Market Power with Tradable Performance-Based CO_2 Emissions Standards in the Electricity Sector

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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 standards when they are subject to imperfect competition. We limit our attention to (1) short-run analyses so that investment in new capacity is not allowed and (2) a situation in which all states are subject to the same type of standard. We show that while the cross-subsidy inherent in the performance-based standard might effectively reduce power prices, it could also inflate energy consumption, thereby rendering permits scarce. A dominant firm with a relatively clean endowment under the performance-based standard would be able to manipulate the electricity market as well as to elevate 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.

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

1 Introduction

While market-based policy is a generic label for various types of environmental standards that take advantage of incentives in polluting industries, it typically 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 or C&T) regulates the pollution quantity, in which a regulatory body first allocates property rights of emitting pollutions, i.e., permits or

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allowances, to affected facilities by either auctioning, grandfathering, technology- or fuel-based updating or other approaches. 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 Clean Air Act (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 market-based approaches on the grounds of economic efficiency. 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 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 U.S. federal Clean Power Plan (CPP) brings a new dimension.

CPP was 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 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. The performance-based standard essentially is an *intensity* standard, which limits the average emission rate allowed for a system, a market or a state. The tradable performance-based credits under the CPP are called emission rate credits (ERCs) with a physical unit of \$/MWh. Each generating unit owned by a firm when subject to the policy might incur an emission cost or earn an emission revenue. In particular, given a state-level 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 $\frac{E^{policy}-E}{E^{policy}}$ amount of ERCs credits, 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]

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

[1] Another example of performance-based standard is the RPS with RECs. Under a RPS, a renewable producer maximizes its profit function $pq_r - C_r(q_r) + (1-\alpha)p^{REC}q_r$, where p, q_r, C_r, α, and p^{REC} indicate the power price, renewable output, renewable cost, the percentage requirement under the RPS policy and the REC price, respectively. Given that $\alpha < 1$, the term $(1-\alpha)p^{REC}q_r$ represents a profit for renewable firms. For a fossil unit, its profit function is given by $pq_f - C_f(q_f) - \alpha p^{REC}q_f$. Thus, the term, $\alpha p^{REC}q_f$, represents a cost incurred in order to comply with RPS policy.

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 lowers its production cost, thereby making the generator more competitive.[2] As such units are the typically price-setting marginal units during peak periods, the policy would likely lower the power price, thereby inflating energy consumption in those periods (Bushnell et al., 2014).

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 distribution of economic rent or welfare analysis also 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.[3] 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. We focus on a short-run analysis within the partial equilibrium framework so that investment in new generation by existing firms, new entry and interactions with other sectors are not considered. Moreover, while states are allowed to decide their choice of instruments under the CPP, we assume in our analysis that states opt for the same instrument, either performance- or mass-based policy, and are subject to a regional permit trading agreement. Currently, the enforcement of the plan is halted by Supreme Court until a lower court rules in the lawsuit against the plan (Hurley and Volcovici, 2016). President Trump also signed an executive order on March 28, 2017 mandating the EPA to review the plan (Davenport and Rubin, 2017). While the nation remains divided with regard to the CPP, states within a regional electricity market will have an economic incentive to form an alliance, such as the Regional Greenhouse Gas Initiative, by subjecting themselves to a regional emission trading program with either a performance- or a mass-based standard in order to lower their compliance cost, see, for example, Southwest Power Pool (Herman, 2015). Moreover, strategic choice of instruments under the CPP is studied by Bushnell

[2]Under a mass-based standard or C&T, an alternative way of allocating pollution permits is based on an "output-updating" approach. Output-updating can be fuel specific, so-called fuel-based updating. Supporters of this approach argue that it can help ease the transition to carbon regulation or mitigate emission leakage by allocating disproportionately more permits to relatively carbon-intensive producers (Bushnell and Chen, 2012). Although fuel-based updating is similar to the performance-based standard insofar as it treats technologies differently based on their emission intensities, fundamentally, the two approaches have contrasting implications for revenue. In particular, while the fuel-based updating is effectively a fuel-specific "subsidy," facilities with emission rates higher than the performance rate still need to pay for their emissions under the performance-based standard.

[3]Of course, how the permits are allocated in a C&T program is often imbued with political consideration for balancing interests among various constituents. For example, most SO_2 permits under the US CAA Title IV program are allocated by grandfathering in order to ensure buy-in from industry (Stavins, 1998). The second phase of EU ETS distributed most of its allowances by auctions in fear of the possible windfall profits (Chen et al., 2008). More recently, Virginia's C&T relies on a combination of free permits based on historical generation and an output-updated approach. In particular, 95% of the permits is allocated initially to generators on an updating basis, and then the generators are required to consign those permits to be sold in an auction with revenues returned to the generators who got the allocation.

et al. (2014), who conclude that adoption of inefficient performance-based standards is a dominant strategy for states from both a consumer's and a generator's perspective.

The paper proceeds as follows. Stylized duopoly models considering a performance-based policy are developed to produce representative theories. However, welfare comparison is challenging due to differences in total CO_2 emissions. Therefore, 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 while holding total CO_2 emissions constant across scenarios.[4] Several scenarios are considered in the numerical examples, 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. The impact of the adopted policy is shaped by the nature of the portfolio of generation assets owned by this dominant firm, i.e., relatively clean or dirty. Consequently, our analysis could be used to frame policy measures for the PJM Interconnection or California, where the dominant producers are likely to have relatively dirty or clean portfolios, respectively.

Depending on market structure, we follow Hobbs (2001) and Chen et al. (2006) in formulating the problem as either a mixed linear complementarity problem (MLCP) or a mathematical program with equilibrium 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, to turn the problem into a mixed integer linear program (MILP) (Gabriel and Leuthold, 2010). 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.

