A Leader-follower Model for Tradable Performance-Based CO_2 Emissions Standards

Yihsu Chen
Department of Technology Management
Baskin School of Engineering
University of California Santa Cruz
yihsuchen@ucsc.edu

Makoto Tanaka
National Graduate Institute
for Policy Studies (GRIPS)
mtanaka@grips.ac.jp

Afzal S. Siddiqui
Department of Statistical Science
University College London
afzal.siddiqui@ucl.ac.uk

***Abstract*—The U.S. Clean Power Plan stipulates a state-specific *performance*-based CO_2 emission standard and delegates considerable flexibility to the states for using either a tradable performance-based or a mass-based permit program. This paper analyzes these two instruments when they are subject to imperfect competition. We show that while the cross-subsidy inherent in the performance-based instrument might effectively reduce power prices, it could also inflate energy demand, thereby rendering permits scarce. A dominant firm with a relatively clean endowment under the performance-based policy would be able to manipulate the electricity market as well as to lower permit prices, which might worsen market outcomes compared to its mass-based counterpart. On the other hand, the "cross-subsidy" could be the dominant force leading to a higher social welfare if the leader has a relatively dirty endowment.**

***Index Terms*—electricity industry; mathematical program with equilibrium constraints; performance-based standards**

I. INTRODUCTION

The U.S. federal Clean Power Plan (CPP) is introduced by the U.S. Environmental Protection Agency to cut CO_2 emissions from existing fossil-fuel power plants by 30% below 2005 levels by 2030. While the proposal establishes a state-specific target with various building blocks that lay out possible reduction strategies, it leaves states and the power sector with considerable flexibility in attaining their targets. More specifically, a state can decide to adopt either 1) a default performance-based standard under which tons of CO_2 emissions per MWh of electricity generated is measured, or 2) an equivalent mass-based standard, such as in a cap-and-trade (C&T) regime based on GDP growth projections. Furthermore, those states will form an alliance that allows them to trade under either a "mass-based" or a "performance-based" standard.

Theory suggests that the two approaches would provide incentives that might alter a firm's production decisions in a very different way [2]. In particular, a "performance-based" standard involves cross-subsidies from high-emitting sources to low-emitting sources [9], [11]. In the case where a generating unit's emission rate is greater than the performance standard, it will need to pay a cost to cover its emissions, thereby effectively elevating its marginal cost of production. On the other hand, when a generator's emission rate is less than the performance standard, the negative cost becomes a subsidy that owers its production cost, thereby making the generator more competitive.

One emerging issue that has received little attention is the possibility of strategic behavior under the tradable performance-based standard as well as its repercussions for the product market. This paper analyzes the efficiency properties of the CPP tradable performance-based standard with considerations of ownership, heterogeneous technologies, and transmission networks, which affect firms' output decisions and market outcomes. Several scenarios are considered, differing by their assumptions concerning 1) types of tradable permit markets (e.g., mass- or performance-based standard) and 2) whether firms possess market power in the power and the permit markets. If firms are allowed to exercise market power in the permit market, then a Stackelberg-type of leader-follower formulation is considered where a leader could fully and correctly anticipate reactions by followers, including follower producers, system operator, and consumers.

Depending on market structure, we follow [7] and [3] in formulating the problem either as a mixed linear complementarity problem (MLCP) or a mathematical program with equilibirum constraints (MPEC). When formulating the Stackelberg leader-follower problem as an MPEC, the problem is challenging to solve because of 1) complementarity conditions representing followers' first-order conditions so that constraint qualification is violated and 2) bilinear terms in leader's objective function. We overcome these difficulties by replacing complementarity conditions with disjunctive constraints and binary expansion, respectively, and turn the problem into a mixed integer linear program (MILP) [5]. While this transformation might be at the expense of precision of the solution, the mixed integer algorithm guarantees convergence and enables inferring the solution quality through the duality gap.

