Tradable Performance-Based CO_2 Emissions Standards: Walking on Thin Ice?

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Abstract

Climate policy, like climate change itself, is subject to debate. Partially due to the political deadlock in Washington, DC, US climate policy, historically, has been driven mainly by state or regional effort until the recently introduced federal Clean Power Plan (CPP). Instead of a traditional mass-based standard, the US CPP stipulates a state-specific *performance*-based CO_2 emission standard and delegates considerable flexibility to the states in achieving the standard. Typically, there are two sets of policy tools available: a tradable performance-based and a mass-based permit program. We analyze these two related but distinct standards when they are subject to imperfect competition in the product and/or permit markets. Stylized models are developed to produce general conclusions. Detailed models that account for heterogenous technologies and the transmission network are developed to evaluate policy efficiency. Depending on the scenarios under consideration, the resulting problem could be either a complementarity problem or a Stackelberg leader-follower game, which is implemented as a mathematical program with equilibrium constraints (MPEC). We overcome the nonconvexity of MPECs by reformulating them as mixed integer problems. We show that while the cross-subsidy inherent in the performance-based standard that might effectively reduce power prices, it could inflate energy demand, thereby rendering permits scarce. When the leader in a Stackelberg formulation has a relatively clean endowment under the performance-based standard, its ability to manipulate the electricity market as well as to lower permit prices might worsen the market outcomes compared to its mass-based counterpart. On the other hand, when the leader has a relatively dirty endowment, the "cross-subsidy" could be the dominant force leading to a higher social welfare compared to the mass-based program. This paper contributes to the current policy debates in regulating emissions from the US power sector and highlights different incentives created by the mass- and performance-based standards.

Keywords: Climate policy; electricity industry; mathematical program with equilibrium constraints; performance-based standards.

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1 Introduction

Regulating emissions is challenging because the negative externality of pollution is not fully internalized by the producers in a market so that more pollution is emitted than socially optimal. In order to address this externality, two types of governmental interventions are typically considered: command-and-control (C&C) and market-based policies. While the former mandates the installation of a specific control technology, the latter stipulates an emissions limit on sources beyond which a penalty will be imposed. Examples of technology standards, one type of C&C, include scrubbers and selective non-catalytic reduction systems (SNCRs) for SO_2 and NO_x emissions from power plants under the US Clean Air Act (CAA). Industry would favor the performance standard over the technology one due to its flexibility, whereas government might be inclined to set the technology standard if the transaction cost is substantially higher under the performance standard.

While the market-based policy is a generic label for various types of environmental standards that take advantage of competition in the polluting industries, it generally refers to price and quantity instruments. The price instrument, commonly known as a "tax," acts as a cost adder that penalizes polluting industries by internalizing pollution damage. The second type (known as cap-and-trade (C&T)) regulates the pollution quantity, in which a regulatory body first allocates property rights of emitting pollutions, i.e., permits or allowances, to affected facilities by either auctioning, grandfathering, or a combination of the two. These facilities need to demonstrate their compliance by surrendering sufficient allowances to cover their emissions at the end of each compliance cycle, e.g., the annual cap for SO_2 and summer months for NO_x. The allowances can be traded freely in secondary markets such as the SO_2 trading program under the CAA, the European Union Emission Trading System (EU ETS), CO_2 trading, and renewable energy credit (REC) trading under several state-level renewable portfolio standards (RPS).

Economists have long advocated for market-based approaches on the grounds of economic efficiency. A number of frequently cited advantages of market-based instruments over C&C policies include equating marginal abatement cost, static efficiency, dynamic efficiency, and double dividend, thereby inducing technology adoption (Stavins, 1995; Parry et al., 1997). However, a tax and C&T are fundamentally different since the level of an emissions tax is pre-set by an authority and exogenous to the product market. By contrast, permit prices fluctuate constantly reflecting market participants' expectations concerning demand and supply conditions. Comparison of the tax and the C&T has, therefore, received considerable attention following early work by Weitzman (1974). Mansur (2013) shows that, in contrast to a tax, the polluters' decisions under a tradable permits system would affect the permit price, which might actually increase a strategic firm's output, thereby leading to a lower deadweight loss relative to a tax system. Green (2008) examines market risks faced by generators under the tax and permits systems with the finding that a tax increases (decreases) the volatility for a fossil-fuel (nuclear) plant. Chen and Tseng (2011) conclude that price volatility under a C&T would induce early adoption of clean technology compared to a tax. While the efficiency properties of these two types of policies are well known through years of research, the newly introduced the US federal Clean Power Plan (CPP) brings a new dimension, which is the focus of this paper.

Due to its federal structure along with recent political gridlock, the US has seen climate policy driven forward largely based on regional efforts, e.g., the Regional Greenhouse Gas Initiative (RGGI) in the northeastern United States and California Assembly Bill (AB) 32.

In contrast, the CPP is a new federal-level policy introduced by the US 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 C&T regime based on GDP growth projections. Furthermore, those states will form an alliance that allows them to trade either under a "mass-based" or a "performance-based" standard.

Economic theory suggests that the two approaches would provide incentives that might alter a firm's production decisions in a very different way (Bushnell et al., 2014). In particular, similar to an RPS, a "performance-based" standard involves cross-subsidies from high-emitting sources to low-emitting sources (Tanaka and Chen, 2013; Siddiqui et al., 2016). 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 effectively lowers its production cost, thereby making the generator more competitive. This effectively lowers the marginal costs of those low-emitting units, which are more likely to have high marginal costs in the production merit order. As those units are the typically price-setting marginal units, the policy would likely lower the power price, thereby inflating energy demand. The tradable performance-based standard under the CPP is called emission rate credits (ERCs) with a physical unit of \$/MWh. Given a policy rate of E^{policy}, for a generating unit with an emission rate of E, producing 1 MWh of energy will be equivalent to generating $\frac{E^{policy}-E}{E^{policy}}$ ERCs, either positive or negative. When a state opts for implementing this tradable performance-based standard, it will comply with policy by collecting a non-negative net ERC.[1]

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. The consequences of market power can include price distortions, production inefficiencies, and a redistribution of income from consumers to suppliers. In fact, the distribution of economic rent or welfare analysis needs further attention when comparing performance- with mass-based standards. In particular, while the government collects all the proceedings from auctioning off mass-based tradable permits, the tradable performance-based standard is inherently revenue neutral since it involves transfers of economic rent from high-emitting to low-emitting units. This paper analyzes the efficiency properties of the CPP tradable performance-based standard under imperfect competition and compares it to the traditional mass-based policies. 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

[1] Zhang et al. (2016) address the equivalence between an RPS-type performance-based and a mass-based permit system and its efficiency properties. In particular, while a joint tradable performance-based standard with more than two regions with different policy rates is believed to allow for equating marginal abatement cost of the two regions (i.e., equivalent ERC permit prices) through permit tradings, Zhang et al. (2016) show that, under some conditions, this could lead to different ERC permit prices, thereby undermining the efficiency of a joint performance-based permit program. They, therefore, conclude that a joint mass-based tradable permit program will perform better on the grounds of economic efficiency.

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.

The paper proceeds in two ways. First, stylized duopoly models considering a performance-based policy are developed to produce generalized theories. Second, more *structured* models that are generalized to more than two firms and account for the fact that firms might own multiple facilities with different emission intensities and compete in a transmission-constrained network are developed to reflect more realistic market conditions.

The general conclusion from the stylized analysis indicates that the outcomes of the Cournot duopoly lie between that of the perfect competition and Stackelberg ones when a performance-based allowance market is considered. That is, the power price is highest in the Stackelberg followed by the Cournot and perfect competition, while the the total emission and output are in a reversed order. These findings are in contrast to the general observation that the outcomes of Stackelberg lie between least competitive Cournot and perfect competition when only a product market is considered. Interestingly, the strategy undertaken by a Stackelberg leader depends on its emission rate relative to the policy rate. In particular, when its emission rate is lower than the policy rate, it would withhold its output, and reduce allowance supply, thereby leading to a higher allowance price.