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 under Stackelberg followed by Cournot and perfect competition, while the total emissions and output are in a reversed order. These findings are in contrast to the general observation that the outcomes of Stackelberg lie between the least-competitive Cournot and perfect competition scenarios when only a product market is considered.

Our numerical analysis bypasses explicitly accounting for damage caused by pollution in each scenario 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 find that while the cross-subsidy property of the performance-based standard effectively reduces power prices, its inflation of the energy consumption 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

[4]The approach explicitly accounts for the detailed physical system in the electricity sector, where the flow in the network follows Kirchhoff's laws, and has also been used in other studies, e.g., Egerer et al. (2016), Kunz et al. (2017), Perez et al. (2016), Mount et al. (2012), and Bertsch et al. (2017).

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 surplus compared to its mass-based counterpart. In both cases, the power price under the Stackelberg performance-based standard is higher when compared to that under oligopoly and perfect competition scenarios, thus, consistent with the findings from the analytical model even when the CO_2 is held constant in the numerical examples.

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 formulations of models that consider transmission grid and generating technologies are 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. All proofs and mathematical reformulations are in the appendices.

2 Literature Review

There is a rich body of research studying mass-based tradable permit markets under imperfect competition. Hahn (1984) theoretically studies the market power problem in a tradable permit system by using a dominant firm-competitive fringe model. He shows that a dominant firm inflates (suppresses) the permit price if it acts as a net seller (buyer) in the market. Market power vanishes when the permit allocation of the dominant firm is exactly equal to its demand. However, his model assumes market power only in the permit market without explicitly considering the output market.

Misiolek and Elder (1989) extend the market structure of Hahn (1984) to the output market and investigate the interaction with the permit market. They show that a single dominant firm manipulates the permit market in an effort to drive up the fringe firm's cost in the output market. Hahn's result of full permit allocation no longer holds when a dominant firm can manipulate both the permit and output markets. Sartzetakis (1997) and von der Fehr (1993) extend the model of Misiolek and Elder (1989) to incorporate Cournot competition and discuss the strategy of raising rivals' costs. Eshel (2005), Hintermann (2011), and Tanaka (2012) further investigate the incentive of a dominant firm to manipulate both the permit and output prices in order to raise profits, which could lead to significant inefficiencies. Hintermann (2017) provides empirical evidence for permit price manipulation by the ten largest electricity firms during phase 1 of the EU ETS.

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.[5] 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. A zero REC price would negate price impacts in the power market, thereby mitigating market power of the dominant

[5]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.

firm. However, they note that this could lead to 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. One exception is the paper by Boom et al. (2009) that compares the mass- and performance-based policy. They find that a performance-based policy with tradable permits leads to higher abatement cost and higher output compared to mass-based ones. Their more recent work, Boom et al. (2014), studies the long-run aspect of these two policies and concludes that with free entry-and-exit, a mass-based policy can generate the first-best outcome. Directly related to CPP, Bushnell et al. (2014) focus on states' incentives for adopting tradable performance- or mass-based standards. Their emphasis 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 U.S. Western electricity market also finds 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.

Similar to Bushnell et al. (2014), Fischer (2003a) also 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 U.S. electricity sector. While holding the rest of the U.S. 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 upper Midwest adopts some form of mass-based standard, the performance-based standard offers the rest of the U.S. 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 higher net carbon emissions as decreased emissions from high-carbon fuel production are 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, 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 welfare under various relevant cases. In particular, we demonstrate that comparisons between mass- and performance-based standards might not be 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 contrasting economic incentives under alternative 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. All proofs are in Appendix A.

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.[6] Total CO_2 emissions are expressed as $e = E_1 g_1 + E_2 g_2$. Let $p(g)$ denote the inverse demand function, in which $g = g_1 + g_2$. We assume $p' < 0$ and $p'' \leq 0$.

[6]This allows allowance trading to take place.

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

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

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, $\rho > 0$:

$$(F - E_1)g_1 + (F - E_2)g_2 = 0 \tag{2}$$

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:

$$\underset{g_i}{\text{Maximize}}\ p g_i - c_i(g_i) - \rho(E_i - F)g_i \tag{3}$$

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, the equilibrium conditions for perfect competition are (2) and the following:

$$p(g) - c_i'(g_i) - \rho(E_i - F) = 0,\ \ i = 1, 2 \tag{4}$$

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. (2) 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. (4) for $i = 2$ can be rearranged as follows:

$$\begin{aligned} \rho &= f(g_1) \\ &= \frac{1}{E_2 - F}\Big(p\big(b(g_1)\big) - c_2'\big(a(g_1)\big)\Big) \end{aligned} \tag{5}$$

Finally, substituting $b(g_1)$ and $f(g_1)$ into Eq. (4) for $i = 1$ yields:

$$p\big(b(g_1)\big) - c_1'(g_1) - f(g_1)(E_1 - F) = 0 \tag{6}$$

The equilibrium output g_1^* of firm 1 under perfect competition satisfies Eq. (6). We can, thus, characterize the equilibrium outcome for perfect competition using g_1^*, i.e., $\big\{g_1^*, g_2^* = a(g_1^*), g^* = b(g_1^*), \rho^* = f(g_1^*), p^* = p\big(b(g_1^*)\big), e^* = E_1 g_1^* + E_2 a(g_1^*)\big\}$.

