# Regulatory Jurisdiction and Policy Coordination: a Bi-Level Modeling Approach for Performance-Based Environmental Policy

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**Abstract**

This study discusses important aspects of policy modeling based on a leader-follower game of policymakers. We specifically investigate non-cooperation between policymakers and the jurisdictional scope of regulation via bi-level programming. Performance-based environmental policy under the Clean Power Plan (CPP) in the U.S. is chosen for our analysis. We argue that cooperation of policymakers is welfare enhancing. Somewhat counterintuitively, full coordination among policymakers renders performance-based environmental policy redundant. We also find that distinct state-by-state regulation yields higher social welfare than broader regional regulation. This is because power producers can participate in a single power market even under state-by-state environmental regulation and arbitrage away the $CO_2$ price differences by adjusting their generation across states. Numerical examples implemented for a stylized test network illustrate the theoretical findings.

Keywords: OR in environment and climate change, bi-level modeling, leader-follower game, power market, performance-based policy

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# 1 Introduction

In this paper, we discuss two relevant issues of policy modeling: non-cooperation between policymakers and the jurisdictional scope of regulation. As for the first issue, we are interested in how different degrees of coordination among policymakers affect the welfare outcome. In reality, cooperation between policymakers is often challenging to achieve because of institutional boundaries or conflicts between policymakers. For instance, the department of environment protection and the department of economic affairs in one country may have the same goal of improving social welfare but may not be able to cooperate fully with each other due to influence from respective advocacies and stakeholders with different or competing interests.[1] With regard to the second issue, our interest lies in how different jurisdictional coverage of regulation impacts social welfare. In practice, regulatory instruments range from state-by-state to regional coverage (Ross and Murray, 2016). We contrast localized state-by-state regulation and system-wide regional regulation.

In contrast to much of the extant literature, we focus on policymakers with a hierarchical structure. One agency decides its policy variables as a first-mover and then another agency determines its policy variables as a follower. This is typical in environmental regulation, in which the environmental protection agency devises policy to comply with possibly international agreements on mitigating climate change. Subsequently, other agencies responsible for specific energy sectors craft measures given the environmental protection agency's decision. This hierarchical structure can be regarded as a leader-follower or a Stackelberg game (Stackelberg, 1952) and, hence, can be formulated as a bi-level programming problem (Bard, 1998; Dempe, 2002).[2]

A Stackelberg game among private firms has been extensively studied in the literature (Sherali et al., 1983; Sherali, 1984; DeMiguel and Xu, 2009; Chen et al., 2006, among many others). There is another strand of literature that examines a Stackelberg game between the regulator and firms (Jørgensen and Zaccour, 1999; Siddiqui et al., 2016; Chick et al., 2016). However, studies on a Stackelberg game among regulators or policymakers remain more limited compared to the torrent of literature on leader-follower competition among firms. The findings regarding cooperative behavior of policymakers are mixed. Some works are in favor of policy coordination to improve efficiency. Examples include a game between an environmental protection agency and a public utility commission (Baron, 1985), a pollution-control game between two sovereign governments or countries (Long, 1992), and a game between two countries for international tax policy (Aronsson

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[1] Landis (1960) provides several examples of separate regulatory agencies and lack of policy coordination in the U.S.

[2] In a usual Stackelberg game, leader and follower players (e.g., companies) have different objective functions. Our bi-level models in this paper somewhat differ from typical ones in that leader and follower policymakers have exactly the same form of objective function, viz., maximizing social welfare. Even if the objective functions are the same, policymakers can still face different constraints because of contrasting institutional roles and perspectives (e.g., environmental protection vs. power system operation).

and Johansson-Stenman, 2015). By contrast, several studies find that cooperation of policymakers is not necessarily superior to non-cooperation. Martimort (1999) argues that non-cooperation between multiple regulatory agencies in the government dominates policy integration when regulators have a limited ability to commit. Neck (1999) concludes that non-cooperative and cooperative outcomes are rather close to each other, by examining a game between a fiscal policymaker (government) and a monetary policymaker (central bank). Caplan and Silva (1999) demonstrate that when the local governments are Stackelberg leaders in setting pollution taxes, the outcomes are socially optimal, whereas it is not the case when the central government is the leader. The current paper adds to this mixed literature on leader-follower modeling of policymakers, specifically by focusing on jurisdictional coverage of environmental regulation.