Nevertheless, the simplified duopoly models do not allow us to evaluate social surplus among different policy choices (i.e., *mass*, and *performance-based*) or market structures (i.e., *perfect, Cournot and Stackelberg competition*) as the damage caused by pollution is not explicitly accounted for. To overcome this, we turn our attention to the detailed modeling by equating the amount of total emission across different scenarios to that of the Stackelberg case under performance-based policy. In a way, the "Stackelberg-performance-based" scenario serves as a benchmark case. We have following central findings of the paper from our detailed modeling. While the property of cross-subsidy inherent in the performance-based standard might effectively reduce power prices, its inflation of the energy demand might create scarcity in the permit market. When the leader has a relatively clean endowment under the performance-based standard, its ability to manipulate the market might worsen the market outcomes compared to its mass-based counterpart. On the other hand, when the leader has a relatively dirty endowment, 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. In Section 2, we review the relevant literature. In Section 3, we present a qualitative analysis based on stylized models. The formulation of detailed models is given in Section 4. A case analysis based on a simplified three-node example is implemented in Section 5. We conclude the paper in Section 6.

2 Literature Review

There is a rich body of research studying mass-based tradable permit policies (Sartzetakis, 1997; Misiolek and Elder, 1989; Hahn, 1984; von der Fehr, 1993; Chen and Hobbs, 2005; Chen et al., 2006). Their overall conclusion is that market power in a mass-based standard could be a concern as it distorts the permit price, and the effect could spill over to the product market, thereby leading to significant inefficiencies. On the other hand, research concerning market power in tradable performance standards is relatively thin, partially due to the fact that the policy is less common.[2] Focusing on RPS standards rather than performance-based standards directly, Tanaka and Chen (2013) apply a dominant-fringe framework to analyze market power in tradable RECs. The paper shows that market power could have significant impacts on the REC and power prices. In particular, when a non-renewable generator is a dominant firm and a renewable generator is a competitive fringe, the former has a strong incentive to lower the REC price, e.g., even to zero, in order to avoid REC costs. The zero REC price would negate price impacts in the power market, thereby mitigating market power of the dominant firm. However, they note that this could lead to an underinvestment in renewables in the long run as subsidies received by renewables in form of the RECs vanish. Siddiqui et al. (2016) take the perspective of a regulator in setting the optimal RPS target. Via a bi-level model, they demonstrate that compared to a first-best policy of curbing consumption, the use of RPS results in the deployment of "too much" renewable energy. Consequently, the potential exercise of market power by a non-renewable producer may actually improve social surplus *vis-à-vis* a market setting with perfect competition.

In contrast to the analysis of the mass-based standard, only recently did work on performance-based standards receive some attention due to policy debates about the CPP. Bushnell et al. (2014) focus on states' incentives for adopting tradable performance- or mass-based standards. Their focus is on the strategic choices by states that are in the same interconnected power market to adopt different standards. They conclude that the performance-based standard is a dominant strategy by states while a single regional cap will be a Nash equilibrium. Their numerical simulation of the US Western electricity market also find that a mix of performance- and mass-based standards by states within an interconnected power market might lead to emissions leakage. Their results highlight the challenges of the flexibility introduced by the CPP as well as the benefit of coordination among states.

Bushnell et al. (2014) is closely related to Fischer (2003a), who analyzes carbon trading between mass- and performance-based standards and shows that 1) unlimited trade between two types of the standards can raise combined emissions if the goods produced by the industries of the two programs are independent, and 2) the combined emissions, however, could decline if those goods are substitutes and when the effect of own-price elasticity is greater than that of the cross-price elasticity. In a sense, the definition of "sector" in Fischer (2003a) is equivalent to "state," as each state decides to go either with a performance- or mass-based program. However, the general finding (2) in Fischer (2003a) is difficult to apply to the situation in Bushnell et al. (2014). This is mainly because power trading is constrained by the thermal capacity of the transmission lines so that the magnitude of the cross-price elasticity is not easy to gauge even when the power produced by different facilities is perfectly substitutable when available.

Burtraw et al. (2015) examine coordination problems under the CPP using a detailed partial-equilibrium investment operational model of the US electricity sector. While holding the rest of the US constant with its respective emissions rate standards, the paper focuses on policy options in the upper Midwest as the region is subject to a mix of cost-of-service regulation and deregulated industry structures. They show that when the

[2] Fischer (2003b) compares three similar output-based rebating programs in the presence of imperfect competition in *product* markets: tradable performance standards, emissions taxes with rebates according to output share, and output-allocated emissions permits. The paper finds that for a given emission target, output-based rebating raises the marginal abatement cost relative to an efficient policy. In her setting, the tradable performance standard market is assumed to perfectly competitive.

upper Midwest adopts some form of mass-based standard, the performance-based standard offers the rest of the US a substantial cost advantage, thereby causing operations and investments to shift away from the mass-based regions. The possibility of higher national emissions is also noted.

An earlier study by Holland et al. (2009), within a different context, analyzes the federal low carbon fuel standard (LCFS), a performance-based policy to regulate greenhouse gas emissions by limiting the carbon intensity of fuels in the transportation sector. The paper concludes that the policy could possibly lead to increasing net carbon emissions as decreased emissions from high-carbon fuel production is offset by increases in emissions due to low-carbon fuel production. Their work implies that while emissions reduction is the only way by which firms or producers can comply with the standards, firms can satisfy the performance-based standards by inflating the denominator, thereby leading to an increase in overall emissions. Their general results are that a performance-based standard (or intensity standard) cannot attain the first best, is less efficient with a higher abatement cost, and could increase emissions. Although their work briefly touches upon the market power in performance-based standards, their main focus remains on situations with perfect competition. A subsequent work by Holland (2012) compares an emissions tax with mass- and performance-based standards when incomplete regulation is present, i.e., a form of market failure. The paper shows that, in the presence of leakage or incomplete regulation, intensity or performance-based standards can dominate an optimal carbon tax or C&T due to its implicit output subsidy.

Given this background, our paper contributes to the existing literature and current policy debates in a number of ways. First, we allow for market power in a performance-based standards regime to be modeled explicitly and solved in a leader-follower framework (Gabriel and Leuthold, 2010; Chen and Hobbs, 2005; Chen et al., 2006). Second, also compared to other earlier work (Fischer, 2003a; Tanaka and Chen, 2013), we explicitly consider the physical system (transmission network along with heterogeneity in technologies and ownership) that is essential in deciding the substitution of power produced by technologies with different emission intensities when facing environmental policies. Finally, on the policy side, we directly contribute to the recent policy debates in tradable performance standards by comparing social surplus under various relevant cases. In particular, we demonstrate that comparisons between mass- and performance-based standards might not as straightforward as they seem, and the proceedings from permit auctions under the mass-based standard need to be accounted for carefully when ranking policy efficiency.

3 Qualitative Analysis of Performance-Based Policy

The performance-based policy might provide different economic incentives under different market structures, thereby leading to different market outcomes. Based on stylized models, we here conduct a qualitative analysis of the performance-based policy bypassing various institutional, engineering, and market details of power markets, which we will return to in the next section. We also abstract the analysis without assuming a functional form of supply or demand curves to derive generalized results. Our focus is to compare the equilibrium outcome for perfect competition, a Cournot duopoly, and a Stackelberg duopoly, under a given performance-based policy.

3.1 Basic Setup

Consider two firms $i = 1, 2$ with output g_i. Let $c_i(g_i)$ denote the cost function of each firm. We assume $c_i' > 0$ and $c_i'' \geq 0$. CO_2 emissions rates are either $0 < E_1 < F < E_2$ or $E_1 > F > E_2 > 0$, in which F is a regulated emissions rate under performance-based policy.[3] Total CO_2 emissions are expressed as $e = E_1 g_1 + E_2 g_2$. Let $p(g)$ denote inverse demand function, in which $g = g_1 + g_2$. We assume $p' < 0$ and $p'' \leq 0$.