3.3 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:

$$\underset{g_i}{\text{Maximize}}\ p(g) g_i - c_i(g_i) - \rho(E_i - F)g_i \tag{7}$$

Assuming interior solutions and along with the market clearing condition for allowances, the equilibrium conditions for Cournot duopoly are (2) and the following:

$$p(g) + p'(g)g_i - c_i'(g_i) - \rho(E_i - F) = 0, \ i = 1, 2 \tag{8}$$

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. (2) gives the same $g_2 = a(g_1)$ and $g = b(g_1)$ as before. Eq. (8) for $i = 2$ can be then rearranged as follows:

$$\begin{aligned}\rho &= h(g_1) \\ &= \frac{1}{E_2 - F}\Big(p\big(b(g_1)\big) + p'\big(b(g_1)\big)a(g_1) - c_2'\big(a(g_1)\big)\Big)\end{aligned} \tag{9}$$

Substituting $b(g_1)$ and $h(g_1)$ into Eq. (8) for $i = 1$ yields:

$$p\big(b(g_1)\big) + p'\big(b(g_1)\big)g_1 - c_1'(g_1) - h(g_1)(E_1 - F) = 0 \tag{10}$$

The equilibrium output, g_1^c, of firm 1 for Cournot duopoly satisfies Eq. (10). 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:

$$\underset{g_1 \cup \{g_2, \rho\}}{\text{Maximize}} \ p(g)g_1 - c_1(g_1) - \rho(E_1 - F)g_1 \tag{11a}$$

$$\text{s.t.} \ p(g) + p'(g)g_2 - c_2'(g_2) - \rho(E_2 - F) = 0 \tag{11b}$$

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

As in Section 3.3, we can obtain $g_2 = a(g_1), g = b(g_1)$, and $\rho = h(g_1)$ from Eqs. (11b)–(11c). Hence, the mathematical program with equilibrium constraints, (11a)–(11c), can be transformed into an unconstrained optimization problem:

$$\underset{g_1}{\text{Maximize}} \ p\big(b(g_1)\big)g_1 - c_1(g_1) - h(g_1)(E_1 - F)g_1 \tag{12}$$

Assuming interior solutions, the first-order necessary condition for (12) is:

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

The equilibrium output, g_1^s, of the Stackelberg leader satisfies Eq. (13). 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 its output. This is because the allowance price falls by decreasing its quantity demanded 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 highest 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 lowest 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.

4 Detailed Model Formulation

We use a market-equilibrium approach for a single representative time period[7] 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 six main 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 (f) 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) perfect competition with a performance-based policy, (c) Cournot oligopoly with a mass-based policy, (d) Cournot oligopoly with a performance-based policy, (e) Stackelberg (leader-follower) oligopoly with a mass-based policy, and (f) Stackelberg oligopoly with a performance-based policy. Two additional scenarios (g) and (h) are also conducted, respectively, for competitive and oligopoly competition with performance-based standard without constraining total emissions.

[7]While most permit markets have compliance periods that last longer than that of the operation of the power market, in reality, we also see permit price signals throughout the compliance period, not just by the end of compliance period. This implies that firms engage in permit trading based on their perceived supply-demand conditions of permits, which are affected by firms' strategies in the market; for example Downward (2010), who also studies the impact of energy policy based on a representative period.

As alluded to earlier, we follow Hobbs (2001) and Chen et al. (2006) in formulating the problem either as a mixed linear complementarity problem (MLCP) (Scenarios (a)–(d) and (g)–(h)) or a mathematical program with equilibrium constraints (MPEC) (Scenarios (e) and (f)). In Sections 4.1–4.2, we primarily show the formulation for Scenario (f), i.e., Stackelberg oligopoly with a performance-based policy. As discussed in Section 4.3, a Stackelberg oligopoly with a mass-based policy can be obtained by changing the environmental regulation. Scenarios (c) and (d), i.e., Cournot oligopoly with either a mass- or a performance-based policy, can be obtained from the lower-level problem in Section 4.1 without the upper-level problem in Section 4.2. Furthermore, we can derive Scenarios (a) and (b), i.e., perfect competition with a mass- and performance-based policy, by assuming that firms are price-takers instead of Cournot players.

4.1 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 B.

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. (14a), 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 $u \in \mathcal{U}_{n,j}$, where n' and u' are simply aliases for indices n and u, respectively. Our formulation is based on a standard direct current (DC) load-flow model in order to linearize loop flows in a power system resulting from Kirchhoff's laws, 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). 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 $-\sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'}$.[8] Those firms can affect the power price through their generation output *à la* Cournot, while they take other variables as given.

$$\begin{aligned}\underset{g_{n,j,u}\geq 0}{\text{Maximize}} \sum_{n\in\mathcal{N}} \sum_{u\in\mathcal{U}_{n,j}} \Bigg[D_n^{\text{int}} - D_n^{\text{slp}} \Bigg(\sum_{i\in\mathcal{I}} \sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} \Bigg) \\ - \Bigg(C_{n,j,u} + \rho \left(E_{n,j,u} - F \right) \Bigg) \Bigg] g_{n,j,u} \quad \text{(14a)}\end{aligned}$$

$$\text{s.t. } g_{n,j,u} \leq G_{n,j,u} \left(\beta_{n,j,u} \right), \forall n, \forall u \in \mathcal{U}_{n,j} \quad \text{(14b)}$$

Eq. (14a) states that each follower firm dispatches its plants across the network in order to maximize profit. The revenue depends on the nodal price, $\lambda_n = D_n^{\text{int}} - D_n^{\text{slp}} \left(\sum_{i\in\mathcal{I}} \sum_{u'\in\mathcal{U}_{n,i}} g_{n,i,u'} - \sum_{n'\in\mathcal{N}} B_{n,n'} v_{n'} \right)$, 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. Perfect competition instead of Cournot behavior can be implemented if

[8] The network transfer parameters depend on the incidences of lines and nodes along with the reactances and resistances of the lines. When each transmission line has equivalent physical properties, the flow is inversely proportional to transmission line's length.

