-based emissions trading program assigns compliance requirements to in-state LSEs. Consequently, an in-state generation source would not be subject to any emissions regulation if it exports electricity to out-of-state loads. Hence, total in-state GHG emissions may not be reduced. Such an outcome would conflict with the program’s purpose to curb GHG emissions through a cap-and-trade program. One remedy is to put in-state generating sources that export to out-state loads, along with in-state LSEs, under GHG regulation. This is what we refer to as the “modified” load-based approach, and it is the main focus of this subsection. To our knowledge, there is no proposed load-based program that attempts to regulate in-state-to-out-of-state sales. It might be a precautionary requirement, however, to prevent producers from taking advantage of programs to increase their exports or to do “round-trip” trades.

When considering the modified load-based approach, we partition LSEs into two groups: those under cap-and-trade programs (i.e., \( j \in N^C \)) and those not under cap-and-trade (i.e., \( j \in N^B \)). We follow the same assumptions as in §2.1 and model a market in which LSEs buy power through bilateral contracts with generators. However, a subtle difference remains regarding bilateral markets under the source-based approach versus the load-based approach. Strictly speaking, the load-based scheme requires LSEs to trace the exact source of each MWh of electricity procured, to accurately account for the emissions rate, while the source-based scheme has no such requirement. As a result, we were able to use a more general term \( s_{ji} \) to represent firm \( f \)’s sales to demand zone \( j \) in the source-based approach; but under the load-based approach, we need to use variables with finer granularity, \( z_{fji} \) and \( x_{fji} \), to model both the LSEs’ problems and power producers’ problems, respectively.

An LSE in load zone \( j \in N \) attempts to maximize benefits of consumption (integral of the demand curve) minus payments for power and CO₂ emission allowances. For a zone that is subject to a CO₂ emissions cap (that is, \( j \in N^C \)), an LSE’s problem is as follows:

\[
\begin{align*}
\text{maximize} & \quad p_j^0 \left( \sum_{i \in \mathcal{I}} z_{fji} \right) - \frac{p_j^0}{Q_j} \left( \sum_{i \in \mathcal{I}} z_{fji} \right)^2 \\
& \quad - \sum_{i \in \mathcal{I}} p_{fji} z_{fji} - p^{CO₂} \left( \sum_{j, j \in NC} E_{ji} - K^LSE_j \right), \tag{7}
\end{align*}
\]

subject to \( z_{fji} \geq 0, \quad \forall f \in \mathcal{F}, \ i \in N \).

Note that the LSE is not a monopsonist because it takes the prices as fixed; i.e., neither \( p_{fji} \) nor \( p^{CO₂} \) are decision variables in the LSEs problem. The term \( p^{CO₂} \left( \sum_{f, j, i \in NC} E_{ji} - K^LSE_j \right) \) would be omitted when an LSE is not subject to emissions cap. Maximization of this expression yields first-order conditions of two types, one for each type of LSE \( j \):

\[
\begin{align*}
0 \leq \sum_{i \in \mathcal{I}} z_{fji} - p_j^0 + \frac{p_j^0}{Q_j} \left( \sum_{f, i \in \mathcal{I}} \sum_{j \in NC} z_{fji} \right) + p_{fji} + p^{CO₂} E_{ji} & \geq 0, \\
& \quad \forall j \in N^C, f \in \mathcal{F}, i \in N, \\
0 \leq \sum_{i \in \mathcal{I}} z_{fji} - p_j^0 + \frac{p_j^0}{Q_j} \left( \sum_{f, i \in \mathcal{I}} \sum_{j \in NC} z_{fji} \right) + p_{fji} & \geq 0, \\
& \quad \forall j \in N^B, f \in \mathcal{F}, i \in N. \tag{8}
\end{align*}
\]

For all \( j \in N^C \) with \( z_{fji} > 0 \), based on the complementarity constraints (8) the following condition needs to be satisfied:

\[
p_j = p_j^0 - \frac{p_j^0}{Q_j} \left( \sum_{i \in \mathcal{I}} z_{fji} \right) = p_{fji} + p^{CO₂} E_{ji},
\]

where the term \( p_{fji} \) represents the marginal benefit (per MWh) of consumers residing in \( j \in N^C \) for electricity, regardless of its emissions rate. In other words, individual consumers are assumed to view electricity as a homogeneous product, regardless of the type of technology used to generate it. Therefore, their marginal benefit is always \( p_{fji} \). In contrast, an LSE is subject to an emissions cap and treats electricity as a differential product with regard to emissions rates. However, LSEs are allowed to pass on CO₂ costs to consumers in the price of electricity. The term \( p_{fji} = p_j^0 - p^{CO₂} E_{ji} \) is the expenditure by an LSE to purchase one MWh of electricity from a specific generator with an emission rate of \( E_{ji} \). Thus, if a generator has a high emissions rate, it would receive less revenue per MWh compared to cleaner sources. Finally, in a program that instead awards allowances to LSEs in proportion to their load, the terms in the last parentheses of the objective function in
Problem (7) will be replaced with $\sum_{f,j} z_{fj} (E_{fi} - R^f)$, where $R^f$ is the target or default emissions rate.

In the load-based approach, power producers do not face CO$_2$ emissions regulation, except for exports by in-state sources to out-of-state consumers. In this situation, in-state generators have to purchase CO$_2$ allowances to ship power out of the state. This ensures that all emissions within the state are covered by the program. The producer $f$’s profit maximization problem is shown below:

$$\max_{x_{fj}} \sum_{i \in N} p_{fj} x_{fj} - \sum_{i \in N} C_i \left( \sum_{j \in J} x_{fj} \right) - \sum_{i \in N} (w_i - w_i) x_{fj} - p^{CO_2} \left( \sum_{i \in N, j \in NC} x_{fj} E_{fi} \right),$$

subject to $\sum_j x_{fj} \leq X_{fj}, \quad \forall i, j \in N, \quad (p_f)\quad (9)$