The market-clearing condition for CO_2 allowances under the performance-based policy is generally expressed a complementarity condition as follows:

$$0 \leq \rho \perp F - \frac{(E_1 g_1 + E_2 g_2)}{g_1 + g_2} \geq 0, \tag{1}$$

$$0 \leq \rho \perp (F - E_1) g_1 + (F - E_2) g_2 \geq 0, \tag{2}$$

where ρ is the allowance price. For the sake of simplicity, we assume that the market-clearing condition is binding with a positive price for allowances, $\rho > 0$:

$$(F - E_1) g_1 + (F - E_2) g_2 = 0. \tag{3}$$

We examine the market outcomes under perfect competition, a Cournot duopoly, and a Stackelberg duopoly in the next three subsections.

3.2 Perfect Competition

We first consider perfect competition with electricity price, p. The profit-maximization problem of price-taking firm i is expressed as follows:

$$\underset{g_i}{\text{Maximize}}\ p g_i - c_i(g_i) - \rho(E_i - F) g_i. \tag{4}$$

The last term, $\rho(E_i - F) g_i$, is allowance payment (revenue) for a high- (low-) emitting firm with $E_i > F$ ($E_i < F$). We can derive the first-order necessary condition for this problem. Assuming an interior solution together with the market-clearing condition for allowances (3), the equilibrium conditions for perfect competition are expressed as follows:

$$p(g) - c_i'(g_i) - \rho(E_i - F) = 0,\ \ i = 1, 2 \tag{5}$$

$$(F - E_1) g_1 + (F - E_2) g_2 = 0. \tag{6}$$

We can solve the three equations simultaneously with respect to the three variables, g_1, g_2, ρ, to obtain the equilibrium outcome. First, rearranging Eq. (6) yields $g_2 = a(g_1) = -\frac{(F-E_1)}{F-E_2} g_1$. Total output can then be expressed as $g = b(g_1) = \frac{E_1 - E_2}{F - E_2} g_1$. Next, Eq. (5) for $i = 2$ can be rearranged as follows:

$$\begin{aligned} \rho &= f(g_1) \\ &= \frac{1}{E_2 - F}\Big(p\big(b(g_1)\big) - c_2'\big(a(g_1)\big)\Big). \end{aligned} \tag{7}$$

Finally, substituting $b(g_1)$ and $f(g_1)$ into Eq. (5) for $i = 1$ yields:

$$p\big(b(g_1)\big) - c_1'(g_1) - f(g_1)(E_1 - F) = 0. \tag{8}$$

The equilibrium output g_1^* of firm 1 under perfect competition satisfies Eq. (8). We can, thus, characterize the equilibrium outcome for perfect competition using g_1^*, i.e., $\big\{g_1^*, g_2^* = a(g_1^*), g^* = b(g_1^*), \rho^* = f(g_1^*), p^* = p\big(b(g_1^*)\big), e^* = E_1 g_1^* + E_2 a(g_1^*)\big\}$.

[3] This allows allowance trading to take place.

3.3 Cournot Duopoly

Under a Cournot duopoly, firms can exert market power on the electricity price but cannot manipulate the allowance price. The profit-maximization problem of Cournot firm i is expressed as follows:

$$\underset{g_i}{\text{Maximize}}\ p(g)g_i - c_i(g_i) - \rho(E_i - F)g_i. \tag{9}$$

Assuming interior solutions and along with the market clearing condition for allowances, the equilibrium conditions for Cournot duopoly are expressed as follows:

$$p(g) + p'(g)g_i - c_i'(g_i) - \rho(E_i - F) = 0,\ \ i = 1, 2, \tag{10}$$

$$(F - E_1)g_1 + (F - E_2)g_2 = 0. \tag{11}$$

As in Section 3.2, the three equations can be solved simultaneously with respect to the variables g_1, g_2, ρ to obtain the equilibrium outcome. Eq. (11) gives the same $g_2 = a(g_1)$ and $g = b(g_1)$ as before. Eq. (10) for $i = 2$ can be then rearranged as follows:

$$\begin{aligned}\rho &= h(g_1)\\ &= \frac{1}{E_2 - F}\Big(p\big(b(g_1)\big) + p'\big(b(g_1)\big)a(g_1) - c_2'\big(a(g_1)\big)\Big).\end{aligned} \tag{12}$$

Substituting $b(g_1)$ and $h(g_1)$ into Eq. (10) for $i = 1$ yields:

$$p\big(b(g_1)\big) + p'\big(b(g_1)\big)g_1 - c_1'(g_1) - h(g_1)(E_1 - F) = 0. \tag{13}$$

The equilibrium output, g_1^c, of firm 1 for Cournot duopoly satisfies Eq. (13). In a similar way as in perfect competition, we can characterize the equilibrium outcome of Cournot duopoly, $\{g_i^c, g^c, \rho^c, p^c, e^c\}$, accordingly.

3.4 Stackelberg Duopoly

Let firm 1 be the Stackelberg leader, who maximizes its profit anticipating the decision of the follower firm 2 as well as the market clearing for CO_2 allowances. Thus, the leader firm can exercise market power in both the electricity and allowance markets. The profit-maximization problem of the leader firm is expressed as follows:

$$\underset{g_1 \cup \{g_2, \rho\}}{\text{Maximize}}\ p(g)g_1 - c_1(g_1) - \rho(E_1 - F)g_1 \tag{14}$$

$$\text{s.t.}\ \ p(g) + p'(g)g_2 - c_2'(g_2) - \rho(E_2 - F) = 0. \tag{15}$$

$$(F - E_1)g_1 + (F - E_2)g_2 = 0, \tag{16}$$

As in Section 3.3, we can obtain $g_2 = a(g_1), g = b(g_1)$, and $\rho = h(g_1)$ from Eqs. (15)–(16). Hence, the mathematical program with equilibrium constraints, (14)–(16), can be transformed into an unconstrained optimization problem:

$$\underset{g_1}{\text{Maximize}}\ p\big(b(g_1)\big)g_1 - c_1(g_1) - h(g_1)(E_1 - F)g_1. \tag{17}$$

Assuming interior solutions, the first-order necessary condition for (17) is:

$$p\big(b(g_1)\big) + p'\big(b(g_1)\big)b'(g_1)g_1 - c_1'(g_1) - h(g_1)(E_1 - F) - h'(g_1)(E_1 - F)g_1 = 0. \tag{18}$$

The equilibrium output, g_1^s, of the Stackelberg leader satisfies Eq. (18). Therefore, we can characterize the equilibrium outcome for the Stackelberg setting as $\{g_i^s, g^s, \rho^s, p^s, e^s\}$.

3.5 Comparison of Equilibrium Outcomes

We now compare the equilibrium outcomes for perfect competition, Cournot duopoly, and Stackelberg leader-follower settings. More specifically, we compare the output, electricity price, CO_2 allowance price, and emissions at equilibrium under different market structures assuming interior solutions. We first show the result for the output of each firm.

Proposition 3.1. *At equilibrium,* $g_i^s < g_i^c < g_i^*$ *holds.*

The output of each firm is less under Stackelberg than under Cournot duopoly. It is worthwhile noting that this proposition holds no matter whether the firm is the leader or follower in the Stackelberg case. Suppose that the leader firm has a low emissions rate (i.e., *clean*). It would be profitable for the leader firm to suppress its output because the allowance price rises by withholding its supply of permits. If the leader firm has a high emissions rate (i.e., *dirty*), then it would be again profitable for the leader to reduce his/her output. This is because the allowance price falls by decreasing its demand for allowances, thereby reducing the burden of allowance payments. Our result is in contrast to that of a typical Stackelberg duopoly without any environmental regulation in which the leader firm tends to increase its output relative to that of the follower firm by enjoying the first-mover advantage.