the price in Eq. (14a) were simply replaced by λ_n, which is taken as a parameter by each follower firm. 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 $\rho\,(E_{n,j,u} - F)$ 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. (14b) 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. (15a) by deciding the consumption, d_n, and the voltage angle, v_n, as in Gabriel and Leuthold (2010) and Tanaka (2009) taking the output of generating firms as given:

$$\underset{d_n \geq 0, v_n}{\text{Maximize}} \sum_{n \in \mathcal{N}} \left(D_n^{\text{int}} d_n - \frac{1}{2} D_n^{\text{slp}} d_n^2 - \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} C_{n,i,u} g_{n,i,u} \right) \tag{15a}$$

$$\text{s.t.} \quad (\underline{\mu}_\ell) \; - K_\ell \leq \sum_{n \in \mathcal{N}} H_{\ell,n} v_n \leq K_\ell \; (\overline{\mu}_\ell), \; \forall \ell \tag{15b}$$

$$d_n - \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} g_{n,i,u} + \sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'} = 0 \; (\lambda_n), \; \forall n \tag{15c}$$

$$\sum_{n \in \mathcal{N}} \sum_{n' \in \mathcal{N}} B_{n,n'} v_{n'} = 0 \; (\nu) \tag{15d}$$

Eq. (15a) 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, $\sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} C_{n,i,u} g_{n,i,u}$. Eq. (15b) states that the transmission flow, $\sum_{n \in \mathcal{N}} H_{\ell,n} v_n$, cannot exceed line capacity of the line ℓ, K_ℓ.Eq. (15c) 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. (15d) is the total energy balance over all nodes to ensure that total generation matches total consumption 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:

$$0 \leq \rho \perp \sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} (F - E_{n,i,u})\, g_{n,i,u} \geq 0 \tag{16}$$

If the right-hand side of Eq. (16) 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. (14a)–(14b) and (15a)–(15d) are convex, they may be replaced by their KKT conditions (C-5)–(C-13) as in Appendix C. Consequently, the lower-level equilibrium may be characterized as the solution to an MLCP.

4.2 Upper-Level Problem and MPEC Formulation

A Stackelberg leader firm maximizes its profit subject to the lower-level problems in Section 4.1. Upon replacing the lower-level problems from Section 4.1 by their KKT conditions (Appendix C), we can recast the leader's problem as an MPEC by using the lower-level MLCP in Eqs. (C-5)–(C-13):

$$\underset{g_{n,s,u}\geq 0}{\text{Maximize}} \sum_{n\in\mathcal{N}} \sum_{u\in\mathcal{U}_{n,s}} \Bigg(\lambda_n - \Big(C_{n,s,u} + \rho\left(E_{n,s,u} - F\right)\Big)\Bigg) g_{n,s,u} \tag{17a}$$

$$\text{s.t. } g_{n,s,u} \leq G_{n,s,u}\left(\beta_{n,s,u}\right), \forall n, \forall u \in \mathcal{U}_{n,s} \tag{17b}$$

$$\text{Eqs. (C-5)–(C-13)}$$

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 $g_{n,s,u}$ through the conditions (C-5)–(C-13). In practice, such MPECs are solved via reformulation as MILPs in order to resolve non-linearities in both the objective function (17a), 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 KKT conditions (C-5)–(C-13), i.e., related to complementarity conditions of the form $0 \leq a \perp b \geq 0$. We provide the MILP reformulation in Appendix D.

4.3 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. (17a) and the follower firms in Eq. (14a) are modified by replacing $-\rho \sum_{n\in\mathcal{N}} \sum_{u\in\mathcal{U}_{n,i}} \left(E_{n,i,u} - F\right) g_{n,i,u}$ with $-\rho \sum_{n\in\mathcal{N}} \sum_{u\in\mathcal{U}_{n,i}} E_{n,i,u} g_{n,i,u}$. These changes imply that firms need to pay for their emissions regardless of their emissions rates. The market-clearing condition for CO_2 allowances in Eq. (16) is also modified as follows:

$$0 \leq \rho \perp \overline{F} - \sum_{n\in\mathcal{N}} \sum_{i\in\mathcal{I}} \sum_{u\in\mathcal{U}_{n,i}} E_{n,i,u} g_{n,i,u} \geq 0 \tag{18}$$

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 profit with respect to only $g_{n,j,u}$.

5 Numerical Examples

A representative 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. The data were previously used to examine carbon leakage under California climate change policy (Chen et al., 2011).[9] The outcomes of the numerical examples in this section will

[9] As our intention is to document a situation in which possession of market power by the leader under the performance-based standard could lead to a worse market outcome than that under the mass-based standard, we believe that the set of data we use is reasonable. A similar approach was used to illustrate a situation in which imposing a carbon tax might reverse transmission flow, thereby leading to more carbon emissions (Downward, 2010).

complement the more stylized results presented in Section 3. 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

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

Table 2: Characteristics of generating units

Unit	Firm	Node	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 3: Transmission data

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

5.1 Policy Scenarios

We consider eight scenarios (a)–(h) in the analysis depending on the type of regulation, i.e., tradable mass-based or performance-based standard, whether firms possess market power in either (both) the product or (and) tradable permit markets as well as if the total CO_2 emissions are constrained. Table 4 summarizes those scenarios. 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 starting point is a tradable performance-based standard with the leader-follower (or Stackelberg-type) market structure (Scenario (f)). The analysis first designates Firm 1, with a capacity share of more than 55%, as the leader in the market. We later assign the leader role to Firm 3, with a capacity share of 22%, to see if the firm can apply the same strategy to benefit from the markets. Scenario (f), performance-based standard with the leader-follower, 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 social surplus 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. The remaining seven scenarios include a Stackelberg mass-based standard (Scenario (e)), an oligopoly mass- and a performance-based standard (Scenarios (c) and (d), respectively), i.e., firms possess market power only in the product market and not in the tradable permit market, and two other scenarios are a mass- and performance-baed standard with perfect competition in both the product and permit market (Scenario (a) and (b), respectively). While Scenarios (e) and (f) are MPECs (and, thus, require reformulation as MILPs as discussed in Appendix D), Scenarios (c) and (d) are MLCPs, which can be directly tackled by the PATH solver. Moreover Scenarios (a) and (b) can be represented as either a quadratic program or an MLCP. One note on solving Scenarios (b) and (d) is that we iterate over the performance-based standard until the total emissions are equivalent to those under Scenario (f). For the other scenarios, we directly impose the emission cap obtained from Scenario (f). Finally, Scenarios (g) and (h) are, respectively, related to competitive and oligopoly markets with performance-based standards and without constraining CO_2 emissions to the level defined by Scenario (f).