Table 1: Mixed literature on cooperation of policymakers

| | |
|---|---|
| Studies that support policy coordination | This study, Baron (1985), Long (1992), Aronsson and Johansson-Stenman (2015) |
| Studies that favor non-cooperation | Martimort (1999), Neck (1999), Caplan and Silva (1999) |

Jurisdictional scope of regulation is usually related to spatial structure, i.e., an individual state or a broader region comprising states. For instance, tax and environmental standards can be set as state-by-state, regional, or national regulation. Jurisdictional coverage can be incorporated as regulatory constraints in our framework of the bi-level programming problems. For state-by-state regulation, multiple regulatory constraints corresponding to individual states are included in the model along with multiple regulatory decision variables. By contrast, for system-wide regional regulation, a single regulatory constraint across region is incorporated in the model along with a single regulatory decision variable. The results on regulatory jurisdiction are mixed in the literature. Stein (1971) argues that regional or national uniform regulation is superior to a patchwork of heterogenous state-by-state regulation when considering trade of goods or services in a broader market. In the context of tax policy, Levinson (2003) discusses that decentralized state-by-state regulation is less efficient than regional or national regulation under most pertinent real-world conditions. By contrast, Peltzman and Tideman (1972) argue against Stein (1971) and demonstrate that a nationally uniform pollution regulation is not a requirement for a socially efficient outcome. Oates and Schwab (1988, 1996) discuss that decentralized state-by-state regulation can yield a socially optimal outcome with capital mobility. The current paper aims to answer this question on regulatory jurisdiction in the context of environment regulation.

Specifically, our study is motivated by performance-based environmental policy under the Clean Power Plan (CPP) introduced by the U.S. Environmental Protection Agency

Table 2: Mixed literature on regulatory jurisdiction

| | |
|---|---|
| Studies that support system-wide regulation | Stein (1971), Levinson (2003) |
| Studies that favor state-by-state regulation | This study, Peltzman and Tideman (1972), Oates and Schwab (1988, 1996) |

(EPA) in 2015.[3] CPP aims to reduce carbon dioxide ($CO_2$) emissions from fossil-fueled power plants, which we detail in the next section. The case of performance-based policy under CPP would be one suitable example, in which we can model real-world policymakers, i.e., an environmental authority as an upper-level leader and an independent system operator (ISO) of the power system as a lower-level follower. Moreover, we can model real-world regulation from state-by-state or regional perspectives.

Focusing on performance-based environmental policy, this study contributes to the extant literature on both non-cooperative policymakers and regulatory jurisdiction. We develop a unified bi-level programming framework to analyze the efficiency outcomes of non-cooperation between/among policymakers when facing a regulatory problem that goes beyond one jurisdiction. Particularly, we re-cast the policymaker's bi-level problem as a mathematical program with equilibrium constraints (MPEC) and analyze it theoretically and numerically. This is in contrast to most existing studies that consider rather simple and stylized economic models to examine the interaction among regulators. We argue that integration of (or perfect coordination between/among) policymakers, i.e., the environmental protection agency and the ISO in this case, leads to improvement of social welfare. This finding may be intuitive, but we further obtain that as a result of full cooperation among policymakers, performance-based environmental policy becomes redundant, which eventually leads to a mass-based environmental policy. This outcome would be counterintuitive as performance-based environmental policy is no longer needed under coordinated policymakers. We also find that distinct state-by-state regulation yields higher social welfare than that under broader regional regulation under mild conditions (i.e., positive sales and positive $CO_2$ prices in equilibrium). Even under state-by-state environmental regulation, producers can participate in a single power market and arbitrage away the $CO_2$ price differences by adjusting their generation across states. Consequently, localized heterogenous regulation can be superior to system-wide homogenous regulation. The numerical examples implemented for a stylized test network illustrate the theoretical observations.

The rest of the paper is structured as follows. Section 2 provides a compact description of the performance-based environmental policy. Section 3 discusses the detail of leader-follower models from bi-level programming perspectives, while Section 4 presents the

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[3] For example, see `http://www.whitehouse.gov/the-press-office/2013/06/25/presidential-memorandum-power-sector-carbon-pollution-standards`.

theoretical findings. Section 5 implements the numerical examples. Section 6 concludes the paper.