We next describe the result for the total output, electricity price, and total CO_2 emissions.

Proposition 3.2. *At equilibrium,* $g^s < g^c < g^*$ *and* $p^s > p^c > p^*$ *hold.*

Proposition 3.3. *At equilibrium,* $e^s < e^c < e^*$ *holds.*

As expected, the total output is the greatest and the electricity price is the lowest under perfect competition, also accompanied with the greatest CO_2 emissions. In contrast, the total output is the least and the electricity price is the highest under Stackelberg along with the least CO_2 emissions. This result deviates from the typical observation that Stackelberg outcome lies somewhere between perfect competition and Cournot case when a allowance market is not considered.

The CO_2 allowance prices under Cournot and Stackelberg cases, however, depend on the emissions intensities of firms.

Proposition 3.4. *At equilibrium, the following holds:*

$$\text{If } E_1 < F < E_2, \text{then } \rho^s > \rho^c.$$
$$\text{If } E_1 > F > E_2, \text{then } \rho^s < \rho^c.$$

This result is related to Proposition 3.1. If the leader firm in Stackelberg duopoly has a low emissions rate, i.e., $E_1 < F$, then it exerts market power to raise the CO_2 allowance price. In contrast, if the leader firm has a high emissions rate, i.e., $E_1 > F$, then it suppresses the allowance price. On the other hand, the comparison of the allowance price between perfect competition and Cournot/Stackelberg settings is ambiguous.

The stylized models herein are helpful in providing general guidance about how firms might react to a performance-based policy under different market structures. However, in reality, firms might own a set of generating units with various emission intensities, and output-sale decisions might be affected by transmission constraints. Thus, the analytical model is extended to account for the physical power system, detailed institutional rules, market conditions, and other factors that are known to be crucial to the power sector in Section 4. Also as alluded to earlier, comparing various scenarios without accounting for damage costs might be misleading. Thus, our analysis in next section will examine the results when total emissions are equivalent across cases.

4 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 5, 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.

Depending on the market structure, we follow Hobbs (2001) and Chen et al. (2006) in formulating the problem either as a mixed linear complementarity problem (MLCP) or a mathematical program with equilibrium constraints (MPEC). If a firm can exercise market power in the permit market, then a Stackelberg-type leader-follower formulation is considered in which a leader firm could fully anticipate reactions by follower producers and the ISO along with the equilibrium for CO_2 allowances. In this case, the resulting bi-level problem may be re-formulated as an MPEC, which is challenging to solve with currently available commercial solvers because of 1) complementarity conditions of the lower-level problems and 2) bilinear terms in leader's objective function. We circumvent these obstacles by using disjunctive constraints and binary expansion, respectively (Gabriel and Leuthold, 2010), which enable us to re-cast the problem as a mixed-integer linear program (MILP). 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.

In Sections 4.1–4.4, we primarily show the formulation for Scenario (E), i.e., Stackelberg oligopoly with a performance-based policy. As discussed in Section 4.5, 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 4.2 without the upper-level problem in Section 4.3. 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.

4.1 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[4]
$k \in \mathcal{K}$: 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 emissions rate of unit $u \in \mathcal{U}_{n,i}$ from producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (t/MW)
$\underline{F}$: 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)
$\underline{S}_n \in \{0, 1\}$: 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 $u \in \mathcal{U}_{n,i}$ located at node $n \in \mathcal{N}$ (MW)
$M^\lambda, M^y, M^z, M, \overline{M}, \check{M}, \hat{M}, \tilde{M}, \underline{M}$: 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 $n \in \mathcal{N}$ 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 $k \in \mathcal{K}$
$q^z_{n,s,u,k}$: auxiliary variable to linearize the strategic generator's objective function with respect to CO_2 permit revenue at node $n \in \mathcal{N}$ using unit $u \in \mathcal{U}_{n,s}$ at generation level $k \in \mathcal{K}$

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

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_n^λ: 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

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 $-\sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'}$.

4.2 Lower-Level Problem Formulated as MLCP

We here describe the lower-level problems for follower firms and the ISO along with a market-clearing condition for CO_2 allowances.

Follower firms' problem: Follower firms maximize their profits under the performance-based policy as in Eq. (19). Those firms can affect the power price through their generation output *à la* Cournot, while they take other variables as given.

$$\underset{g_{n,j,u} \geq 0, \lambda_n}{\text{Maximize}} \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{U}_{n,j}} \left(\lambda_n - \Big(C_{n,j,u} + \rho \left(E_{n,j,u} - F \right) \Big) \right) g_{n,j,u} \tag{19}$$

$$\text{s.t. } \lambda_n = D_n^{\text{int}} - D_n^{\text{slp}} \left(\sum_{i \in \mathcal{I}} \sum_{u' \in \mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'} \right), \forall n \tag{20}$$

$$g_{n,j,u} \leq G_{n,j,u} \; (\beta_{n,j,u}), \; \forall n, \forall u \in \mathcal{U}_{n,j} \tag{21}$$

where $\sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}}\rho\left(E_{n,j,u}-F\right)g_{n,j,u}$ in Eq. (19) represents CO_2 allowance payment (revenue) if its value is positive (negative). Eq. (20) relates the electricity price to the inverse demand function at each node n. Eq. (21) is the generation capacity constraint. By substituting Eq. (20) into the objective function, we can rearrange the above problem as follows:

$$\underset{g_{n,j,u}\geq 0}{\text{Maximize}}\sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}}\left[D_n^{\text{int}}-D_n^{\text{slp}}\left(\sum_{i\in\mathcal{I}}\sum_{u'\in\mathcal{U}_{n,i}}g_{n,i,u'}-\sum_{n'\in\mathcal{N}}B_{n,n'}v_{n'}\right)\right.$$

$$\left.-\left(C_{n,j,u}+\rho\left(E_{n,j,u}-F\right)\right)\right]g_{n,j,u} \tag{22}$$

$$\text{s.t. } g_{n,j,u}\leq G_{n,j,u}\ (\beta_{n,j,u}),\ \forall n,\forall u\in\mathcal{U}_{n,j} \tag{23}$$

ISO's problem: The ISO maximizes social welfare in Eq. (24) as in Gabriel and Leuthold (2010) and Tanaka (2009) taking the strategic output of generating firms as given:

$$\underset{d_n\geq 0,v_n}{\text{Maximize}}\sum_{n\in\mathcal{N}}\left(D_n^{\text{int}}d_n-\frac{1}{2}D_n^{\text{slp}}d_n^2-\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}}C_{n,i,u}g_{n,i,u}\right) \tag{24}$$

$$\text{s.t.}\quad \sum_{n\in\mathcal{N}}H_{\ell,n}v_n\leq K_\ell\ (\overline{\mu}_\ell),\ \forall\ell \tag{25}$$

$$-\sum_{n\in\mathcal{N}}H_{\ell,n}v_n\leq K_\ell\ (\underline{\mu}_\ell),\ \forall\ell \tag{26}$$

$$S_n\,v_n=0\ (\gamma_n),\ \forall n \tag{27}$$

$$d_n-\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}}g_{n,i,u}+\sum_{n'\in\mathcal{N}}B_{n,n'}v_{n'}=0\ (\lambda_n),\ \forall n \tag{28}$$

$$\sum_{n\in\mathcal{N}}\sum_{n'\in\mathcal{N}}B_{n,n'}v_{n'}=0\ (\nu) \tag{29}$$

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 (Schweppe et al., 1988; Gabriel and Leuthold, 2010). Eqs. (25)–(26) represent the transmission capacity constraints, while Eq. (27) defines a slack bus. Eq. (28) corresponds to the energy-balance constraint at each node, while Eq. (29) 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:

$$0\leq\rho\perp\sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}}\left(F-E_{n,i,u}\right)g_{n,i,u}\geq 0 \tag{30}$$

If the right-hand side of Eq. (30) is not binding, i.e., total CO_2 allowances, $\sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}}Fg_{n,i,u}$, 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., $\rho>0$.