Table 4: Summary of scenario assumptions

Scenario	Competition	Standard	Formulation	Power	Permits	Emissions
(a)	competitive	mass	QP/MLCP	×	×	same as (f)
(b)	competitive	performance	QP/MLCP	×	×	same as (f)
(c)	oligopoly	mass	MLCP	✓	×	same as (f)
(d)	oligopoly	performance	MLCP	✓	×	same as (f)
(e)	Stackelberg	mass	MPEC	✓	✓(leader)	same as (f)
(f)	Stackelberg	performance	MPEC	✓	✓(leader)	same as (f)
(g)	competitive	performance	QP/MLCP	×	×	not constrained
(h)	oligopoly	performance	MLCP	✓	×	not constrained

✓: market power is allowed

×: market power in not allowed.

5.2 Results

This section reports the outcomes of our analyses.[10] We first compare the results from Scenarios (g) and (h) to Scenario (f) to see if they are consistent with the findings in Section 3. The main results when total emissions are constrained at the level of Scenario (f) are discussed in Section 5.2.2 followed by the clean endowment cases, the firm-level breakdown, and a sensitivity analysis in Sections 5.2.3–5.2.5, respectively.

5.2.1 Comparison among Scenarios (f)–(h)

Table 5 gives the CO_2 emissions, power prices, and firms' output in Scenarios (f)–(h). The main conclusion from Section 3 is that (i) the power prices (sales) under the Stackelberg (f) should be higher (lower) than those under competitive (g) and oligopoly (h) scenarios, (ii) total CO_2 emissions from Stackelberg (f) should be the lowest followed by those under oligopoly (g) and competitive (h), as well as (iii) output by each firm should follow the same order among scenarios. Overall, Table 5 indicates that numerical results from the model in Section 4 are aligned with the conclusions in Section 3 in both (i) and (ii), while (iii) is valid only for Firm 2. A closer examination suggests that Firm 1, in Scenarios (f)–(h), operates its units 2 and 3 at their full capacity while completely shutting down high-emitting units 7-9, leading to an equal output. The solutions represent "corner solutions," which are different from our assumed interior solutions in Section 3. This suggests that considering the transmission grid and heterogeneous technologies with limited thermal capacity under a situation of more than two firms might lead to conclusions that deviate from the duopoly analysis.

Table 5: CO_2 emissions, power prices and firms' output in Scenarios (f)–(h)

Variables \ Scenarios	(g)	(h)	(f)
CO_2 emissions [t]	755.7	705.6	633.9
Sale-weighted price [$/MW]	61.0	69.5	79.2
Firm output [MW]			
1	350.0	350.0	350.0
2	650.0	523.4	420.0
3	511.3	537.9	557.0

5.2.2 Base Case

Table 6 summarizes the main results of the analysis. The columns from left to right correspond to Scenarios (a)–(f), 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, government revenue, and social surplus), and the lower panel details producer surplus by firms as well as

[10]Of course, making discretization at a finer scale would enhance the quality of the solutions but would be at expense of increasing the number of iterations and solution time required for convergence significantly. We, therefore, explore the trade-off between the discretization and solution time and decide to discretize the models at a 1 MW level as any smaller size increases the solution time considerably. Another noteworthy technical detail is the selection of parameter M. As alluded to in Gabriel and Leuthold (2010), M can be reasonably chosen based on the properties of the underlying physical system, e.g., generating capacity. In our analyses, we rely on the possible maximum levels of emissions, outputs, and power prices (D_n^{int}) to decide the values of parameter M.

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).

Table 6: Summary of results under the relatively dirty endowment

	Scenarios					
	(a)	(b)	(c)	(d)	(e)	(f)
Sale-weighted price [$/MW]	76.6	65.1	81.3	70.8	85.7	79.2
Permit price [$/t]	73.2	260.1	40.9	109.7	39.4	120.7
Total CO_2 emissions [t]	663.9	663.9	663.9	663.9	663.9	663.9
Consumer surplus [$]	73,745.5	86,463.0	68,733.8	79,775.4	61,897.0	69,251.9
Producer surplus [$]	11,547.2	43,683.1	39,396.5	51,960.8	43,949.4	61,949.4
ISO revenue [$]	8,034.0	10,023.2	6,187.1	9,758.5	8,589.2	10,486.6
Government revenue[a] [$]	48,588.1	0.0	27,160.4	0.0	26,170.1	0.0
Social surplus [$]	141,914.8	140,169	141,477.8	141,494.7	140,605.8	141,687.9
Net producer surplus[b] [$]	60,135.3	43683.1	66,556.9	51,960.8	70,119.5	61,949.4
Producer surplus [$]						
1	1,123.0	6,014.2	9317.8	10,831.5	11,190.6	14,115.4
2	0.0	3,768.9	11,615.9	13,484.6	10,409.5	14,962.0
3	10,424.2	33,900.0	18,462.8	27,644.7	22,349.3	32,872.0
Price [$/MW]						
A	80.7	68.9	85.8	75.3	95.8	87.5
B	52.8	41.0	61.1	44.8	57.6	47.8
C	86.2	96.7	80.4	92.4	76.7	84.7
Consumption [MW]						
A	904.4	977.2	873.3	937.9	811.7	862.4
B	233.9	302.1	185.8	280.0	205.9	263.0
C	191.0	112.1	234.5	144.3	262.9	202.4
Total [MW]	1,329.3	1,391.4	1,293.6	1,362.2	1,280.5	1,327.9