## 2 Background of Performance-Based Environmental Policy

Policy combating climate change in the U.S. has been driven mainly by state or regional effort, such as the Regional Greenhouse Gas Initiative (RGGI) in the northeast and California AB 32. In 2015, the Clean Power Plan (CPP) was introduced by the U.S. Environmental Protection Agency (EPA) under the federal Clean Air Act to cut $CO_2$ emissions from existing fossil-fuel power plants by 32% below 2005 levels by 2030 (Burtraw et al., 2015).[4] CPP is a federal regulation that requires state-specific emissions limits/goals. Under CPP, the EPA has authority to establish a distinct emission rate standard of performance (intensity standard) for each state. At the same time, states are granted considerable flexibility for planning, implementing, and enforcing the program to attain the emissions target. States are allowed to form alliances to propose multi-state plans to average emission rates across states.

A "performance-based" policy under CPP stipulates an average emission rate with which each power producer needs to comply. A performance-based standard may be met by either reducing total emissions or increasing energy output, especially from low-emitting or non-emitting sources (Bushnell et al., 2017). Under the proposed rules of the EPA's CPP, power plants are allowed to purchase so-called emission rate credits (ERC) to cover their emissions. ERC is a tradable instrument representing the MWh of energy generated or saved from low-emitting units. In other words, ERCs are created to allow power plants to offset their actual emission rate to meet the state-level performance-based standard. By contrast, conventional mass-based policy, such as a cap-and-trade program, imposes a cap to limit the aggregate emissions from the whole power sector.

There is a growing interest in understanding efficiency properties of performance-based environmental policies. Holland et al. (2009) examine the properties of a performance-based carbon standard in the transportation sector, called the low-carbon fuel standard (LCFS). The study identifies the possibility that increases in emissions from ramping up output from low-carbon fuel can outweigh decreases in emissions from high-carbon fuel production, thereby leading to a net increase in emissions. A later study by Holland et al. (2015), also with a focus on LCFS, concludes that performance-based policy cannot be efficient due to the cross-subsidy effect, which is an implicit tax on technologies with a

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[4] At time of writing, the enforcement of the plan is halted by Supreme Court until a lower court rules in the lawsuit against the plan (Wolf, 2016). President Trump also signed an executive order on March 28, 2017 mandating the EPA to review the plan (Davenport and Rubin, 2017). Although CPP is faced with daunting challenges, its theoretical properties remain interesting to academic communities.

carbon intensity above the standard and a subsidy for technologies with a carbon rate below the standard. This is mainly because the efficiency principle, which would require any technology emitting carbon to be taxed but not subsidized, could not be satisfied.

On the other hand, Holland (2012) shows that a performance-based environmental policy can dominate a mass-based policy in the presence of emission leakage. This is because an implicit output subsidy to cleaner technologies could potentially mitigate leakage, which otherwise could have occurred under the mass-based policy. Using the Haiku Electricity Market Model of Resources for the Future (RFF), Palmer and Paul (2015) compare the performance-based trading standard and the mass-based policy. The analysis focuses on each policy's effectiveness, distributional consequences, administrative burden, and other environmental outcomes. They conclude that the efficiency and distributional outcomes are affected by the way tradable permits are allocated as well as the types of technologies that are covered by the program.

More recently, Bushnell et al. (2017) discuss that implementing state-by-state performance-based regulation results in an inefficient market outcome with varied abatement costs. The market may be efficient only when the carbon price is equal to the social cost of carbon and the performance standard is equal across all the states.[5] However they do not derive the socially optimal rates for state-by-state regulation, which we will explore in this paper. More recently, Abito et al. (2017) analyze inefficiencies stemming from regulating a global pollutant in separate markets for $CO_2$ compared to a single market. The paper highlights the fact that the inefficiencies associated with separate markets for $CO_2$ could be mitigated by the coordination of firms that own power plants across these markets and also participate in a single power market.