We then derive the KKT conditions for the above problems. The lower-level problems are formulated as an MLCP as follows.

$$0 \leq g_{n,j,u} \perp D_n^{\mathrm{slp}} \sum_{u' \in \mathcal{U}_{n,j}} g_{n,j,u'} + C_{n,j,u} + \beta_{n,j,u} - \lambda_n + \rho \left(E_{n,j,u} - F \right) \geq 0, \forall n, \forall j, \forall u \in \mathcal{U}_{n,j} \tag{31}$$

$$0 \leq d_n \perp -D_n^{\mathrm{int}} + D_n^{\mathrm{slp}} d_n + \lambda_n \geq 0, \forall n \tag{32}$$

$$\sum_{\ell \in \mathcal{L}} \overline{\mu}_\ell H_{\ell,n} - \sum_{\ell \in \mathcal{L}} \underline{\mu}_\ell H_{\ell,n} + \gamma_n S_n - \sum_{n' \in \mathcal{N}} (\lambda_{n'} - \nu) B_{n',n} = 0 \text{ with } v_n \text{ u.r.s.}, \forall n \tag{33}$$

$$0 \leq \beta_{n,j,u} \perp G_{n,j,u} - g_{n,j,u} \geq 0,\ \forall n, \forall j, \forall u \in \mathcal{U}_{n,j} \tag{34}$$

$$0 \leq \overline{\mu}_\ell \perp K_\ell - \sum_{n \in \mathcal{N}} H_{\ell,n} v_n \geq 0\ ,\ \forall \ell \tag{35}$$

$$0 \leq \underline{\mu}_\ell \perp K_\ell + \sum_{n \in \mathcal{N}} H_{\ell,n} v_n \geq 0\ ,\ \forall \ell \tag{36}$$

$$S_n v_n = 0 \text{ with } \gamma_n \text{ u.r.s.}, \forall n \tag{37}$$

$$d_n - \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} g_{n,i,u} + \sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'} = 0 \text{ with } \lambda_n \text{ u.r.s.}, \forall n \tag{38}$$

$$\sum_{n \in \mathcal{N}} \sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'} = 0 \text{ with } \nu \text{ u.r.s.} \tag{39}$$

$$0 \leq \rho \perp \sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} \left(F - E_{n,i,u} \right) g_{n,i,u} \geq 0 \tag{40}$$

4.3 Upper-Level Problem and MPEC Formulation

A Stackelberg leader firm maximizes its profit subject to the lower-level problems in Section 4.2. Since all the lower-level problems in Section 4.2 are convex, they may be replaced by their KKT conditions in the leader's problem. Thus, we can recast the leader's problem as an MPEC by using the lower-level MLCP in Eqs. (31)–(40):

$$\underset{\Gamma \cup \Xi \cup \Psi}{\text{Maximize}} \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{U}_{n,s}} \Big(\lambda_n - \Big(C_{n,s,u} + \rho \left(E_{n,s,u} - F \right) \Big) \Big) g_{n,s,u} \tag{41}$$

$$\text{s.t. } g_{n,s,u} \leq G_{n,s,u} \left(\beta_{n,s,u} \right), \forall n, \forall u \in \mathcal{U}_{n,s} \tag{42}$$

$$\text{Eqs. (31)–(40)}$$

where $\Gamma = \{g_{n,s,u} \geq 0\}$, $\Xi = \{g_{n,j,u} \geq 0, d_n \geq 0, v_n\}$, and $\Psi = \{\beta_{n,j,u} \geq 0, \overline{\mu}_\ell \geq 0, \underline{\mu}_\ell \geq 0, \gamma_n, \lambda_n, \nu, \rho \geq 0\}$.

4.4 MILP Reformulation

The complementarity conditions in Eqs. (31)–(32), (34)–(36), and (40) can be converted to disjunctive constraints using sufficiently large constants (Fortuny-Amat and McCarl, 1981; Gabriel and Leuthold, 2010). Another computational difficulty is the bilinear terms, $\lambda_n g_{n,s,u}$ and $\rho \left(E_{n,s,u} - F \right) g_{n,s,u}$ in Eq. (41). We apply binary expansion to linearize those bilinear terms (Barroso et al., 2006; Gabriel and Leuthold, 2010). Taking discrete generation level k of strategic producer's unit $u \in \mathcal{U}_{n,i}$ located at node $n \in \mathcal{N}$, i.e., $\overline{G}_{n,s,u,k}$, we consider the following linearization.

$$y_{n,s,u,k} = \begin{cases} \lambda_n \overline{G}_{n,s,u,k} & \text{if } q_{n,s,u,k} = q_n^\lambda = 1 \\ 0 & \text{otherwise} \end{cases} \tag{43}$$

$$z_{n,s,u,k} = \begin{cases} -\rho \left(E_{n,s,u} - F\right) \overline{G}_{n,s,u,k} & \text{if } q_{n,s,u,k} = \underline{r} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{44}$$

If generation level $\overline{G}_{n,s,u,k}$ is selected and power price λ_n is positive, then we have the strategic generator's electricity sales revenue, $y_{n,s,u,k}$. Moreover, if generation level $\overline{G}_{n,s,u,k}$ is selected and the CO_2 allowance price ρ is positive, then we have strategic generator's CO_2 permit revenue (or cost), $z_{n,s,u,k}$. Our formulation is an extension of Gabriel and Leuthold (2010) in which one type of bilinear term was considered.

$$\underset{\Phi}{\text{Maximize}} \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{U}_{n,s}} \left(\sum_{k \in \mathcal{K}} y_{n,s,u,k} + \sum_{k \in \mathcal{K}} z_{n,s,u,k} - C_{n,s,u} g_{n,s,u} \right) \tag{45}$$

$$\text{s.t. } (33), (37), (38), (39)$$

$$0 \leq \lambda_n \leq M^\lambda q_n^\lambda, \ \forall n \tag{46}$$

$$g_{n,s,u} = \sum_{k \in \mathcal{K}} q_{n,s,u,k} \overline{G}_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s} \tag{47}$$

$$\sum_{k \in \mathcal{K}} q_{n,s,u,k} = 1, \ \forall n, \forall u \in \mathcal{U}_{n,s} \tag{48}$$

$$q^y_{n,s,u,k} \leq q_n^\lambda, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{49}$$

$$q^y_{n,s,u,k} \leq q_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{50}$$

$$q_{n,s,u,k} + q_n^\lambda - 1 \leq q^y_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{51}$$

$$y_{n,s,u,k} \leq \lambda_n \overline{G}_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{52}$$

$$0 \leq y_{n,s,u,k} \leq M^y q^y_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{53}$$

$$q^z_{n,s,u,k} \leq \underline{r}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{54}$$

$$q^z_{n,s,u,k} \leq q_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{55}$$

$$q_{n,s,u,k} + \underline{r} - 1 \leq q^z_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{56}$$

$$z_{n,s,u,k} \leq -\rho \left(E_{n,s,u} - F\right) \overline{G}_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{57}$$

$$0 \leq z_{n,s,u,k} \leq M^z q^z_{n,s,u,k}, \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{58}$$

$$0 \leq -D_n^{\text{int}} + D_n^{\text{slp}} d_n + \lambda_n \leq M r_n, \ \forall n \tag{59}$$

$$0 \leq d_n \leq M \left(1 - r_n\right), \ \forall n \tag{60}$$

$$0 \leq D_n^{\text{slp}} \sum_{u' \in \mathcal{U}_{n,j}} g_{n,j,u'} + C_{n,j,u} - \lambda_n + \beta_{n,j,u} \leq \overline{M} \overline{r}_{n,j,u}, \ \forall n, j, u \in \mathcal{U}_{n,j} \tag{61}$$