We have following central findings of the paper. While the cross-subsidy property of the performance-based standard effectively reduces power prices, its inflation of the energy demand might create scarcity in the permit market. When the leader has a relatively clean endowment, e.g., as in California, under the performance-based standard, its ability to manipulate the market might worsen market outcomes compared to its mass-based counterpart. On the other hand, when the leader has a relatively dirty endowment, e.g., as in PJM, the "cross-subsidy" could be the dominant force leading to a higher social welfare compared to its mass-based counterpart.

The rest of this paper is organized as follows. The formulation of models is given in Section II. A case analysis based on a simplified three-node example is implemented in Section III. We conclude the paper in Section IV.

II. PROBLEM FORMULATION

We use a market-equilibrium approach for a single representative time period that accounts for transmission constraints, nodal pricing, and market power. At each node, we allow for a number of generating fleets that could be owned by different companies. These firms compete in a pool-type power market while subjecting themselves either to a mass- or a performance-based policy. An independent system operator (ISO) is assumed to maximize the usage of transmission resources.

We consider five scenarios in our analysis by varying choices of polices or assumptions concerning strategic behavior in power and emissions permit markets. In the numerical examples of Section III, Scenario (E) is solved first to obtain the total emissions, which will be used as an effective emissions cap for the other scenarios: (A) perfect competition with a mass-based policy, (B) Cournot oligopoly with a mass-based policy, (C) Cournot oligopoly with a performance-based policy, (D) Stackelberg (leader-follower) oligopoly with a mass-based policy, and (E) Stackelberg oligopoly with a performance-based policy.

As alluded to earlier, we follow [7] and [3] in formulating the problem either as a mixed linear complementarity problem (MLCP) (Scenarios A, B, and C) or a mathematical program with equilibrium constraints (MPEC) (Scenarios D and E). In Sections II-A–II-B, we primarily show the formulation for Scenario (E), i.e., Stackelberg oligopoly with a performance-based policy. As discussed in Section II-C, we can obtain Scenario (D), i.e., a Stackelberg oligopoly with a mass-based policy by changing the environmental regulation. Scenarios (B) and (C), i.e., Cournot oligopoly with either a mass- or a performance-based policy, can be obtained from the lower-level problem in Section II-A without the upper-level problem in Section II-B. Furthermore, we can derive Scenario (A), i.e., perfect competition with a mass-based policy, by assuming that firms are price-takers instead of Cournot players.

A. Lower-Level Problems

We here describe the lower-level problems for follower firms and the ISO along with a market-clearing condition for CO_2 allowances. The nomenclature is listed in Appendix A.

Follower firms' problem: Follower firms (denoted by j) maximize their profits by deciding their output level $g_{n,j,u'}$ under the performance-based policy as in Eq. (1), where D_n^{int} and D_n^{slp} denote the intercept and the slope of the inverse demand curve at node n. The generation units owned by producer j at node n are defined by $u \in \mathcal{U}_{n,j}$. Our formulation is based on a standard DC load-flow model, which uses the network transfer matrix H and the susceptance matrix B with the voltage angle v [5], [8]. Using the definition of voltage angles, the power flow on line ℓ is $\sum_{n\in\mathcal{N}} H_{\ell,n} v_n$ and the imported power at node n is $-\sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'}$. Those firms can affect the power price through their generation output *à la* Cournot, while they take other variables as given.

$$\underset{g_{n,j,u}\geq 0}{\text{Max}} \sum_{n\in\mathcal{N}} \sum_{u\in\mathcal{U}_{n,j}} \Bigg[D_n^{\text{int}} - D_n^{\text{slp}} \Bigg(\sum_{i\in\mathcal{I}} \sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} \Bigg) - \Bigg(C_{n,j,u} + \rho\left(E_{n,j,u} - F\right) \Bigg) \Bigg] g_{n,j,u} \tag{1}$$

$$\text{s.t. } g_{n,j,u} \leq G_{n,j,u}\ (\beta_{n,j,u}),\ \forall n, \forall u \in \mathcal{U}_{n,j} \tag{2}$$