[a]: Government revenue (emission rent) = Permit price×Total CO_2 emissions

[b]: Net producer surplus = Producer surplus + Government revenue

Several observations emerge from Table 6 regarding the overall market-level outcomes. First, the sale-weighted power prices are lower among performance-based Scenarios, (b), (d), and (f), compared to their counterparts. For example, the sale-weighted power price under Scenario (f) is 7.5% (or $6.5/MW) lower than that of Scenario (e). 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 (bottom of Table 6) under the performance-based scenarios are generally higher when compared to those under their mass-based counterparts. To our surprise, the sale-weighted power price under Scenario (d), oligopoly with performance-based standard, is actually lower than that of Scenario (a) or perfect competition with mass-based standard by $8/MW. This suggests that the market power effect is offset by the cross-subsidy effect, leading to a lower power price under Scenario (d) compared to Scenario (a). Second, while theory suggests that market outcomes under the leader-follower Stackelberg setting will lie somewhere in between perfect competition and less-competitive Cournot outcomes, our results actually deviate from that ordering when constraining total emissions across scenarios (Tirole, 1988; Gibbons, 1992). Broadly consistent with Proposition 3.2 in Section 3, the sale-weighted price of Scenario (f), Stackelberg case, is highest among scenarios with performance-based standards, e.g., Scenarios (b), (d), and (f). Third, although with equal CO_2 emissions of 663.9 t, the resulting permit prices under the performance-based scenarios, (b), (d), and (f), are greater than those in Scenarios (a), (c), and (e), respectively. The cross-subsidy effect of the performance-based standard lowers power prices, inflates power sales, and elevates quantity demanded 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 surplus. Due to the cross-subsidy by the performance-based standards, the lower power prices also result in a higher consumer surplus when comparing Scenarios (b), (d), and (f) and to (a), (c), and (e), respectively. Table 6 indicates that producer surplus of Firm 1, the leader, is in general less than that of Firm 3 given that its capacity share is 55%. In fact, the profit that can be earned by a firm depends on power prices of where the power generated is sold as well as marginal costs of the units. The fact that Firm 1 has the largest capacity share does not necessarily imply that its producer surplus is higher than other firms'.

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. To see this, we compute the *net* producer surplus assuming that economic rent from the mass-based permits is retained by the producers. This is equivalent to assuming that the producers received the mass-based permits from government by grandfathering.[11] Otherwise, producer surplus will be lower under the mass-based standards as the economic rent from tradable permits is retained by the government. Of course, had the permits been given out by the government through a combination of grandfathering and auction, producer surplus could have been calculated accordingly.[12] Finally, the social surplus varies by about 1% across the six scenarios for the given set of data, implying that most impacts are associated with the distribution among ISO, producers, and consumers.

Turning to the ISO's revenue, to our surprise, we find that it is consistently higher under the performance-based standards, Scenarios (b), (d), and (f), 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 surplus, 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 (d) and (f) in the bottom panel of Table 6 indicates that exercise of market power in the permit market under

[11]This way of allocating permits is consistent with earlier C&T programs, e.g., SO_2 trading under the CAA (Clean Air Act) and first phase of the EU ETS. We are aware of the fact that more recent programs, e.g., RGGI and AB32 and later phases of the EU ETS, rely mostly on auctions to distribute permits.

[12]Our implicit assumption is that firms acquire permits sufficient only to cover their emissions but not to store extra permits for strategic use or in anticipation for future demand. Also, had the permits been grandfathered to producers, their incentives to manipulate the permit market might change, depending on their net position in the market. Analyzing permit banking, while interesting, would require a dynamic modeling approach, see for example, Chen and Tanaka (2018).

the performance-based standard by Firm 1 (the leader) enables it to earn considerably more profit ($14,115-$10,831=$3,284) or a 30% higher. Likewise, Scenarios (e) and (f) suggest that the leader (Firm 1) under the performance standard could earn 26% higher profit ($14,115- $11,090=$3,025) than under the mass-based standard. Concerning power prices, Table 6 also implies that under the performance-based standards, Scenarios (b), (d), and (f), there is a significant increase in power price differences among nodes. This is also reflected in the increases in the ISO's revenue as alluded to earlier.

5.2.3 Relatively Clean Endowment Case

One possible threat to our general conclusion in Section 5.2.2 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-based standard. In particular, the finding about the welfare-enhancing impact of the performance-based standard may hold for PJM, where the dominant producer is likely to have a coal-based portfolio. By contrast, the incentives of a dominant firm to withhold output with a relatively clean portfolio, e.g., as in California, may actually be enhanced under a performance-based 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 t/MW. This deliberate reduction of the emission rate is intended to create a situation that would favor the leader to manipulate the permit market. Table 7 summarizes the results of the sensitivity analysis with the same layout as Table 6.