$$0 \leq g_{n,j,u} \leq \overline{M} \left(1 - \overline{r}_{n,j,u}\right), \ \forall n, j, u \in \mathcal{U}_{n,j} \tag{62}$$

$$0 \leq K_\ell - \sum_n H_{\ell,n} v_n \leq \hat{M} \hat{r}_\ell, \ \forall \ell \tag{63}$$

$$0 \leq \overline{\mu}_\ell \leq \hat{M} \left(1 - \hat{r}_\ell\right), \ \forall \ell \tag{64}$$

$$0 \leq K_\ell + \sum_n H_{\ell,n} v_n \leq \tilde{M} \tilde{r}_\ell, \ \forall \ell \tag{65}$$

$$0 \leq \underline{\mu}_\ell \leq \tilde{M}\left(1-\tilde{r}_\ell\right), \ \forall \ell \tag{66}$$

$$0 \leq -g_{n,j,u} + \overline{G}_{n,j,u} \leq \check{M}\check{r}_{n,j,u}, \ \forall n,\ j,\ u \in \mathcal{U}_{n,j} \tag{67}$$

$$0 \leq \beta_{n,j,u} \leq \check{M}\left(1-\check{r}_{n,j,u}\right), \ \forall n,\ j,\ u \in \mathcal{U}_{n,j} \tag{68}$$

$$0 \leq \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}}\left(F-E_{n,i,u}\right)g_{n,i,u} \leq \underline{M}(1-\underline{r}) \tag{69}$$

$$0 \leq \rho \leq \underline{Mr} \tag{70}$$

$$\underline{r} \in \{0,1\}; r_n \in \{0,1\}, \ \forall n; \overline{r}_{n,j,u} \in \{0,1\}, \check{r}_{n,j,u} \in \{0,1\}, \ \forall n,\ j,\ u \in \mathcal{U}_{n,j};$$
$$\hat{r}_\ell \in \{0,1\}, \ \tilde{r}_\ell \in \{0,1\} \ \forall \ell \tag{71}$$

$$q_n^\lambda \in \{0,1\} \ \forall n; q_{n,s,u,k} \in \{0,1\}, \ q^y_{n,s,u,k} \in [0,1]\,, \ q^z_{n,s,u,k} \in [0,1] \ \forall n, \forall u \in \mathcal{U}_{n,s}, \forall k \tag{72}$$

where we define:
$\Phi = \{d_n, g_{n,i,u}, v_n, \lambda_n, \nu, \overline{\mu}_\ell, \underline{\mu}_\ell, \beta_{n,j,u}, \gamma_n, \rho, \underline{r}, r_n, \overline{r}_{n,j,u}, \check{r}_{n,j,u}, \hat{r}_\ell, \tilde{r}_\ell, y_{n,s,u,k}, q_{n,s,u,k}, q_n^\lambda, q^y_{n,s,u,k}, q^z_{n,s,u,k}\}$.

4.5 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. (41) and the follower firms in Eq. (19) are respectively modified as follows:

$$\underset{\Gamma\cup\Xi\cup\Psi}{\text{Maximize}} \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,s}}\left(\lambda_n - C_{n,s,u}\right)g_{n,s,u} - \rho\sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,s}} E_{n,s,u}g_{n,s,u} \tag{73}$$

$$\underset{g_{n,j,u}\geq 0,\lambda_n}{\text{Maximize}} \sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}}\left(\lambda_n - C_{n,j,u}\right)g_{n,j,u} - \rho\sum_{n\in\mathcal{N}}\sum_{u\in\mathcal{U}_{n,j}} E_{n,j,u}g_{n,j,u} \tag{74}$$

The market-clearing condition for CO_2 allowances in Eq. (30) is also modified as follows:

$$0 \leq \rho \perp \overline{F} - \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{u\in\mathcal{U}_{n,i}} E_{n,i,u}g_{n,i,u} \geq 0 \tag{75}$$

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 removing Eq. (20) and maximizing Eq. (74) with respect to only $g_{n,j,u}$.

5 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. This setup is sufficiently generalized as it allows firms to own facilities and to compete across different locations. The information concerning demand is in Table 1. Table 2 summarizes the characteristics of those ten generating units, including their location, ownership, marginal cost, emission rate, and generating capacity. These parameters are obtained by solving a cost-minimization problem while subjecting each location to a fixed demand. The flows in the network are governed by Kirchhoff's laws with the information on thermal limits given in Table 3.

Table 1: Demand parameters

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

Table 2: Characteristics of generating units

Unit	Owner	Location	Marginal cost [$/MWh]	Emission rate [ton/MWh]	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 3: Transmission data

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

5.1 Policy Scenarios

We consider five scenarios in the analysis depending on the type of regulation, i.e., tradable mass-based or performance-based standard, and whether firms possess market power in either (both) the product or (and) tradable permit markets. We assume that a performance standard of 0.5 ton/MWh 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 starting point is a tradable performance-based standard with the leader-follower (or Stackelberg-type) market structure (Scenario E). This serves as a benchmark as its resulting total CO_2 emissions will be used as the emission cap in other scenarios. 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 be misleading. The remaining four scenarios include a Stackelberg mass-based standard (Scenario D), an oligopoly mass- and a performance-based standard (Scenarios B and

C, respectively), i.e., firms possess market power only in the product market and not in the tradable permit market, and the final scenario is a mass-based standard with perfect competition in both the product and permit market (Scenario A). While Scenarios D and E are MPECs (and, thus, require reformulation as MILPs as discussed in Section 4.4), Scenarios B and C are MLCPs, which can be directly tackled by the PATH solver. Finally, Scenario A can be represented as either a quadratic program or an MLCP. One note on solving Scenario C is that we iterate over the performance-based standard until the total emissions are equivalent to those under Scenario E. For the other scenarios, we directly impose the emission cap obtained from Scenario E.

5.2 Results

This section reports the main outcomes of our analyses. All the results are based on the models presented as in Section 4, 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 solve to optimality in the case of MILPs. The main results are discussed in Section 5.2.1 followed by a sensitivity analysis as well as firm-level results in Sections 5.2.2 and 5.2.3, respectively.

5.2.1 Base Case

Table 4 summarizes the main results of the analysis. 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 surplus, 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 4 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/MWh) 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. Finally, lower output and higher prices under the Stackelberg setting *vis-à-vis* the Cournot one are also established in Proposition 3.2.

Turning to welfare analysis, consistent with theory, perfect competition (Scenario A) leads to the highest social surplus. Due to the cross-subsidy by the performance-based

Table 4: Summary of results under the relatively dirty endowment

	Scenario				
	(A)	(B)	(C)	(D)	(E)
Sale-weighted price [$/MWh]	76.6	81.3	70.8	85.7	79.2
Permit price [$/ton]	73.2	40.9	109.7	39.4	120.7
Total CO_2 emissions [tons]	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 [$]	60,135.3	66,556.9	51,960.8	70,119.5	61,949.4
Total sales [MWh]	1,329.3	1,293.6	1,362.2	1,280.5	1,327.9
Producer surplus [$]					
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 [$/MWh]					
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

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 (Tirole, 1988; Gibbons, 1992). 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.

While the performance-based standard is essentially revenue neutral due to cross-subsidy by default, this is not necessarily the case for the mass-based standard; rather, it depends on how the proceeds from permit auctions are distributed among the entities. Thus, directly contrasting producer surplus between performance- and mass-based standards could actually be misleading. In our analysis, when the proceeds from the permit auctions under the mass-based standard are returned to the producers, producer surplus under the mass-based standard will outperform that of the performance-based standards.[5] Otherwise, producer surplus will be lower under the mass-based standards as the economic rent from tradable permits is retained by the government.

[5]To see this, we compute the *net* producer surplus assuming that economic rent from the mass-based permits is retained by the producers.