Eq. (1) states that each follower firm dispatches its plants across the network in order to maximize profit. The revenue depends on the nodal price, $\lambda_n = D_n^{\text{int}} - D_n^{\text{slp}}\Bigg(\sum_{i\in\mathcal{I}} \sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} \Bigg)$, which is itself a function of local generation at that node, $\sum_{i\in\mathcal{I}} \sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'}$, plus net imports, $-\sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'}$. Thus, the price at node n depends on the consumption at that node. The operating cost not only depends on the generation cost, $C_{n,j,u}$, but also the endogenous CO_2 allowance price, ρ, the policy rate, F, and the emission rate, $E_{n,j,u}$. The term $\rho\left(E_{n,j,u} - F\right)$ represents a payment (revenue) if its value is positive (negative). This problem is constrained by the installed capacity, $G_{n,j,u}$, as indicated by Eq. (2) with the dual variable associated with the constraint listed within the parenthesis to the right.

ISO's problem: The ISO maximizes social welfare in Eq. (3) by deciding the demand, d_n, and the voltage angle, v_n, as in [5] and [10] taking the output of generating firms as given:

$$\underset{d_n\geq 0, v_n}{\text{Max}} \sum_{n\in\mathcal{N}} \Big(D_n^{\text{int}} d_n - \frac{1}{2} D_n^{\text{slp}} d_n^2 - \sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{n,i}} C_{n,i,u} g_{n,i,u} \Big) \tag{3}$$

$$\text{s.t. } \sum_{n\in\mathcal{N}} H_{\ell,n} v_n \leq K_\ell\ (\overline{\mu}_\ell),\ \forall \ell \tag{4}$$

$$-\sum_{n\in\mathcal{N}} H_{\ell,n} v_n \leq K_\ell\ (\underline{\mu}_\ell),\ \forall \ell \tag{5}$$

$$S_n v_n = 0\ (\gamma_n),\ \forall n \tag{6}$$

$$d_n - \sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{n,i}} g_{n,i,u} + \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} = 0\ (\lambda_n),\ \forall n \tag{7}$$

$$\sum_{n\in\mathcal{N}} \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} = 0\ (\nu) \tag{8}$$

Eq. (3) indicates that the social welfare at each node is the gross consumer surplus, $D_n^{\text{int}} d_n - \frac{1}{2} D_n^{\text{slp}} d_n^2$, minus the generation cost, $\sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{n,i}} C_{n,i,u} g_{n,i,u}$. Eqs. (4)–(5) state that the transmission flow, $\sum_{n\in\mathcal{N}} H_{\ell,n} v_n$, cannot exceed line capacity of the line ℓ, K_ℓ, while Eq. (6) defines a slack bus to set a voltage angle equal to zero. Eq. (7) corresponds to the energy-balance constraint at each node, i.e., consumption

d_n must equal local generation ,$\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} g_{n,i,u}$, plus net imports, $-\sum_{n'\in\mathcal{N}} B_{n,n'}v_{n'}$, while Eq. (8) is the total energy balance over all nodes to ensure that total generation matches total demand in the system, i.e., the imported power is netted out over all nodes.

Market-clearing condition for CO$_2$ allowances: Under the performance-based policy, the equilibrium for CO$_2$ allowances is expressed as a complementarity condition as follows:

$$0 \le \rho \perp \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} \left(F - E_{n,i,u}\right) g_{n,i,u} \ge 0 \qquad (9)$$

If the right-hand side of Eq. (9) is not binding, i.e., total CO$_2$ allowances, $\sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} F g_{n,i,u}$, are greater than their demand, $\sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} E_{n,i,u} g_{n,i,u}$, then the allowance price, ρ, is 0. Otherwise, we have a positive allowance price, i.e., $\rho > 0$.