The optimality conditions of Problem (9) are given below:

$$0 \leq x_{fj} \perp -p_{fj} + w_j + \nabla_i C_i \left( \sum_{j \in J} x_{fj} \right) - w_i + p_f \geq 0, \quad \forall i \in N^C \text{ or } j \in N^{NC}, \quad (10)$$

$$0 \leq x_{fj} \perp -p_{fj} + w_j + \nabla_i C_i \left( \sum_{j \in J} x_{fj} \right) - w_i + p_f + p^{CO_2} E_{fi} \geq 0, \quad \forall i \in N^C \text{ and } j \in N^{NC}, \quad (10)$$

$$0 \leq p_f \perp X_j - \sum_{i \in N} x_{fj} \geq 0, \quad \forall i \in N. \quad (10)$$

The ISO’s problem is the same as in the source-based approach (4). The new set of market clearing conditions are as follows:

$$w_j \text{ free, } \quad y_i = \sum_{f, i} x_{fj} - \sum_{j \in J} x_{fj}, \quad \forall i \in N, \quad (11)$$

$$0 \leq p^{CO_2} \perp \sum_{f, i, j \in NC} z_{fj} E_{fi} - \sum_{f, i, j \in NC} x_{fj} E_{fi} \geq 0, \quad p_{fj} \text{ free, } \quad z_{fj} = x_{fj}, \quad \forall f \in F, \quad i, j \in N. \quad (11)$$

We refer to the model consisting of Equations (8), (10), (5), and (11) as the modified load-based model, or Model LB.

### 2.3. First-Seller Emissions Trading Scheme

In the first-seller approach we consider here, the point of regulation is the first entity that brings energy into California. Our interpretation is that for the in-state generating sources, the first-seller approach is equivalent to the source-based approach. In our model setting, we do not consider power producers buying electricity from other firms, nor do we consider power marketers. Hence, only LSEs are responsible in our model for bringing out-of-state power into California if imports are needed or are more economical. Consequently, in the first-seller approach, imports are treated the same way as in the load-based approach, where the LSEs are the point of regulation. The first-seller approach can therefore be viewed as a hybrid of the source-based and load-based approaches. It could instead be assumed, for example, that a third importing party is responsible for imports (i.e., first-deliverer approach), but this would not materially affect the conclusions of our analysis.

Again we assume that LSEs explicitly sign bilateral contracts with generators to provide electricity to a specified zone $j \in N$. Also, there are in-state LSEs and out-of-state LSEs. Under the first-seller scheme, an in-state LSE (i.e., $j \in N^C$) faces a profit optimization problem as follows:

$$\max_{z_{fj}} p^0_j \left( \sum_{f, i, j \in F} z_{fj} \right) - p^0_j \left( \sum_{f, i, j \in F} z_{fj} \right)^2 - \sum_{f, i, j \in F} (p_{fj} z_{fj}) - p^{CO_2} \left( \sum_{f, i, j \in F} z_{fj} E_{fi} - F_{j} \right),$$

subject to $z_{fj} \geq 0, \quad \forall f \in F, \quad i \in N. \quad (12)$

For an out-of-state LSE there is no cost or profit associated with CO$_2$ emissions:

$$\max_{z_{fj}} p^0_j \left( \sum_{f, i, j \in F} z_{fj} \right) - p^0_j \left( \sum_{f, i, j \in F} z_{fj} \right)^2 - \sum_{f, i, j \in F} (p_{fj} z_{fj}),$$

subject to $z_{fj} \geq 0, \quad \forall f \in F, \quad i \in N. \quad (13)$

The last term within the parentheses of the objective function in Problem (12) would be modified to $\sum_{i \in NC, j \in NC} x_{fj} (E_{fi} - R^f)$ when facing a program that awards allowances in proportion to sales. $R^f$ is the default or target emissions under the first-seller program. The same modification should be applied to Problem (15).

The first-order conditions of the LSEs’ problems are as follows:

$$0 \leq z_{fj} \perp -p^0_j + \frac{p^0_j}{Q_j} \left( \sum_{f, i, j \in F} z_{fj} \right) + p_{fj} + p^{CO_2} E_{fi} \geq 0, \quad \forall f \in F, \quad i \in N^C, \quad j \in N^C; \quad (14)$$

$$0 \leq z_{fj} \perp -p^0_j + \frac{p^0_j}{Q_j} \left( \sum_{f, i, j \in F} z_{fj} \right) + p_{fj} \geq 0, \quad \forall f \in F, \quad i \in N, \quad j \in N^C. \quad (14)$$
Power producer $f$’s problem under the first-seller approach is stated below. Notice that CO$_2$-related costs or revenues apply only to in-state generating sources.

$$\max_{x_{fj}} \sum_{i,j \in \mathcal{E}} p_{fij} x_{fij} - \sum_{i \in \mathcal{N}} C_{fi} \left( \sum_{j \in \mathcal{N}} x_{fij} \right) - \sum_{i,j \in \mathcal{N}} (w_j - w_i) x_{fij} - p_{CO_2} \left( \sum_{i \in \mathcal{N}, j \in \mathcal{N}} x_{fij} E_{fi} - K^p_{fi} \right),$$

subject to

$$\sum_j x_{fij} \leq X_{fi}, \quad \forall i \in \mathcal{N}, \quad (p_f)$$

so are the total GHG emissions and consumer surpluses. Robustness of the results with respect to the assumptions is also discussed.

### 3.1. Existence and Uniqueness

The following results summarize the model properties. For a more succinct presentation, technical proofs appear in the online e-companion. These proofs proceed in the same manner as in Metzler et al. (2003).

**Theorem 1.** If $\max_{i,j \in \mathcal{E}} \{P^0_{f} - \nabla C_{f}(0)\} \geq 0$, $\forall f \in \mathcal{F}$, $i \in \mathcal{N}$, then there exists a solution to Model SB, Model LB and Model FS, respectively.

**Theorem 2.** Let a vector $b$ represent the common variables shared by the three models; that is, $b = (x, p, w, y, \eta, \lambda, P_{CO_2})$. Assume that the system-wide CO$_2$ caps among the three models are the same; namely, $E^{SB} = E^{LB} = E^{FS}$.

Then, the following statements are equivalent:

(a) There exist $s$ and $\theta$ such that $(s, \theta, b)$ solves Model SB.