Table 7: Summary of results under the relatively clean endowment

	Scenarios					
	(a)	(b)	(c)	(d)	(e)	(f)
Sale-weighted price [$/MW]	40.8	47.5	58.8	58.5	62.3	65.1
Permit price [$/t]	2.6	43.1	0.9	0.9	<u>0.0</u>	19.8
Total CO_2 emissions [t]	833.7	833.7	833.7	833.7	<u>830.6</u>	833.7
Consumer surplus [$]	131,963.0	121,273.0	100,706.0	101,286.0	92,313.0	88,501.2
Producer surplus [$]	30,578.7	42,470.2	55,038.1	55,424.8	61,382.5	63,312.7
ISO revenue [$]	1,604.7	834.7	3,869.9	3,869.9	5,169.8	5,844.8
Government revenue[a] [$]	2,134.5	0.0	774.8	0.0	0.0	0.0
Social surplus [$]	166,281.0	164,575.0	160,388.7	160,058.7	161,000.3	157,658.7
Net producer surplus[b] [$]	32,713.2	42,470.2	55,812.9	55,424.8	61,382.5	63,312.7
Producer surplus [$]						
1	7,480.8	18,972.2	18,153.4	18,285.4	20,438.6	21,868.9
2	11,760.8	8,946.6	17,432.4	17,562.3	17,827.2	17,295.0
3	11,337.1	14,548.3	19,452.3	19,577.1	23,116.7	24,148.8
Price [$/MW]						
A	55.5	52.1	67.3	66.9	81.1	82.1
B	37.7	44.8	46.6	46.2	47.8	47.8
C	19.8	39.6	48.2	47.9	38.5	44.1
Consumption [MW]						
A	1059.2	1,080.0	986.9	988.9	902.0	895.9
B	321.6	280.0	269.8	271.7	263.0	263.0
C	690.7	542.3	477.2	479.7	550.0	508.4
Total [MW]	2,071.5	1,902.3	1,733.9	1,740.3	1,715.0	1,667.3

[a]: Government revenue (emission rent) = Permit price×Total CO_2 emissions

[b]: Net producer surplus = Producer surplus + Government revenue

We bypass discussing the conclusions that are similar to those in Table 6 and focus on those that are different. First, lowering the emission rate of Unit 7 directly suppresses the quantity of permits demanded and reduces permit prices across all scenarios. The permit price under Scenario (e) (Stackelberg leader-follower setting with the mass-based standard) even crashes to zero, meaning that Scenario (e)'s total emissions (830.6 t) are below the cap set by Scenario (f) (833.7 t).[13] This observation might suggest 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 surplus between Scenarios (e) and (f) is reversed in contrast to Table 6. In particular, the inflation of power consumption due to the cross-subsidy under the performance-based standard (f) creates permit scarcity that would enable Firm 1 (now with a relatively clean portfolio) to manipulate the market more aggressively. This implies that in Table 6, the cross-subsidy effect on the power price dominates the market power effect, thereby resulting in a higher social surplus in Scenario (f). The reverse relationship is prevalent in Table 7 because the market can maintain the permit price, \$19.8/t compared to a zero permit price in mass-based standard in (e) and a marginally positive permit price in (c) and (d) to the extent such that the power price remains higher under Scenario (f) than that of (e), leading to a lower social surplus.

Another way to understand this outcome is to compare producer surplus when the proceedings from the permit auctions are granted to the producers in Tables 6 and 7. (In fact, with a zero permit price reported in Table 7, producer surplus will be equal to *net* producer surplus.) While the net producer surplus in Table 6 of Scenario (f) is less than that of Scenario (e), it is greater than Scenario (e) by \$1,930.2 (= 63,312.7-61,382.5) or 3% in Table 7, suggesting an economic advantage for the leader when its asset is relatively clean under the performance-based standard as withholding output achieves its twin objectives of increasing the power price and creating scarcity in the permit market. Overall, the increase in producer surplus is at the expense of consumers, as consumer surplus in Table 7 drops from \$92,313 in Scenario (e) to \$88,501 in (f). On the contrary, consumer surplus in Table 6 under Scenario (f) is greater than that in Scenario (e) by roughly \$7,355 (=69,251.9-61,897.0). Finally, the observation that the reported permit prices of Scenarios (c) and (d) in Table 7 are close to zero, i.e., \$0.9/t, implies that neither the performance- nor the mass-based standard has much impact on the market equilibrium. In other words, without any standard, the total emissions will be only slightly higher than 833.7 t. The fact that sale-weighted power price under Scenario (d) is only marginally lower than that of Scenario (c) is also intuitive as it implies that the subsidy effect is minimal.

5.2.4 Firm-Level Outcomes

Tables 8–9 report output by generating units under the baseline or relatively dirty and clean 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

[13]Had the leader of the market been allowed to "withhold" the permits, the firm 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.

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 operations of relatively dirty Units, 7, 8, and 9. In particular, among the five scenarios, Units 7 and 8 are completely shut down while Unit 9 operates at only 5% of its capacity under Scenario (e) (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 (d) vs. (c) and Scenarios (f) vs. (e), respectively. Those are marked in Tables 8–9 as "(d)-(c)" and "(f)-(e)" by subtracting (c) and (e) from (d) and (f), respectively. Generally, moving from a mass-based to a performance-based standard has a direct impact on those units whose emission rates are modestly higher than the policy rate of 0.5 t/MW. For a generating unit whose emission rate is greater than the policy rate under the performance-based standard, the emission cost that it needs to pay is in proportion to the difference between its emission rate and the policy rate, which is equal to $(E - E^{policy}) \times \rho^{CO_2}_{performance}$. By 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' operations 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. As alluded to in Table 8, this is the case under the "dirty" scenario as the output by Units 3 and 10 is reduced by 62 and 90 MW, respectively. On the other hand, however, when the two Scenarios, (c) and (d), experience compatible power prices under the relatively "clean" case, the impact is negligible for Units 3 and 10 under the performance-based standard with their outputs increasing by 0 and 1 MW, 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 t/MW), under the performance-based standard (reduced from 270 MW in (e) to 220 MW in (f)) in order to push the permit price to \$19.8/t in Scenario (f) from zero in the mass-based standard Scenario (e). Such a cost-squeezing strategy is also reported elsewhere (Chen and Hobbs, 2005; Chen et al., 2006). This strategy is more effective under the performance-based rather than the mass-based standard as the permit price crashes to zero in the latter case. Another interesting observation is the fact that Unit 9 produces zero MW even when the permit price under Scenario (e) is zero. A close examination shows that Firm 1 owns three units 7–9 at Node C among which Unit 9's marginal cost is the highest. Thus, when Firm 1 exercises market power by withholding its capacity in order to push up the power price in Node C, it prefers to reduce output from the most expensive unit, i.e., Unit 9. This is consistent with economic theory that firms would like to withhold output from those units that otherwise would be at the margin in the absence of market power. Furthermore, a comparison between relatively dirty and clean scenarios demonstrates 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.