Since the problems in Eqs. (1)–(2) and (3)–(8) are convex, they may be replaced by their KKT conditions. Consequently, the lower-level equilibrium may be characterized as the solution to an MLCP.

B. Upper-Level Problem and MPEC Formulation

A Stackelberg leader firm maximizes its profit subject to the lower-level problems in Section II-A. Upon replacing the lower-level problems from Section II-A by their KKT conditions, we can recast the leader's problem as an MPEC by using the lower-level MLCP:

$$\underset{g_{n,s,u}\ge 0}{\text{Max}} \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,s}} \left(\lambda_n - \Big(C_{n,s,u} + \rho\left(E_{n,s,u} - F\right)\Big)\right) g_{n,s,u} \qquad (10)$$

$$\text{s.t. } g_{n,s,u} \le G_{n,s,u}\ (\beta_{n,s,u}),\ \forall n, \forall u \in \mathcal{U}_{n,s} \qquad (11)$$

Eq. (9) and KKT conditions of the lower-level MLCP

where $g_{n,s,u}$ denotes the decision variable of leader firm s. All the variables of the followers, including the ISO and other producers, will be implicitly represented as functions of $g_{n,s,u}$. In practice, such MPECs are solved via reformulation as MILPs in order to resolve non-linearities in both the objective function (10) (i.e., stemming from bilinear terms $\lambda_n g_{n,s,u}$ and $\rho\left(E_{n,s,u} - F\right) g_{n,s,u}$), and Eq. (9) and the KKT conditions of the lower-level MLCP (i.e., related to complementarity conditions of the form $0 \le a \perp b \ge 0$) [4], [1], [5].

C. Other Formulations

We briefly discuss other formulations in Scenarios (A)–(D). In Scenario (D), i.e., Stackelberg oligopoly with mass-based policy, the objective functions of the leader firm in Eq. (10) and the follower firms in Eq. (1) are respectively modified as follows:

$$\underset{g_{g,s,u}\ge 0}{\text{Max}} \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,s}} \left(\lambda_n - C_{n,s,u}\right) g_{n,s,u} - \rho \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,s}} E_{n,s,u} g_{n,s,u} \qquad (12)$$

$$\underset{g_{n,j,u}\ge 0}{\text{Max}} \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}} \left(D_n^{\text{int}} - D_n^{\text{slp}}\Big(\sum_{i\in\mathcal{I}}\sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n'\in\mathcal{N}} B_{n,n'}v_{n'}\Big) - C_{n,j,u}\right) g_{n,j,u} - \rho \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}} E_{n,j,u} g_{n,j,u} \qquad (13)$$

Equations (12) and (13) imply that firms need to pay for their emissions regardless of their emissions rates. The market-clearing condition for CO$_2$ allowances in Eq. (9) is also modified as follows:

$$0 \le \rho \perp \overline{F} - \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} E_{n,i,u} g_{n,i,u} \ge 0 \qquad (14)$$

where $\overline{F}$ denotes the mass-based cap. Scenarios (B) and (C), i.e., Cournot oligopolies with mass- and performance-based policies, respectively, can be obtained from the lower-level problem of the follower firms without the upper-level problem for the leader firm. Furthermore, we can derive Scenario (A), i.e., perfect competition with mass-based policy by assuming that firms are price-takers instead of price-makers. This can be implemented by inserting λ_n as the nodal price instead of the inverse demand function and maximizing Eq. (13) with respect to only $g_{n,j,u}$.

III. NUMERICAL EXAMPLES

A simple three-node network with three firms, ten generating units, and three transmission lines is used to analyze welfare outcomes under various emission policies (Tables I–III). This setup is sufficiently generalized as it allows firms to own facilities and to compete across different locations. We assume that a performance standard of 0.5 t/MW is implemented by a regulatory agency. This level of the emission rate is chosen such that some generating units will be either above or below the standard. The analysis designates firm 1, with a capacity share of more than 55%, as the leader in the market. In effect, we are interested in comparing market outcomes as well as welfare when the damage caused by the emitted pollution is equivalent across scenarios. Had the damage caused by pollution varied by different scenarios, the welfare ranking of the scenarios could have been misleading.