(b) There exist $z$ and $p$ such that $(z, b, p)$ solves Model LB.

(c) There exist $z$ and $p$ such that $(z, b, p)$ solves Model FS.

Some of the results to be shown in the next theorem strictly require convexity of the production cost function with respect to total generation. (To be more precise, they are items (b) and (c) in Theorem 3.) Assume that the cost function for each firm $f \in \mathcal{F}$ at a zone $i \in \mathcal{N}$ is as follows:

$$C_{fi} \left( \sum_{j \in \mathcal{N}} x_{fij} \right) = c_{fi} \left( \sum_{j \in \mathcal{N}} x_{fij} \right) + \frac{1}{2} d_{fi} \left( \sum_{j \in \mathcal{N}} x_{fij} \right)^2.$$  

In addition, we assume that $d_{fi} > 0$ for each $f \in \mathcal{F}$ and $i \in \mathcal{N}$.

To show the uniqueness and equivalence of consumer surpluses in the equilibria of the three models, we assume that consumers’ willingness to pay is captured by a linear inverse demand function, as in §2. Consumers’ surplus is the integral of the inverse demand function minus the costs for purchasing electricity. LSEs are assumed to charge consumers the marginal cost of supplying electricity, including the shadow price of allowances; in equilibrium, this is the marginal willingness to pay. The resulting expression for consumers’ surplus is given below:

$$CS^m = \sum_{j \in \mathcal{N}} \left[ P^0_f \left( \sum_{f \in \mathcal{N}} s_{fj} \right) - \frac{P^0_f}{2Q_f} \left( \sum_{f \in \mathcal{N}} s_{fj} \right)^2 \right] - \sum_{f \in \mathcal{N}} \left( P^m_f s_{fj} \right), \quad m = SB;$$

$$CS^m = \sum_{j \in \mathcal{N}} \left[ P^0_f \left( \sum_{f \in \mathcal{N}, i \in \mathcal{N}} z_{fij} \right) - \frac{P^0_f}{2Q_f} \left( \sum_{f \in \mathcal{N}, i \in \mathcal{N}} z_{fij} \right)^2 \right] - \sum_{f \in \mathcal{N}, i \in \mathcal{N}} \left( P^m_f z_{fij} \right), \quad m = LB \text{ or } FS;$$

3. Properties of the Models

In this section, we present some properties of the three market models (modified source- and load-based and first-seller) introduced above. The properties show that under mild conditions, the models constructed in the previous section are well posed in the sense that an equilibrium exists in each of the models. More importantly, the properties show that although the three approaches to implement a cap-and-trade program are structurally different, electricity producers’ generation patterns and costs are the same, and
where
\[ P_j^m = P_j^0 - \frac{P_j^0}{Q_j} \left( \sum_{f \in \mathcal{F}} s_{jf} \right) \quad m = SB; \]
\[ P_j^m = P_j^0 - \frac{P_j^0}{Q_j} \left( \sum_{f \in \mathcal{F}, i = E} z_{jf} \right) \quad m = LB \text{ or } FS. \]
An alternative expression for the consumers’ surplus could be derived from the assumption that all LSE profits (e.g., resulting from free granting of allowances) are returned to consumers as a lump-sum payment. That is, LSEs are regulated entities (as the largest ones are in California), but lump sum costs or revenues from the fixed allocations of allowances are rebated to consumers in a way that does not distort consumption. Furthermore, an assumption could also be made that all allowances rents earned by producers in the SB and FS models are actually returned to consumers, for example, because allowances are auctioned with the proceeds going to consumers.

**Theorem 3.** Assume that the set of solutions to any of the three models is nonempty. Under the same condition (18) as in Theorem 2, together with the cost function (19), the following statements are true for the equilibrium solutions of the three models:

(a) The total sales to each LSE are unique and are the same across the three models.

(b) Firm \( f \)'s total production in each production zone \( i \in \mathcal{N} \) is unique and the same across the three models, for each \( f \in \mathcal{F} \).

(c) Total emissions are unique and are the same across the three models.

(d) The consumers’ marginal willingness-to-pay (price charged to consumers) is unique at each zone \( j \in \mathcal{N} \) and is the same across the three models. In addition, the consumers’ surpluses are unique and the same across the three models.

(e) Assume that
\[ \bar{E}_{SB} = \bar{E}_{LB} = \bar{E}_{FS} = \bar{E}, \]
where \( \bar{E} \) is the initial \( CO_2 \) allowance. Then the total social surplus (the sum of consumers', producer, ISO, and LSE surpluses) is unique and is the same across the three models.

The definition of consumers’ surplus in the above theorem assumes that all allowance rents accrue to either LSEs or producers and none to consumers. As noted, regulation of LSEs and auctioning of allowances with the proceeds going to consumers could instead result in all allowances rents being returned to consumers. Consumers’ surplus would then increase by the amount of the rent, but would still be identical in each of the three systems.

Thus, we have refuted the assertion that has been made in Synapse Energy Economics (2007) that load-based systems result in lower costs to consumers than source-based systems because LSEs are able to price-discriminate among producers. Despite that price discrimination, the costs to consumers (more generally, their surpluses) are the same in all three systems.

Although total social surplus and consumers’ surpluses are unique in each of the three equilibrium models, ISO’s surplus, producers’ surplus, and most interestingly, the market clearing price of \( CO_2 \), might not be unique due to possible degeneracies created jointly by capacity constraints, transmission constraints, and emissions constraints. An example is shown in Appendix A. (Note that this example is to illustrate that even under the conditions of Theorem 3, the above-mentioned three quantities are not necessarily unique. More general results regarding under what conditions these quantities are unique in an equilibrium are not readily available.)