Turning to the ISO's revenue, to our surprise, we find that it is consistently higher under the performance-based standards (Scenarios C and E) by a sizable margin (25%-60%), suggesting that cross-subsidy *might* lead to more congestion. However, this causal relationship might be speculative at this moment, and further analyses will be needed to disentangle the effect. Finally, 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.

Focusing on locational outcomes, a comparison of Scenarios C and E in the bottom panel of Table 4 indicates that exercise of market power in the permit market under the performance-based standard by firm 1 (the leader) enables it to earn considerably more profit ($14,115-$10,831=$3,284) or 30% higher. Likewise, Scenarios D and E suggest that the leader (firm 1) under the performance standard could earn 26% higher profit ($14,115-$11,090=$3,025) than that of the mass-based standard. Concerning power prices, Table 4 also implies that under the performance-based standards (Scenarios C and E), there is a significant increase in power price differences among nodes. This also reflects on the increases in the ISO's revenue as alluded to earlier.

5.2.2 Sensitivity Analysis: a Leader with a Relatively Clean Endowment

One possible threat to our general conclusion in Section 5.2.1 is that the firms' incentives to manipulate the permit market are associated with the characteristics of their endowment, i.e., whether a leader's generating asset is clean or dirty relative to the performance standard. We investigate this conjecture by reducing the emission rate of unit 7 owned by the leader (firm 1) from 1.216 to 0.216 tons/MWh. This deliberate manipulation of the emission rate is intended to create an environment that would be in favor of the leader to manipulate the permit market. Table 5 summarizes the results of the sensitivity analysis with the same layout as Table 4.

We bypass discussing the conclusions that are similar to those in Table 4 and focus on those that are different. 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).[6] 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 4. 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 4, the cross-subsidy effect on the power price dominates the market power effect, thereby resulting in a higher social welfare in Scenario E. The

[6]Had the leader of the market been allowed to "withhold" the permits, the company would likely withhold some permits and push the permit price above zero (Chen et al., 2006). Allowing for withholding the permits will undoubtedly enhance the market power of the leader. However, considering this under the current MILP reformulation is challenging as it would require discretizing the product of the permit price and withholding quantity. While the former is endogenously determined by the model, the latter variable could in principle be bounded by a rather large number.

Table 5: Summary of results under the relatively clean endowment

	Scenario				
	(A)	(B)	(C)	(D)	(E)
Sale-weighted price [$/MWh]	40.8	58.8	58.5	62.3	65.1
Permit price [$/ton]	2.6	0.9	0.9	0.0	19.8
Total CO_2 emissions [tons]	833.7	833.7	833.7	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 [$]	32,713.2	55,812.9	55,424.8	63,517.5	63,312.7
Total sales [MWh]	2,071.5	1,733.9	1,740.4	1,715.0	1,667.4
Producer surplus [$]					
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 [$/MWh]					
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

reverse relationship is prevalent in Table 5 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 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. Another way to understand this is to compare producer surplus when the proceedings from the permit auctions are entitled to the producers. As alluded to in Table 5, this *net* producer surplus under Scenario E ($63,312.7) is greater than that in Scenario B ($55,812.9), which suggests an economic advantage for the leader when its asset is relatively clean under the performance-based standard.

5.2.3 Firm-Level Outcomes

Table 6 reports output by generating units under the baseline or relatively dirty (left) and clean (right) endowment, respectively. Outcomes are also grouped vertically by three sections, corresponding to units owned by the three firms: firm 1 (2, 4, 7, 8, and 9), firm 2 (3 and 5), and firm 3 (1, 6, and 10).

The output is affected by a number of factors, including types of regulation (mass- or performance-based standards), competition or market structure, and endowment (dirty or clean), through changes in the permit and power prices. The higher permit prices under the relatively dirty endowment cases reduce firms' operations of relatively dirty units, 7, 8, and 9. In particular, among the five scenarios, units 7 and 8 are completely shut down while the unit 10 operates at only 5% of its capacity under Scenario D (or 10 MW).

One way to study the impacts of mass- and performance-based policies is to compare the changes in output while holding the market structure unchanged, i.e., comparing Scenarios C vs. B and Scenarios E vs. D, respectively. Those are marked in Table 6 as △CB and △ED by subtracting B and D from C and E, respectively. Overall, moving from a mass-based to a performance-based standard has a direct impact on those units whose emission rate is modestly higher than the policy rate of 0.5 tons/MWh. For a generating unit whose emission rate is greater than the policy rate under the performance-based standard, the amount of emission cost that needs to pay is in proportion to the difference of its emission rate relative to the policy rate, which is equal to $(E - E^{policy}) \times \rho^{CO_2}_{performance}$. In contrast, a unit's emission cost under a mass-based standard is the product of its emission rate and the permit price, $E \times \rho^{CO_2}_{mass}$. While the term $E - E^{policy}$ is smaller than E, $\rho^{CO_2}_{performance}$ is typically greater than $E \times \rho^{CO_2}_{mass}$. Overall, the impact on firms' operation decisions also depends on the power prices. On the one hand, a lower power price under the performance-based standard would likely make it economically less desirable to produce even when the incurred emission cost, $(E - E^{policy}) \times \rho^{CO_2}_{performance}$, is relatively low. This is the case under the "dirty" scenario as the output by the units 3 and 10 is reduced by 62 and 90 MW, respectively. On the other hand, however, when the two Scenarios, C and B, experience compatible power prices under the relatively "clean" case, it could actually encourage output production from units 3 and 10 under the performance-based standard. Consequently, their outputs increase by 23 and 1 MW, respectively.

A similar observation also emerges if comparing Scenarios E and D for units owned by firms 2 and 3 when the power prices are significant lower under the performance-based case than the mass-based case. For instance, unit 10 owned by firm 3 cuts its output by 51 and 21.6 MW, respectively, under the relatively dirty and clean scenarios, respectively. One interesting result is that under the relatively clean scenario, the leader (firm 1) suppresses the output from a relatively clean source, unit 7 (0.216 tons/MWh) under the performance-based standard in order to push the permit price to $19.8/ton from zero in the mass-based standard.[7] The higher permit price under a Stackelberg setting as opposed to a Cournot one is also consistent with Proposition 3.4. This strategy is more effective under the performance-based rather than the mass-based standards as the permit price crashes to zero in the latter case. Furthermore, a comparison between relatively dirty and clean scenarios shows that the lower permit price under the relatively clean case provides economic incentives for relatively dirty units, which otherwise will be shut down or produce less under the relatively dirty scenario, to produce more.

6 Conclusions

Considerable flexibility is given by the US Environmental Protection Agency to each state to achieve the state-specific performance standard under the federal CPP. Conventional wisdom believes there are two sets of tools available on the table: a tradable performance-based and a mass-based permit program. While both approaches intend to harness economic efficiency through trading either mass-based or performance-based credits, fundamentally these two types of programs are different in a number of ways. First,

[7]Such a cost-squeezing strategy is also reported elsewhere (Chen and Hobbs, 2005; Chen et al., 2006).

Table 6: Output by generating units under the relative dirty (left) and clean (right) scenarios

	Relatively Dirty Scenarios							Relatively Clean Scenarios						
Unit	(A)	(B)	(C)	(D)	(E)	△CB	△ED	(A)	(B)	(C)	(D)	(E)	△CB	△ED
2	200	200	200	200	200	0	0	200	200	200	200	200	0	0
4	150	150	150	150	150	0	0	150	150	150	150	150	0	0
7	0	0	0	0	0	0	0	400	0	225	270	220	225	-50
8	0	0	0	0	0	0	0	0	0	19	40	70	19	30
9	0	0	0	10	0	0	-10	0	0	0	0	0	0	0
3	274	370	308	217	237	-62	20	218	370	393	272	266	23	-6
5	154	106	200	126	183	94	57	109	106	192	183	183	86	0
1	250	124	250	215	245	126	30	250	124	216	250	250	92	0
6	200	200	200	200	200	0	0	200	200	200	200	200	0	0
10	101	144	54	163	112	-90	-51	0	144	146	150	128	1	-22

the tradable performance-based standard is essentially revenue neutral as it involves a cross-subsidy from *relatively* high-emitting generators to *relatively* low-emitting generators. The standard effectively lowers the marginal cost of low-emitting generators through awarded tradable permits. On the other hand, the tradable mass-based standard increases the marginal cost of all generators in proportion to their emission rates. Depending on how the program is designed, the sizable economic rent associated with tradable permits under the mass-based standard (by auctions for example) can be re-distributed either to producers, consumers, or retained by the government for other purposes. The cross-subsidy under the performance-based standard would effectively subsidize low-emitting units, which are more likely at margin. This, in turn, will lower power prices, thereby encouraging more consumption as well as enhancing permit demand.