TABLE I
DEMAND PARAMETERS

Location	Vertical intercept [$/MW]	Horizontal intercept [MW]
A	228.00	1400
B	93.12	540
C	111.60	840

TABLE II
CHARACTERISTICS OF GENERATING UNITS

Unit	Owner	Location	Marginal cost [$/MW]	Emission rate [t/MW]	Capacity [MW]
1	3	A	38.00	0.580	250
2	1	A	35.72	0.545	200
3	2	A	36.80	0.600	450
4	1	B	15.52	0.500	150
5	2	B	16.20	0.500	200
6	3	B	0.00	0.000	200
7	1	C	17.60	1.216	400
8	1	C	16.64	1.249	400
9	1	C	19.40	1.171	450
10	3	C	18.60	0.924	200

TABLE III
TRANSMISSION DATA

Lines	Thermal limit [MW]
AB	255
BC	120
AC	30

A. Base Case

Table IV summarizes the main results of the analysis.[1] The columns from left to right correspond to Scenarios A–E, respectively. The table comprises two parts, in which the upper panel gives the aggregated market outcomes (i.e., sale-weighted prices, permit price, total emissions, consumer surplus, producer surplus, ISO revenue, arbitrageur profit, government revenue, social welfare, and total power sales), and the lower panel details producer surplus by firms as well as locational prices and sales. It is worth noting that when calculating government revenue under the mass-based standards, we explicitly assume that the permits are auctioned off so that the revenue is equal to the product of the permit price and the total emissions (= emission cap).

Several observations emerge from Table IV regarding the overall market-level outcomes. First, the sale-weighted power prices are lower among performance-based scenarios (C and E) compared to their counterparts. For example, the sale-weighted power price under Scenario E is 7.5% (or \$6.5/MW) lower than that of Scenario D. This is directly due to the cross-subsidy under the performance-based standard that effectively lowers the marginal cost of high-cost but low-emitting units. Consequently, total power sales under the performance-based scenarios are generally higher when compared to those under their mass-based counterparts. Second, although with equal CO_2 emissions of 663.9 tons, the resulting permit prices under the performance-based scenarios, i.e., C and E, are greater than those in Scenarios B and D, respectively. The cross-subsidy effect of the performance-based standard lowers power prices, inflates power sales, and elevates demand for tradable permits, thereby leading to an increase in the permit price. Comparing these scenarios, permit prices under the performance-based policies are two to three times higher than those under the mass-based standards.

Turning to welfare analysis, consistent with theory, perfect competition (Scenario A) leads to the highest social welfare. Due to the cross-subsidy by the performance-based standards, the lower power prices also result in higher consumer surplus when comparing Scenarios E and C to D and B, respectively. Moreover, while the theory suggests that market outcomes under the leader-follower Stackelberg setting will lie somewhere in between that of perfect competition and less competitive Cournot outcomes, our results actually deviate from that ordering [6], [12]. This is mainly because the higher permit price under the leader-follower Scenario E somehow offsets its beneficial effects, thereby leading to lower consumer surplus by 6.7% compared to Scenario C. When summing over the economic rent to calculate the social welfare, performance-based standards perform better under the Stackelberg setting compared to the mass-based policy. This implies that exertion of market power under the performance-based standard could mitigate some of the market distortion caused by firms' strategic behavior in the product markets.

B. Relatively Clean Endowment Case

We investigate the case in which the emission rate of unit 7 owned by the leader (firm 1) is reduced from 1.216 to 0.216 t/MW. This deliberate reduction of the emission rate is intended to create an environment that would incentivize the leader to manipulate the permit market. Table V summarizes the results of the sensitivity analysis with the same layout as Table IV.