### 3.2. Economic Intuition

The equivalence result shown by Theorem 3 might be surprising. However, the economic intuition is relatively simple. In the competitive market setting presented, competitive market outcomes can also be obtained by maximizing total social surplus, subject to three sets of constraints—capacity constraints, transmission constraints, and emissions constraints (in a similar fashion to Samuelson 1952). There might be internal wealth transfers among producers, LSEs, consumers, and the ISO, causing different surplus distributions among these participants across the three proposed cap-and-trade systems. However, such transfers cancel out and do not affect aggregate social surplus. That is, the sum of the surpluses remains the same regardless of the point of regulation of GHG emissions. The capacity and transmission constraints are certainly not affected by point of regulation, either. Because all GHG emissions associated with electricity produced within or sold to California are accounted for, although at different points, the emissions constraints of the three GHG cap-and-trade programs (modified source-based, modified load-based, and first-seller) are expected to be equivalent as well. As a result, the equivalence of market outcomes as shown in Theorem 3 follows naturally.

### 3.3. Robustness of the Results

Theorems 1 to 3 are derived under a set of assumptions. Among them, the assumption of perfect competition (namely, both power suppliers and LSEs are price-takers) might be the most debatable, as California’s electricity market could be subject to market power abuse due to its highly concentrated market and transmission constraints. The uniqueness results are still expected to hold under imperfect competition, in light of the results shown in Metzler et al. (2003). The equivalence results, however, are less clear in the presence of market power and will be studied in the future. Whether a linear inverse demand function is a reasonable assumption to capture consumers’ willingness-to-pay is an empirical question.
the other hand, we conjecture that all the results will still hold for any inverse demand function that yields a concave objective function for LSEs/consumers. The assumptions of convex and differentiable cost functions to power suppliers are essential in our derivation of the uniqueness and equivalence results. However, differentiability should not be restrictive. One would expect that if a realistic cost function is indeed nondifferentiable, the nondifferentiability should occur only at a finite number of singletons in the form of kinks. As long as the cost functions and their derivatives are nondecreasing with respect to production quantities, cost functions with kinks can be represented by piecewise convex functions, with each piece being a differentiable function. Each piece of the piecewise function (with proper lower and upper bounds on generation quantities) could be viewed as a cost function associated with a distinct power generating firm. Consequently, all results presented above follow. Convexity of cost functions imply nonincreasing marginal returns, which correspond to nondecreasing marginal cost functions. Because we do not consider investments or any fixed costs in our models, the marginal costs refer to short-run marginal costs. As discussed in Considine (1999), if we disregard the discreteness of start-up decisions, nondecreasing short-run marginal costs functions of generation units, which lead to convex cost functions, are generally observed and hence are reasonable assumptions. The assumption of strictly convex quadratic cost functions is indeed needed only for (b) and (c) of Theorem 3. This is intuitive because if costs were merely convex rather than strictly convex, then if two (or more) generators have the same marginal cost, it is possible to have multiple equilibria in which one generator is in the equilibrium and the other is out, or vice versa. However, the total sales of electricity, consumer surplus, and social surplus are unchanged, whichever of the identical-cost firms is in the equilibrium.

4. Numerical Example

In this section, we present a simple example to illustrate the equivalence of modified load-based, modified source-based, and first-seller approaches. We also compare them with three other scenarios: the pure load-based, pure source-based, and no-cap scenarios.

4.1 Assumptions

We assume that there are three zones \((i = \{CA, NW, SW\})\) connected with transmission lines with fixed capacities (Figure 1). Zone CA is the regulated zone (referred to below as in-state or California), and zones NW (Pacific Northwest) and SW (Southwest) are unregulated but trade with zone CA (and are jointly referred to as out-of-state). A number of generating firms \((f = \{1, 2, \ldots, 10\})\) are located in each zone. Consumers reside in each zone, with their willingness-to-pay represented by linear inverse demand curves. For simplicity, we model the markets for a single hour. A larger model with varying load over a number of hours could readily be solved but would not provide additional insight. The specific input assumptions used in this example are presented in Appendix B. Figure 2 plots marginal cost against cumulative capacity with the corresponding CO\(_2\) emissions rates for zones CA, NW, and SW, respectively. The marginal cost for zone CA ranges between 35 $/MWh and 55 $/MWh, with a stable emissions rate around 550 kg/MWh. Zone NW has two types of generating technologies: hydropower with zero variable production cost and zero emissions, and moderately expensive units with a marginal cost and emissions rate of approximately 25 $/MWh and 550 kgs/MWh, respectively. Zone SW has units with higher emissions but lower costs. The capacity-weighted average CO\(_2\) emissions rate is 582, 367, and 1,171 kg/MWh for zones CA, NW, and SW, respectively. (These numbers are based on typical values for coal, combined-cycled, and combustion turbine technologies, and the curves in Figure 2 reflect the mixes of generation capacity within each of those regions.) Thus, whereas zone CA is designed to resemble California’s electricity system primarily with natural gas plants, zones NW and SW represent northwest and southwest states with abundant hydropower and coal plants, respectively. In the baseline (or no-cap) case, roughly 20% and 10% of the electricity demand in zone CA is met by imports from zone NW and SW, respectively. This is an exaggeration of the actual conditions in the western market, but it allows us to investigate possible contract shuffling and carbon leakage. We assume a demand elasticity of \(-0.2\) at the price-quantity pair in the baseline solution.

We simulate six scenarios. In scenarios 1–3, zone CA is subject to an emissions cap of 400 tons under modified load-based, modified source-based, and first-seller approaches, respectively. An additional three scenarios are designed to illustrate the cases when there are pure
load- and source-based programs or no cap at all. First, in scenario 4, a 400-ton emissions cap is imposed exclusively on the in-state LSEs with no restriction on emissions associated with exported electricity (pure load-based). Second, in scenario 5, we impose a 400-ton cap on just in-state emissions sources (pure source-based). Finally, scenario 6 has no emissions cap on either in- and out-of-state sources. In the next section we report the results, including electricity and CO\textsubscript{2} allowances prices, sales, CO\textsubscript{2} emissions, CO\textsubscript{2} leakage, and contract shuffling and welfare outcomes. The results of scenarios 1–3 and 4–6 are displayed in Tables 2 and 3, respectively.

4.2. Results

This section reports the results of the six scenarios. We report price and welfare results in §4.2.1 and address the equivalence of three proposed programs in §4.2.2, followed by discussion of CO\textsubscript{2} leakage and contract shuffling in §4.2.3.