This paper studies 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. A stylized analytical model is developed to produce generalized conclusions, and a simulation-based model is used to evaluate policy efficiency while subjecting each scenario to a same level of total CO_2 emissions. For numerical simulations, depending on market structure, we follow Hobbs (2001) and Chen et al. (2006) in formulating the problem either as an MLCP or an MPEC. 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. While a Stackelberg firm might be more capable of manipulating the market under the performance-based standard, the impact on the power market is somehow attenuated by the cross-subsidy from high-emitting to low-emitting units through a lowering of the power prices. Interestingly, we find that 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.

Our paper contributes to the existing literature and current policy debates in a number of ways. First, we extend the previous work to allow for market power in a performance-based standard to be modeled explicitly and solved in a leader-follower framework. Second, also compared to other earlier work, we explicitly consider the physical transmission system that is essential in deciding substitution of power generation from technologies with different emission intensities when facing performance-based standards. Finally, on the policy side, we directly contribute to recent policy debates on tradable performance standards by comparing welfare under various relevant scenarios.

However, there are a number of unresolved issues that are also important in understanding the performance-based standard and deserve further attention. First, we limit our attention to a situation in which the market is subject to a single or uniform performance-based standard. In reality, a regional interconnected power market is composed of many states, and each could have a different policy type (i.e., performance-based or mass-based standard) or with a different rate requirement. Second, our analysis seemingly suggests that a performance-based standard might interact with the transmission network in a way that creates a greater spatial price divergence, thereby leading to a more congested network. Whether this observation is robust to different network topologies remains an open question and deserves further investigation. Overall, our analysis indicates that under some circumstances, a performance-based standard might be more vulnerable to imperfect competition. Its impact might be to some extent softened by the lower power prices due to cross-subsidy effects. Even with that, a regulatory agency still needs to be cautious when implementing these policies as the permits represent a sizable economic rent. Any transfer of this economic rent among entities under different types of standards will have significant distributional implications. Finally, we leave considerations concerning the aforementioned unresolved issues in a larger test network (Ruiz and Conejo, 2009) to future research.

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Appendix: Proofs of Propositions

Proof of Proposition 3.1

Noting the assumption that $E_i < F < E_j$, we have $a' = -\frac{(F-E_1)}{F-E_2} > 0$, and $b' = \frac{E_1-E_2}{F-E_2} > 0$. Recall also the assumption that $p' < 0, p'' \leq 0, c_i' > 0$, and $c_i'' \geq 0$. Let $m^*(g_1)$ denote the left-hand side of Eq. (8). We first calculate the derivative of $m^*(g_1)$:

$$\begin{aligned} m^{*\prime}(g_1) &= p'b' - c_1'' - (E_1 - F)f' \\ &= p'b' - c_1'' - \frac{(E_1 - F)}{E_2 - F}\Big(p'b' - c_2''a'\Big) \\ &< 0. \end{aligned} \tag{76}$$

Thus, $m^*(g_1)$ is strictly decreasing, and g_1^*, which is a solution to $m^*(g_1) = 0$ (or Eq. (8)), is unique if an interior solution exists. Next, let $m^c(g_1)$ denote the left-hand-side of Eq. (13) and calculate the derivative as follows:

$$\begin{aligned} m^{c\prime}(g_1) &= p'b' + p' + g_1 p''b' - c_1'' - (E_1 - F)h' \\ &= p'b' + p' + g_1 p''b' - c_1'' - \frac{(E_1 - F)}{E_2 - F}\Big(p'b' + ap''b' + p'a' - c_2''a'\Big) \\ &< 0. \end{aligned} \tag{77}$$

Hence, $m^c(g_1)$ is strictly decreasing, and g_1^c, which is a solution for $m^c(g_1) = 0$ (or Eq.(13)), is unique if an interior solution exists. We now compare g_1^* and g_1^c by calculating the following:

$$\begin{aligned} m^c(g_1) - m^*(g_1) &= p'g_1 - (h - f)(E_1 - F) \\ &= p'g_1 - \frac{(E_1 - F)}{E_2 - F}ap' \\ &< 0. \end{aligned} \tag{78}$$

Since $m^c(g_1) < m^*(g_1)$, we obtain $g_1^c < g_1^*$. We then compare g_1^c and g_1^s with the assumption of interior solutions by calculating the following:

$$\begin{aligned} m^s(g_1) - m^c(g_1) &= g_1(b' - 1)p' - (E_1 - F)g_1 h' \\ &= -\frac{(E_1 - F)}{E_2 - F}\Big(p' + p'b' + ap''b' + p'a' - c_2''a'\Big)g_1 \\ &< 0. \end{aligned} \tag{79}$$

It follows from $m^s(g_1) < m^c(g_1)$ that $g_1^s < g_1^c$ holds for any interior solutions. We, thus, obtain $g_1^s < g_1^c < g_1^*$. Since $a' > 0$, $g_2 = a(g_1)$ is strictly increasing. We, thus, have $g_2^s < g_2^c < g_2^*$. □

Proof of Proposition 3.2

It is straightforward from Proposition 3.1 that $g^s < g^c < g^*$. Since $p' < 0$, $p(g)$ is strictly decreasing. Hence, $p^s > p^c > p^*$ holds. □

Proof of Proposition 3.3

From Eq. (3), $e = E_1 g_1 + E_2 g_2 = Fg$. Hence, e, which is a function of g, is strictly increasing since $e' = F > 0$. It follows from this and Proposition 3.2 that $e^s < e^c < e^*$. □

Proof of Proposition 3.4

We compare ρ^s and ρ^c by calculating the following:

$$\begin{aligned} \rho^s - \rho^c &= h(g_1^s) - h(g_1^c) \\ &= \frac{1}{E_2 - F}\Big\{\Big(p(g^s) - p(g^c)\Big) - \Big(c_2'(g_2^s) - c_2'(g_2^c)\Big) + \Big(p'(g^s)g_2^s - p'(g^c)g_2^c\Big)\Big\}. \end{aligned} \tag{80}$$

From Proposition 3.2, $p(g^s) - p(g^c) > 0$. It follows from the assumption $c_i'' \geq 0$ and Proposition 3.1 that $c_2'(g_2^s) - c_2'(g_2^c) \leq 0$. From the assumption $p'' \leq 0$ and Proposition 3.2, we have $p'(g^s) - p'(g^c) \geq 0$. Assuming an interior solution $g_2^s > 0$, this inequality can be further rearranged as follows:

$$p'(g^s)g_2^s - p'(g^c)g_2^s \geq 0 \tag{81}$$

$$p'(g^s)g_2^s - p'(g^c)g_2^c \geq p'(g^c)(g_2^s - g_2^c) > 0. \tag{82}$$

The last inequality in (82) follows from the assumption $p' < 0$ and Proposition 3.1. The terms in the curly bracket in (80) are consequently positive and the sign of $\rho^s - \rho^c$ depends on that of $E_2 - F$. Therefore, if $E_1 < F < E_2$, then $\rho^s > \rho^c$. If $E_1 > F > E_2$, we have $\rho^s < \rho^c$. $\square$