First, lowering the emission rate of unit 7 directly suppresses the demand for permits and reduces permit prices across all scenarios. The permit price under Scenario D (Stackelberg leader-follower setting with the mass-based standard) even crashes to zero, meaning that Scenario D's total emissions (830.6 tons) are below the cap set by Scenario E (833.7 tons). This observation suggests that a mass-based standard might be less susceptible than the performance-based standard to the manipulation of the permit market by the leader. Second, consumers would benefit from lower permit as well as lower power prices. Third, the rank of the social welfare between Scenarios B and E is reversed in contrast to Table IV. In particular, the inflation of power consumption due to the cross-subsidy under the performance-based standard (E) creates permit scarcity that would enable firm 1 (now with a relatively clean portfolio) to manipulate the market. This implies that in Table IV, the cross-subsidy effect on the power price dominates the market power effect, thereby resulting in a higher social welfare in Scenario E. The reverse relationship is prevalent in Table V because the market can maintain the permit price (compared to a zero permit price in mass-based standard in D and a marginally positive permit price in B and

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[1] All the results are based on the models presented as in Section II, which is implemented in the modeling system AMPL and is solved via either CPLEX (for MILPs) or PATH (for MLCPs). The problem instances are executed on a MacBook Pro running OS X 10.7.5 with 8 GB of RAM and take about ten minutes to four hours to solve to optimality in the case of MILPs.

TABLE IV

SUMMARY OF RESULTS UNDER THE RELATIVELY DIRTY ENDOWMENT

	Scenario				
	(A)	(B)	(C)	(D)	(E)
Sale-weighted price [\$/MW]	76.6	81.3	70.8	85.7	79.2
Permit price [\$/t]	73.2	40.9	109.7	39.4	120.7
Total CO_2 emissions [t]	663.9	663.9	663.9	663.9	663.9
Consumer surplus [\$]	73,745.5	68,733.8	79,775.4	61,897.0	69,251.9
Producer surplus [\$]	11,547.2	39,396.5	51,960.8	43,949.4	61,949.4
ISO revenue [\$]	8,034.0	6,187.1	9,758.5	8,589.2	10,486.6
Arbitrageur profit [\$]	0.0	0.0	0.0	0.0	0.0
Government revenue [\$]	48,588.1	27,160.4	0.0	26,170.1	0.0
Social welfare [\$]	141,914.8	141,477.8	141,494.7	140,605.8	141,687.9
Net producer surplus [\$]	60,135.3	66,556.9	51,960.8	70,119.5	61,949.4
Total sales [MW]	1,329.3	1,293.6	1,362.2	1,280.5	1,327.9
Producer surplus [\$]					
1	1123.0	9317.8	10,831.5	11,190.6	14,115.4
2	0.0	11,615.9	13,484.6	10,409.5	14,962.0
3	10,424.2	18,462.8	27,644.7	22,349.3	32,872.0
Price [\$/MW]					
A	80.7	85.8	75.3	95.8	87.5
B	52.8	61.1	44.8	57.6	47.8
C	86.2	80.4	92.4	76.7	84.7
Consumption [MW]					
A	904.4	873.3	937.9	811.7	862.4
B	233.9	185.8	280.0	205.9	263.0
C	191.0	234.5	144.3	262.9	202.4

C) to the extent such that the power price remains higher under Scenario E than that of B, thereby leading to a lower social welfare.

IV. CONCLUSIONS

This paper has studied the impact of the mass- and performance-based standard under imperfect competition either in the product market only or in both the product and the permit markets. Our analysis shows that the market equilibrium is determined not only by the types of the standards, i.e., mass- or performance-based, but also by market structure as well as the asset endowment of the leader. When the endowment of the Stackelberg leader is relatively dirty, the performance-based standard can outperform the mass-based standard as the cross-subsidy leads to higher consumption and scarcer permits. Consequently, the leader's incentive to behave strategically in both product and permits markets is mitigated due to the higher permit price. On the other hand, when the endowment of the Stackelberg leader is relatively clean, the leader will act more aggressively to extract economic rent under the performance-based standard, thereby worsening market outcomes when compared to the counterpart mass-based standards. This is partially due to the fact that the lower permit price when the leader is relatively clean cannot lower the power price adequately to benefit consumers.