4.2.1. Electricity and Allowances Prices and Social Surplus Analysis. The extent to which electricity prices would increase under emissions trading depends on the level of allowances prices as well as the emissions rate of the marginal unit that determines the electricity price. As for the level of allowances prices, it depends on how the programs are designed. In particular, the key parameter is whether the in-state-to-out-of-state and out-of-state-to-in-state electricity sales are regulated under the emissions programs. Overall, higher allowances prices (and thus higher electricity prices) occur in the three approaches that regulate imports to zone CA (modified load-based and source-based and first-seller based), as shown in Table 2. When compared to the pure load-based and pure source-based scenarios, zone CA's electricity price increases by $5.8/MWh (=78.1 – 72.3) and $24.1/MWh (=78.1 – 54), respectively. This is primarily because in-state-to-out-of-state (e.g., CA to NW) and out-of-state-to-in-state (e.g., SW to CA) electricity sales are not regulated under the pure load- and source-based programs, respectively, while both types of transactions are regulated under the first-seller and modified load-based and modified source-based approaches.

The level of allowances prices under the pure source-based approach relative to the pure load-based program depends on the relative costs of in-state and out-of-state generating sources (i.e., the direction of flow). The allowances price under the first-seller (or modified source-based or load-based) approach is $61.0/ton when cross-state electricity sales in both directions are under regulation. Under the pure load-based approach, exports from from zone CA to zones NW and SW increase (because such exports incur no CO\textsubscript{2} cost); this would suppress the demand for CO\textsubscript{2} allowances, and thus reduce allowance prices. Yet, because zone CA is a net importer, the effect on allowances prices would be minor (i.e., dropping from $61.0/ton to $52.3/ton). In contrast, increased out-of-state imports to CA from regions not under the cap under a pure source-based approach would significantly suppress demand for CA CO\textsubscript{2} allowances. Thus, the allowances price drops even further (i.e., from $61.0/ton to $12.5/ton). In a more extreme case in which the out-of-state sources can meet a significant portion of zone CA's load while transmission constraints are not binding, the allowances price under a pure source-based system that applies just to zone CA could crash to zero.

The welfare analysis shows that the overall social surplus (the sum of consumer, producer, LSE, and ISO's surpluses) is higher in the pure load- and source-based programs than in the modified programs. This is only because emissions externality are not included in the welfare calculation, and the emissions reductions are smaller in the pure programs, which reduces production costs. The pure source-based program has only a slightly lower social surplus than
Table 2. Summary of market equilibria under modified source-based, modified load-based, and first-seller programs.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Zone</th>
<th>Modified load-based</th>
<th>Modified source-based</th>
<th>First-seller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission cap [tons]</td>
<td></td>
<td>400.0</td>
<td>400.0</td>
<td>400.0</td>
</tr>
<tr>
<td>Consumer surplus [$]</td>
<td></td>
<td>107,953</td>
<td>107,953</td>
<td>107,953</td>
</tr>
<tr>
<td>Producer surplus [$]</td>
<td></td>
<td>25,889</td>
<td>50,272</td>
<td>45,232</td>
</tr>
<tr>
<td>ISO surplus [$]</td>
<td></td>
<td>4,834</td>
<td>4,834</td>
<td>4,834</td>
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<tr>
<td>LSE surplus [$]</td>
<td></td>
<td>24,383</td>
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</tr>
<tr>
<td>Social surplus [$]</td>
<td></td>
<td>163,059</td>
<td>163,059</td>
<td>163,059</td>
</tr>
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</table>

<table>
<thead>
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<th>Zone</th>
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<th>NW</th>
<th>SW</th>
<th>CA</th>
<th>NW</th>
<th>SW</th>
<th>CA</th>
<th>NW</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price [$/MWh]</td>
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<td>78.1</td>
<td>20.8</td>
<td>78.1</td>
<td>20.8</td>
<td>78.1</td>
<td>20.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions [tons] (from (\rightarrow))</td>
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<td>317.3</td>
<td>0</td>
<td>317.3</td>
<td>0</td>
<td>317.3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NW</td>
<td></td>
<td>82.7</td>
<td>82.7</td>
<td>82.7</td>
<td>91.5</td>
<td>82.7</td>
<td>75.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td></td>
<td>0</td>
<td>620.0</td>
<td>0</td>
<td>368.9</td>
<td>0</td>
<td>206.3</td>
<td>0</td>
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<td>Zonal CO₂ emissions [ton]*</td>
<td></td>
<td>317.3</td>
<td>175</td>
<td>90.7</td>
<td>317.3</td>
<td>175</td>
<td>90.7</td>
<td>317.3</td>
<td>155</td>
<td></td>
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<tr>
<td>Associated CO₂ emission [tons]</td>
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<td>277.4</td>
<td>82.7</td>
<td>167</td>
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<td>Total CO₂ emissions [ton]</td>
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<td>1,443.1</td>
<td>0</td>
<td>1,443.1</td>
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<td>1,443.1</td>
<td>0</td>
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<tr>
<td>CO₂ price [$/ton]</td>
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<td>61.0</td>
<td>0</td>
<td>61.0</td>
<td>0</td>
<td>61.0</td>
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<tr>
<td>Generating cost [$]</td>
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<td>0</td>
<td>43,358.0</td>
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<td>24,384.0</td>
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Table 3. Summary of market equilibria under no-cap, pure source-based, and pure load-based programs.