5.2.5 Sensitivity Analysis

One interesting aspect to explore is whether a firm with a smaller capacity share, thus possessing less market power potential, will lead to a similar ranking of social surplus when

Table 8: Output in MW by generating units under the relatively dirty scenarios

Firm	Unit	Emission rate	(a)	(b)	(c)	(d)	(e)	(f)	(d)–(c)	(f)-(e)
1	2	0.545	200	200	200	200	200	200	0	0
1	4	0.500	150	150	150	150	150	150	0	0
1	7	1.216	0	0	0	0	0	0	0	0
1	8	1.249	0	0	0	0	0	0	0	0
1	9	1.171	0	0	0	0	10	0	0	-10
2	3	0.600	274	341	370	308	217	237	-62	20
2	5	0.500	154	200	106	200	126	183	94	57
3	1	0.580	250	250	124	250	215	245	126	30
3	6	0.000	200	200	200	200	200	200	0	0
3	10	0.924	101	0	144	54	163	112	-90	-51

Table 9: Output in MW by generating units under the relatively clean scenarios

Firm	Unit	Emission rate	(a)	(b)	(c)	(d)	(e)	(f)	(d)–(c)	(f)-(e)
1	2	0.545	200	200	200	200	200	200	0	0
1	4	0.500	150	150	150	150	150	150	0	0
1	7	0.216	400	400	234	225	270	220	-9	-50
1	8	1.249	0	0	8	19	40	70	11	30
1	9	1.171	0	0	0	0	0	0	0	0
2	3	0.600	218	450	393	393	272	266	0	-6
2	5	0.500	109	200	190	192	183	183	2	0
3	1	0.580	250	250	214	216	250	250	2	0
3	6	0.000	200	200	200	200	200	200	0	0
3	10	0.924	0	52.3	145	146	150	128	1	-22

it acts as a leader to manipulate the markets. That is, to what extent the cross-subsidy effect under the performance-based policy will be dominated by the market-power effect when the leader owns a relatively smaller market share. To investigate this, we run a set of alternative scenarios with Firm 3, who owns a capacity share of 22% and a zero-emission Unit 6, as a leader in the market. (We report herein the comparison of social welfare only as the discussions of other outcomes are repetitive.) When leader Firm 3 owns a relatively dirty portfolio, the effect of inflated consumption due to the cross-subsidy effect under the performance-based policy remains dominant, thereby leading to a higher social surplus of $142,018 under Scenario (f) compared to $140,728 under mass-based policy Scenario (e). Similar to the main analyses, we then reduce the emission rate of Unit 10 owned by Firm 3 from 0.924 to 0.5 t/MW to see if the cross-subsidy effect will be more than offset by the market-power effect when Firm 3 owns a relatively clean portfolio. However, the reversal of the social surplus order between Scenarios (f) and (e) compared to relatively *dirty* scenarios was not observed in this case. In particular, the social surplus under (f) is $151,429, which is still higher than $149,980 under Scenario (e). One possible explanation is that the ability of Firm 3 to exercise market power is greatly limited by its relatively smaller capacity share in contrast to Firm 1. Thus, the cross-subsidy effect remains dominant, which results in higher social surplus in Scenario (f) when compared to Scenario (e). Finally, even if we reduce the emission rate of Unit 10 to 0.25 t/MW so that the permit price under the performance-based Scenario (f) drops by 25% (diminishing the cross-subsidy effect), the cross-subsidy effect remains dominant, leading to a higher social surplus under Scenario (f) compared to that under Scenario (e). The equilibrium permit prices under Scenario (f) for emission rates of Unit 10 equal to 0.5 t/MW and 0.25 t/MW are \$53/t and \$39/t, respectively.

6 Conclusions

Considerable flexibility is given by the U.S. 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, 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 quantity demanded.

This paper studies the *short-run* 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 more realistic model implemented numerically is used to evaluate policy efficiency while subjecting each scenario to a same level of total CO_2 emissions. The numerical examples, depending on market structure, 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. We document in this paper an interesting finding 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.

Given that incumbent firms located in the PJM Interconnection with a sizable market share typically own coal-based facilities, the performance-based policies might less likely be subject to market power manipulation than what we described herein. On the other hand, given that leading utilities in California, e.g., PG&E, San Diego Gas & Electric, and Southern California Edison, own a significant amount of zero-emission renewables, the performance-based policies might be more likely out-performed by the traditional mass-based policy on the ground of market power. In this paper, rather than predicting market consequences, we document the possible counterintuitive market outcomes that *might* occur when the leader owns a relatively clean portfolio and is subject to the performance-based policy. Of course, different capacity mixes with different emission rates might alter the outcomes. However, we believe our numerical example is reasonable because 1) our intention is to illustrate the impacts of the format of regulation, market structure, and leader's endowment on market outcomes, and 2) our numerical findings are also supported by analytical results in Section 3.

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. The interplay between the choice of instruments and regional electricity markets might either worsen or alleviate the possibility of emission leakage. 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. Third, our work is a short-run analysis with a fixed capital stock so that investment is not modeled. New capacity would likely diminish the economic rent that can be earned in the markets, thereby affecting the leader's economic incentives and strategies accordingly. Examining the effects of new entrants under the performance-based standards demands extending the current models to a dynamic setting. 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) or in a dynamic modeling framework to future research.

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