APPENDIX A
NOMENCLATURE

Indices and Sets

Γ: upper-level decision variables

Ξ: lower-level primal decision variables

Ψ: lower-level dual variables

Φ: decision variables for MILP

$i \in \mathcal{I}$: power producers

s: strategic producer index

$j \in \mathcal{J}$: non-strategic producers[2]

$k \in \mathcal{K}$: discrete generation level

$\ell \in \mathcal{L}$: transmission lines

$n \in \mathcal{N}$: power network nodes

$u \in \mathcal{U}_{n,i}$: generation units of producer $i \in \mathcal{I}$ at network node $n \in \mathcal{N}$

Parameters

$B_{n,n'}$: element (n, n') of node susceptance matrix, where $n, n' \in \mathcal{N}$ $(1/\Omega)$

$C_{n,i,u}$: generation cost of unit $u \in \mathcal{U}_{n,i}$ from producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (\$/MW)

D_n^{int}: intercept of linear inverse demand function at node $n \in \mathcal{N}$ (\$/MW)

D_n^{slp}: slope of linear inverse demand function at node $n \in \mathcal{N}$ (\$/MW^2)

$E_{n,i,u}$: CO_2 emission rate of unit $u \in \mathcal{U}_{n,i}$ from producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (t/MWh)

F: regulated CO_2 emissions rate under performance (rate)-based policy (t/MW)

$\overline{F}$: regulated CO_2 emissions cap under mass-based policy (t)

$G_{n,i,u}$: maximum generation capacity of unit $u \in \mathcal{U}_{n,i}$ from producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW)

$H_{\ell,n}$: element (ℓ, n) of network transfer matrix, where $\ell \in \mathcal{L}$ and $n \in \mathcal{N}$ $(1/\Omega)$

K_ℓ: maximum capacity of power line $\ell \in \mathcal{L}$ (MW)

$S_n \in \{0, 1\}$: dummy parameter for slack node, where $n \in \mathcal{N}$ (–)

$\overline{G}_{n,s,u,k}$: discrete generation level $k \in \mathcal{K}$ of strategic producer's unit $u \in \mathcal{U}_{n,s}$ located at node $n \in \mathcal{N}$ (MW)

$\overline{E}_{n,s,u,k}$: discrete CO_2 emissions associated with discrete generation level $k \in \mathcal{K}$ of strategic producer's unit $u \in \mathcal{U}_{n,i}$ located at node $n \in \mathcal{N}$ (t)

$M^\lambda, M^y, M, \overline{M}, \check{M}, \hat{M}, \tilde{M}, \underline{M}$: large constants used in disjunctive constraints and binary expansion

Primal Variables

$g_{n,i,u}$: generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using unit $u \in \mathcal{U}_{n,i}$ (MW)

d_n: consumption at node $n \in \mathcal{N}$ (MW)

v_n: voltage angle at node $n \in \mathcal{N}$ (rad)

$y_{n,s,u,k}$: strategic generator's electricity sales revenue at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$ (\$)

$z_{n,s,u,k}$: strategic generator's CO_2 permit revenue (or cost) at node $n \in \mathcal{N}$

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[2] $\mathcal{J} \cap \{s\} = \emptyset$, $\mathcal{J} \cup \{s\} = \mathcal{I}$