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<th>Variable</th>
<th>Zone</th>
<th>Pure load-based</th>
<th>Pure source-based</th>
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<tr>
<td>Emission cap [tons]</td>
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<td>400</td>
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<tr>
<td>Consumer surplus [$]</td>
<td></td>
<td>113,532</td>
<td>131,854</td>
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<td>Producer surplus [$]</td>
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<td>25,635</td>
<td>28,369</td>
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<td>ISO surplus [$]</td>
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<td>3,986</td>
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<td>LSE surplus [$]</td>
<td></td>
<td>20,934</td>
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<tr>
<td>Social surplus [$]</td>
<td></td>
<td>164,088</td>
<td>166,882</td>
<td>166,430</td>
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<th>NW</th>
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<th>NW</th>
<th>SW</th>
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<th>SW</th>
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<tr>
<td>Price [$/MWh]</td>
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<td>72.3</td>
<td>20.8</td>
<td>54.0</td>
<td>43.1</td>
<td>20.7</td>
<td>48.3</td>
<td>41.4</td>
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<td>CO₂ emission [tons] (from (\rightarrow))</td>
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<td>225.0</td>
<td>31.2</td>
<td>87.8</td>
<td>209.2</td>
<td>35.7</td>
<td>155.1</td>
<td>198.8</td>
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<td>Zonal CO₂ emissions [ton]</td>
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<td>344.0</td>
<td>175.0</td>
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<td>947.2</td>
<td>425.8</td>
<td>175.0</td>
<td>950.0</td>
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<td>Associated CO₂ emission [tons]</td>
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<td>400.0</td>
<td>364.5</td>
<td>710.7</td>
<td>783.5</td>
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<td>451.2</td>
<td>878.9</td>
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<td>Import (+)/export (−) emissions [ton]</td>
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<td>−245.5</td>
<td>383.5</td>
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<td>115.0</td>
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<td>1,550.7</td>
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<td>CO₂ price [$/ton]</td>
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<td>52.3</td>
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<td>12.5</td>
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<td>51.451</td>
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<td>Generating cost [$]</td>
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<td></td>
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<td>Allowances rents [$]</td>
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<td>0</td>
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<table>
<thead>
<tr>
<th>Electricity sales (from (\rightarrow))</th>
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<th>NW</th>
<th>SW</th>
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<th>NW</th>
<th>SW</th>
<th>CA</th>
<th>NW</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td></td>
<td>400.0</td>
<td>148.0</td>
<td>362.5</td>
<td>61.9</td>
<td>268.9</td>
<td>343.4</td>
<td>82.9</td>
<td>309.9</td>
<td></td>
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<tr>
<td>NW</td>
<td></td>
<td>550.0</td>
<td>0.0</td>
<td>302.4</td>
<td>21.4</td>
<td>226.2</td>
<td>248.5</td>
<td>25.2</td>
<td>276.2</td>
<td></td>
</tr>
<tr>
<td>SW</td>
<td></td>
<td>0.0</td>
<td>535.6</td>
<td>403.4</td>
<td>206.7</td>
<td>188.7</td>
<td>511.8</td>
<td>191.9</td>
<td>97.6</td>
<td></td>
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<tr>
<td>Total sales [MWh]</td>
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<td>950.0</td>
<td>683.6</td>
<td>1,068.3</td>
<td>290.0</td>
<td>683.9</td>
<td>1,103.7</td>
<td>300.1</td>
<td>683.8</td>
<td></td>
</tr>
</tbody>
</table>

*Note: The zonal CO₂ emissions is the row sum of CO₂. For example, the zonal emissions under the modified source-based program for zone CA equals 317.3 + 0 + 0 = 317.3 tons.
the no-cap baseline. However, this is not to say that the pure programs are superior. If the policy goal is to control CO₂ emissions in the WECC region or beyond California state territory, first-seller, modified load-based, and modified source-based approaches would be appropriate because they allow agencies to reach out to and to regulate transactions in both directions. As for allocative inefficiency due to higher power prices under modified approaches, when measured by the change in social surplus, it is in the magnitude of 0.6%, 2.2%, and 2.0% compared to pure load-based, pure source-based, and no-cap cases, respectively. As discussed below, these differences are remarkably low due to contract shuffling and CO₂ leakage.

As shown in Table 2, the total welfare gained in the first-seller, modified load-based, and modified source-based approaches is the same. This total amount is distributed differently among producers, consumers, LSEs, and the ISO because different parties receive free allowances in each of the systems. If, instead, all allowance rents were returned to consumers, then each market participant would have the same net benefits in each scenario, and consumers’ surplus would increase by the amount of that rent (from $109,000 to $133,000). We discuss this particular comparison in more detail in the next section.

4.2.2. Equivalence of First-Seller, Modified Load-Based, and Modified Source-Based Approach. As indicated in §2, the first-seller, modified load-based, and modified source-based approaches share the following characteristic: all regulate in-state-to-out-of-state and out-of-state-to-in-state electricity sales, even though their point of regulation is different. Nevertheless, the three approaches differ in two aspects. First, although the total sales (see Table 2) and thus retail electricity prices are the same in the three approaches, the distribution of bilateral generator-LSE electricity sales could be different, as implied by Theorem 2 in §3. However, the pattern of generation and total production costs are unaffected.

Second, the distribution of economic rents among market parties is different even though the total social surplus is equal under three cases. This results basically because the distribution of allowance rents ($61/ton times the 400-ton cap = $24,400) differs among the three solutions in Table 2. In particular, the decision as to who should retain the LSEs’ profits (i.e., \(\sum_{i,j} (p_{fij} \cdot z_{fij}) - p^{CO}_{z} (\sum_{j} E_I_E - K^j_{LSE})\)) in Equations (7) and (12) in the modified load-based and first-seller approaches, and how producers are allocated allowances are important policy questions that affect the distribution of allowance rents. On one hand, if producers receive all allowances for free and LSEs purchase allowances from producers in compliance with the first-seller requirement, the LSE’s economic rents of $24,383 and $5,040 under the modified load-based and first-seller program, respectively, should instead be incorporated into the producers’ surplus. On the other hand, if allowances are first given to consumers, and producers and LSEs must then purchase those allowances from consumers (perhaps via a state-administered auction), the allowances rents will accrue to consumers and will partially compensate for the pass-through of CO₂ allowances costs. Hence, those three programs will be equivalent from the perspective of welfare distribution if a consistent set of assumptions is made concerning the distribution of allowances rents. (Wolak et al. appendix) analyze load- and source-based programs assuming a closed system with inelastic loads and only bilateral trading. They conclude that if allowances are owned by consumers, and producers need to purchase allowances from consumers, the two systems are economically equivalent (Wolak et al. 2007). But they also point out a number of practical and important disadvantages of load-based systems, including impacts on the efficiency of the pool-type markets.)

4.2.3. Contract Shuffling and CO₂ Leakage. The distribution of emissions among zones under different programs is a consequence of how the programs are designed and the degree of transmission congestion. We examine total emission, contract shuffling, and emissions leakage in this section. Overall emissions reflect how stringent the program is designed and its impact on the market. As the modified approaches are most stringent, the total emissions are 1,443.1 tons, which is 2.2, 5.2, and 6.9% smaller than emissions under the pure load-based, pure source-based, and no-cap scenarios. As discussed below, these differences are remarkably low due to contract shuffling and CO₂ leakage.

In electricity markets, most sales are financial transactions because actual flows in the network must follow physical laws. Contract shuffling in the current context refers to the situation in which the rearrangement of financial contracts results in no actual emissions reduction in an emissions trading program. Whether contract shuffling would occur under different cases can be analyzed by examining variables \(z_{fij}\) over subscripts \(j\) and \(h\) to get electricity sales \(s_{ij}\) from \(i\) to \(j\) (see Electricity Sales in Tables 2 and 3).

We focus on a comparison of the no-cap case in Table 3 with other approaches in Tables 2 and 3. First, we consider the issue of leakage, and we then turn to contract shuffling.

Consistent with definitions elsewhere (for example, Ruth et al. 2008), we defined leakage as the difference between the decrease in regulated emissions and the decrease in total regional emissions. That is, increases in unregulated emissions elsewhere could, to some degree, offset the decline in regulated emissions. To obtain a gross indicator of leakage, we first calculate for each of the load-, source-, and first-seller-based proposals the decrease in emissions of generators in zone CA plus imports to zone CA, compared to the no-cap case (row 2 of Table 4, called \(E_i\)). These are the emissions that are subject to regulation in the modified and first-seller proposals (Table 2), and for consistency, we also consider them for the pure source- and load-based proposals (Table 3). We then calculate the total decrease in...
emissions in zones CA + NW + SW relative to the no-cap case (row 4 of Table 4, called \( \hat{E}_2 \)). The percentage leakage is then \( 100\% (1 - \hat{E}_2/\hat{E}_1) \).

Table 4 shows that in all cases, most of the apparent emission reductions in regulated emissions are lost due to leakage—i.e., increases in nonregulated emissions. For instance, for the modified and first-seller-based proposals (Table 2), the leakage is 85%. This is because regulated emissions fall from 1,056 tons (no-cap case) to 400 tons (the cap), but total emissions fall by much less (1,551 to 1,443). Thus, leakage means that the overall emissions reduction is small, 7.0% (\( = (1,551 - 1,443)/1,551 \)), 4.9%, and 1.9% tons for modified, pure-load, and pure-source based approaches, respectively. The average CO\(_2\) regulation cost measured by the ratio of the changes in social surplus and CO\(_2\) emissions is equal to $31.2/ton (\( = (166,430 - 163,059)/(1,551 - 1,443) \)). This value is within the upper range of market prices that have been experienced under the EU ETS but is an order of magnitude higher than the prices occurring under RGGI.

This leakage is in large measure due to contract shuffling. We define contract shuffling as the difference between the apparent decrease in emissions associated with power imports to zone CA (called \( \hat{E}_1 \) in Table 4) and the actual decrease in emissions in zones NW and SW (\( \hat{E}_2 \) in Table 4). In our simulations, emissions in zones NW and SW are actually unchanged, even though the emissions associated with bilateral transactions from zones NW and SW to zone CA decrease. If we define the percentage of contract shuffling as \( 100\% (1 - \hat{E}_2/\hat{E}_1) \), then this percentage is actually equal to 100%. Thus, the apparent emissions decreases due to changes in the composition of imports to zone CA are completely illusory, as emissions elsewhere are actually increasing under regulation.

For example, the percentage of contract reshuffling for the modified and first-seller-based proposals (Table 2) is 100% (last row, Table 4). This is because although emissions associated with imports by zone CA fall from 680 tons (no-cap) to 83 tons (Table 2), emissions in zones NW and SW are actually approximately unchanged (1,125 tons = 78.7 (from B) + 601.3 (from C)). This occurs because the large amounts of dirty power that used to be exported from zone SW to zone CA in the no-cap case (512 MWh, Table 3) is diverted to zone NW under regulation. As a result, zone NW is then able export more of its clean power to zone CA (compare Tables 2 and 3). Of course, these are financial transactions, and the shifts in physical power flows are much less dramatic. (The distribution of bilateral contracts in the no-cap model is not unique, which implies that the calculations of leakage and contract shuffling in this section are also not unique. For instance, if a no-cap solution with more zone NW to CA bilateral contracts was instead used as the baseline, then the estimated amounts of leakage and shuffling would be smaller. However, these illustrative calculations demonstrate that large amounts of leakage and contract shuffling are very likely to occur under these regulatory proposals.)

### 5. Conclusion and Discussion

California has been considering three proposals to regulate greenhouse gasses emitted by electric power plants under the Assembly Bill 32: source-based, load-based, and first-seller approaches. These three proposals differ by their point-of-regulation and possibly the “jurisdiction” of the regulation. Our interpretation is that the three proposals will regulate emissions associated with in-state and cross-state electricity transactions. However, if in-state-to-out-of-state sales, or vice versa, are not subject to a cap, greater amounts of contract shuffling and CO\(_2\) leakage with fewer real emissions reductions could possibly occur, as shown in the pure load-based and pure source-based scenarios simulated in §4.

We have formulated equilibrium models for the three proposals. In addition to existence and uniqueness properties of the solutions, this paper shows that the three proposals are essentially equivalent in that they produce the same zonal sales, the same production and emission patterns, the same allowance and retail electricity prices, and
the same social surplus. This occurs under the assumption that imports to California would be subject to the emissions cap, as well as sales from California plants to other states.

However, the proposals can differ in the distribution of social surplus; when this occurs, it is because of assumptions concerning the distribution of allowance rents. If the markets are designed so that all emissions allowance rents accrue to consumers, then the consumer surplus is the same in all three proposals.