TABLE V

SUMMARY OF RESULTS UNDER THE RELATIVELY CLEAN ENDOWMENT

	Scenario				
	(A)	(B)	(C)	(D)	(E)
Sale-weighted price [\$/MW]	40.8	58.8	58.5	62.3	65.1
Permit price [\$/t]	2.6	0.9	0.9	$\underline{0.0}$	19.8
Total CO_2 emissions [t]	833.7	833.7	833.7	$\underline{830.6}$	833.7
Consumer surplus [\$]	131,963.0	100,706.0	101,286.0	92,313.0	88,501.2
Producer surplus [\$]	30,578.7	55,038.1	55,424.8	61,382.5	63,312.7
ISO revenue [\$]	1,604.7	3,869.9	3,869.9	5,169.8	5,844.8
Arbitrageur profit [\$]	0.0	0.0	0.0	0.0	0.0
Government revenue [\$]	2,134.5	774.8	0.0	2,135.0	0.0
Social welfare [\$]	16,6281.0	160,388.7	160,058.7	161,000.3	157,658.7
Net producer surplus [\$]	32,713.2	55,812.9	55,424.8	63,517.5	63,312.7
Total sales [MW]	2,071.5	1,733.9	1,740.4	1,715.0	1,667.4
Producer surplus [\$]					
1	7,480.8	18,153.4	18,285.4	20,438.6	21,868.9
2	11,760.8	17,432.4	17,562.3	17,827.2	17,295
3	11,337.1	19,452.3	19,577.1	23,116.7	24,148.8
Price [\$/MW]					
A	55.5	67.3	66.9	81.1	82.1
B	37.7	46.6	46.2	47.8	47.8
C	19.8	48.2	47.9	38.5	44.1
Consumption [MW]					
A	1059.2	986.9	988.9	902.0	895.9
B	321.6	269.8	271.7	263.0	263.0
C	690.7	477.2	479.7	550.0	508.4

using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$ (\$)

$q^y_{n,s,u,k}$: auxiliary variable to linearize the strategic generator's objective function with respect to electricity sales at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$

$p_{n,s,u,k}$: auxiliary variable used to associate CO_2 permit price for the output level of producer at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$ (\$/t)

Dual Variables

$\beta_{n,i,u}$: shadow price on generation capacity at node $n \in \mathcal{N}$ for generation unit $u \in \mathcal{U}_{n,i}$ of producer $i \in \mathcal{I}$ (\$/MW)

γ_n: dual for slack node $n \in \mathcal{N}$ (–)

$\overline{\mu}_\ell, \underline{\mu}_\ell$: shadow prices on transmission capacity for transmission line $\ell \in \mathcal{L}$ (\$/MW)

λ_n: market-clearing price at node $n \in \mathcal{N}$ (\$/MW)

ν: hub price (\$/MW)

ρ: shadow price on emissions rate (\$/t)

Integer Variables

q^λ_n: auxiliary variable used to indicate whether market-clearing price at node $n \in \mathcal{N}$ is positive

$q_{n,s,u,k}$: auxiliary variable used to discretize the strategic generator's electricity generation at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$

$\overline{r}_{n,j,u}$: auxiliary variable used to handle the Karush-Kuhn-Tucker (KKT) condition with respect to non-strategic producer $j \in \mathcal{J}$'s generation at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,j}$ and $g_{n,j,u}$

r_n: auxiliary variable used to handle the KKT condition with respect to consumption at node $n \in \mathcal{N}$ and d_n

$\check{r}_{n,j,u}$: auxiliary variable used to handle complementarity condition between generation constraint of non-strategic producer $j \in \mathcal{J}$'s unit $u \in \mathcal{U}_{n,j}$ located at node $n \in \mathcal{N}$ and shadow price of generation capacity

$\hat{r}_\ell$: auxiliary variable used to handle the complementarity condition between transmission line ℓ's capacity constraint and the shadow price in positive direction

$\tilde{r}_\ell$: auxiliary variable used to handle the complementarity condition between transmission line ℓ's capacity constraint and the shadow price in negative direction

$\underline{r}$: auxiliary variable used to handle the complementarity condition between the emissions constraint and the CO_2 price

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