This points out the importance of the issue of allowance allocation. The value of those allowances could represent a significant amount of wealth transfer and might also affect program’s political feasibility and acceptability. For instance, it has been shown that significant windfall profits were earned by generators in the European Union Emissions Trading Scheme in 2005, given that generators received most allowances for free (Sijm et al. 2006). Additionally, for first-seller and source-based approaches to survive a legal challenge under the commerce clause of the U.S. Constitution, it is possible that allowances need to be distributed by auctions. Otherwise, in-state sources would be given a financial windfall that their counterparts in neighboring states would not obtain if allowances are grandfathered.

Another assumption made in this paper is that the CO2 intensity of imported electricity can be unambiguously determined. This could prove to be a challenging task in reality, given the complicated operations of the competitive electricity markets. At least two proposals (e.g., TEAC and CO2RC) have suggested using a default or an average emission rate. In this modeling framework, this is equivalent to assigning a uniform emissions rate to all the out-of-state sources. However, whether these two approaches would yield the same market outcomes as the three programs studied in this paper is certainly an interesting issue and deserves separate attention.

As California has traditionally been a leader in pioneering new environmental policies in the United States, if the policy goal is to control regional greenhouse gas emissions in the West, a California-only emissions trading program might prove to have little impact on overall greenhouse gas emissions while possibly disrupting electricity market operations, as argued by Wolak et al. (2007). In contrast, if the policy goal is to take the lead with the hope that a comprehensive federal CO2 cap-and-trade will follow in the near future, careful consideration should be given to how the AB32 program should be designed to minimize interference with the operations of competitive electricity markets and reduce the chance that California consumers will suffer from additional electricity price increases.

6. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://or.journal.informs.org/.

Appendix A. A Degenerate Example

We now present an example of a degenerate network in which ISO’s surplus, producers’ surplus, and the market clearing price of CO2 might not be unique. Consider a network consisting of two nodes and one transmission line that connects them, as illustrated in Figure A.1.

The line is subject to a 50-MW transfer capacity limit. The load is at Zone B, with an inverse demand function of $200 - D$, with $D$ MW of electricity consumption. Two electricity power plants serve the load, sitting at Zones A and B, respectively. Assume that the cost functions for plants A and B are as follows:

$$C_A(x) = 10x + 0.2x^2; \quad C_B(x) = 30x + 0.1x^2. \quad (21)$$

Suppose each plant has a 50-MW capacity constraint. Then the marginal cost of producer A is strictly less than that of producer B, given a generation level $x \in [0, 50$ MW]. Further assume that the emissions rate for plant A is 1 ton/MWh, while 0 for plant B. Hence, plant B is more expensive but cleaner than plant A.

For illustration purposes, we consider only the market equilibrium under the source-based approach. Equilibrium conditions for the other two CO2 cap-and-trade schemes can be derived in the same manner. Let $K_A$ and $K_B$ denote the initial CO2 allocation for plants A and B, and assume the total cap of CO2 emissions is 50 tons. Then their profit optimization problems in the market setting depicted in Figure A.1 are as follows:

Maximize $s_{AB} - (10x_A + 0.2x^2_A) + w_Ax_A$

subject to $X_A = s_{AB} - (\theta_{AB}),$

$\theta_{AB} \geq 0.$

Figure A.1. An example of a degenerate market equilibrium.
Maximize \( p_{BB} s_{BB} - (30x_B + 0.1x_B^2) \) \[ p^{CO}_B(x_B - K_B), \]
subject to \( x_B = s_{BB}, \) \( (\theta_{BB}), \)
\[ x_B \leq 50, \) \( (\rho_B), \)
\[ x_B, s_{BB} \geq 0. \] (Plant B)

The ISO’s profit maximization problem is
maximize \( w_A y_A + w_B y_B, \)
subject to \( y_A \leq 50, \) \( (\lambda^+) \)
\[ -y_A \leq 50, \) \( (\lambda^-). \] (ISO)

Consumers’ willingness-to-pay at zone B is
\[ p_B = 200 - (s_{AB} + s_{BB}). \]
The market clearing conditions are
\[ y_A = -x_A, \]
\[ y_B = s_{AB} + s_{BB} - x_B, \]
\[ 0 \leq p^{CO}_B \leq 50 - x_A \geq 0. \]

\((s_{AB}, s_A, s_{BB}, s_B, y_A, y_B, w_B, p_B)\) are unique in an equilibrium of the above system, with values at \((50, 50, 50, 50, -50, 50, 0, 100). \) \( (w_A, p^{CO}_B), \) however, are not unique in equilibria. This is because the generation capacity constraint for plant A, the transmission constraint, and the emissions cap constraint all create the same constraint \( x_A \leq 50. \) This degeneracy leads to a nonunique wheeling charge at zone CA, \( w_A, \) which ranges continuously within \([0, 70], \) and \( CO_2 \) price ranges within \([0, 60$/ton] \) in equilibria. This example shows that unless stronger regularity conditions are imposed to the equilibrium system, uniqueness for ISO’s profit, power producers’ surplus, and \( CO_2 \) prices does not hold in general.

**Appendix B. Generator Characteristics and Transmission Line Data**

**Table B.1.** Generating data.

<table>
<thead>
<tr>
<th>Firm</th>
<th>Location</th>
<th>( c ) [$/MWh]</th>
<th>( d ) [$/MWh(^2)]</th>
<th>( CO_2 ) Rate[kg/MWh]</th>
<th>Capacity[MW]</th>
</tr>
</thead>
<tbody>
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<td>545</td>
<td>200</td>
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<td>0.04</td>
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<td>450</td>
</tr>
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<td>NW</td>
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<td>0.02</td>
<td>500</td>
<td>200</td>
</tr>
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<td>NW</td>
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<td>SW</td>
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<td>0.01</td>
<td>1,249</td>
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**Table B.2.** PTDF values.

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<td>-0.3333</td>
<td>0</td>
</tr>
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<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-0.6667</td>
<td>-0.3333</td>
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**Table B.3.** Transmission line capacities.

<table>
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<th>Capacity [MW]</th>
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<td>120</td>
</tr>
<tr>
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References


Chen, Liu, and Hobbs: Emissions Trading Programs Under California AB32