# 3 Mathematical Model

## 3.1 Conceptual Framework

We consider bi-level programming problems with a distinct decision maker at each level. The upper-level decision maker is an environmental authority, such as the EPA, who determines the environmental policy, for example, to combat climate change. On the other hand, the lower-level decision maker is a power system authority who runs the whole regional electricity market and operates the corresponding power grid given the environmental policy. One typical form of the lower-level decision maker is the independent system operator (ISO). Thus, this has the structure of a leader-follower game cast as a bi-level programming problem, which we detail in Subsections 3.4 and 3.5.

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[5] A similar finding is also concluded in Zhang et al. (2018) through a two-node analytical model. The paper also derives conditions under which the state-by-state performance-based policies will lead to a uniform price among states.

If the upper- and lower-level decision makers could be virtually integrated as one regulatory entity, the entire decision would be made in a single stage, leading to a usual one-level problem. This may not necessarily mean institutional integration but could be perfect coordination of policy decisions among different regulatory authorities. The integration or coordination of environmental and power system authorities may be difficult in reality because of legal, institutional, or political reasons, but it would serve as a benchmark for efficiency comparison. We will discuss this case in Subsection 3.7.

As for the jurisdictional scope of regulation, our focus is on two different concepts of performance-based environmental policies: state-by-state and regional policies.

State-by-state performance-based policy (SP):

- Distinct state-by-state regulation (more constraints in optimization and, hence, tighter regulation).
- Heterogeneous rates among states (more decision variables in optimization and more flexible regulation).

Regional performance-based policy (RP):

- System-wide regional regulation (fewer constraints in optimization and, hence, looser regulation).
- Single or homogeneous rate among states (fewer decision variables in optimization and, hence, less flexible regulation).

The environmental authority sets either heterogeneous rates under SP or a homogeneous rate under RP. RP can be also regarded as an alliance of different states to develop a multi-state plan for establishing a homogeneous regional emissions standard. The two different performance-based policies have different characteristics in terms of their associated optimization problems. It is not obvious which policy yields higher social welfare (i.e., optimal value). Therefore, we examine and compare those policies primarily from mathematical programming perspectives.

## 3.2 Basic Setup

We assume perfect competition in the power market. It is well known that the outcome of perfect competition can be expressed as a maximization problem of social welfare (e.g., Chao and Peck, 1996). We mainly examine social welfare maximization throughout this section.

Let $n, m \in \mathcal{N}$ and $i, j \in \mathcal{I}$ denote indices for nodes (states) and producers, respectively. There are $N$ nodes (states) and $I$ producers in the system. Let $g_{inm}$ denote a producer's output/sale, where producer $i$ generates power at node $n$ and sells it at node $m$ using transmission lines.[6] Since $CO_2$ emission rates of a producer and regulated $CO_2$ emission rates can vary among nodes, $g_{inm}$ and $g_{imn}$ are different decision variables and both can be positive. Gross consumer benefit from consuming power at node $m$ is expressed as the function, $b_m(\sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}} g_{inm})$, while $c_{in}(\sum_{m\in\mathcal{N}} g_{inm})$ is producer $i$'s cost function to generate power at node $n$. The social welfare function is expressed as follows:

$$sw(\boldsymbol{g}) = \sum_{m\in\mathcal{N}} b_m(\sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}} g_{inm}) - \sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}} c_{in}(\sum_{m\in\mathcal{N}} g_{inm}), \tag{1}$$

where $\boldsymbol{g}$ is a vector of output/sales in the system. We assume that $b_m$ is strictly concave and $c_{in}$ is strictly convex (e.g., Chao and Peck, 1996). Then, $sw$ is a strictly concave function in $\boldsymbol{g}$.

We next define the usual system constraints. A generation capacity constraint for producer $i$ that generates power at node $n$ is written as:

$$h_{in}(\boldsymbol{g}) = G_{in} - \sum_{m\in\mathcal{N}} g_{inm} \geq 0 \ (\beta_{in}), \ \forall i, \forall n, \tag{2}$$

where $G_{in}$ is maximum generation capacity of producer $i$ at node $n$. Let $\ell \in \mathcal{L}$, $K_\ell$, and $PTDF_{\ell n}$ denote, respectively, index of transmission lines, maximum transmission capacity of line $\ell$, and a power transfer distribution factor of $\ell$ that depends on the net injection at $n$.[7] The transmission capacity constraints of line $\ell$ are expressed as:

$$\bar{t}_\ell(\boldsymbol{g}) = K_\ell - \sum_{n\in\mathcal{N}}\Big[PTDF_{\ell n}\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{N}}(g_{inm} - g_{imn})\Big] \geq 0 \ (\bar{\mu}_\ell), \ \forall \ell, \tag{3}$$

$$\underline{t}_\ell(\boldsymbol{g}) = K_\ell + \sum_{n\in\mathcal{N}}\Big[PTDF_{\ell n}\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{N}}(g_{inm} - g_{imn})\Big] \geq 0 \ (\underline{\mu}_\ell), \ \forall \ell, \tag{4}$$

where $\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{N}}(g_{inm} - g_{imn})$ is the net injection at node $n$.[8] Note that $g_{inn}$ is generated and consumed at node $n$, and, hence, the amount of net injection is zero at that node. Because of the balance between supply and demand in the system, the total net injections over all nodes need to be zero as follows:

$$u(\boldsymbol{g}) = \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{N}}(g_{inm} - g_{imn}) = 0 \ (\theta). \tag{5}$$

The system constraints (2), (3), (4), and (5) are all linear in $\boldsymbol{g}$, where the lower-case Greek letters in parentheses denote dual variables.

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[6] We omit the index of individual power plants for brevity.

[7] As is customary in the electric power engineering literature, the power transfer distribution factor, or $PTDF_{\ell n}$, represents the increase in the power flow on line $\ell$ resulting from a unit increase in the net power injected at node $n$.

[8] This is based on so-called DC load flow. The theory of DC load flow is discussed in Schweppe et al. (2013) among others.

Finally, we present environmental regulation. Let $E_{in}$ and $f_m$, respectively, denote $CO_2$ emission rate of producer $i$ at node $n$ and regulated $CO_2$ emission rate at node $m$ under performance-based policy. State-by-state performance-based policy (or SP) can be expressed as follows:

$$r_m(\boldsymbol{g}, f_m) = \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} (f_m - E_{in})\, g_{inm} \geq 0 \ (\rho_m), \ \forall m, \tag{6}$$

where each node (state) $m$ has its own regulated rate $f_m$ as a sale (sink) node. Correspondingly, we have $N$ regulatory constraints as in Eq. (6), where $\sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} E_{in}g_{inm}$ is the mass of $CO_2$ emissions attributed to consumption at node $m$ and $f_m \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} g_{inm}$ are its regulated $CO_2$ emissions. By contrast, the regional performance-based policy (or RP) has a single or homogeneous rate among states, i.e., $f = f_1 = f_2 = \cdots = f_N$. Moreover, regulatory constraints in Eq. (6) are aggregated in a single regional constraint along with a single rate condition as follows:

$$r(\boldsymbol{g}, \boldsymbol{f}) = \sum_{m\in\mathcal{N}} r_m(\boldsymbol{g}, f_m) \geq 0 \ (\rho), \tag{7}$$

$$f_m = f_N \ (\phi_m), \ \forall m \neq N. \tag{8}$$

Eqs. (7) and (8) constitute $N$ constraints in total. On the other hand, a total emissions target $F$ is defined as follows:

$$e(\boldsymbol{g}) = F - \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{N}} E_{in}g_{inm} \geq 0 \ (\lambda). \tag{9}$$

$F$ can be regarded as an overall emissions target of the environmental policymaker such as the EPA under the federal Clean Air Act. The constraints associated with environmental regulation, (6), (7), (8), and (9), are all linear in $\boldsymbol{g}$.

## 3.3 Mass-Based Policy (MP)

Mass-based environmental policy such as a cap-and-trade system imposes a cap to limit the aggregate emissions from the whole power sector. The overall emissions target is exogenously set under the national law, e.g., the federal Clean Air Act. Mass-based policy (MP) can be typically expressed as maximization of social welfare subject to the fixed emissions target constraint (10b) and the power system constraints (10c)–(10f).

$$\text{MP: } \underset{\boldsymbol{g}\geq\boldsymbol{0}}{\text{Maximize}} \ sw(\boldsymbol{g}) \tag{10a}$$

$$\text{s.t. } e(\boldsymbol{g}) \geq 0 \ (\lambda), \tag{10b}$$

$$h_{in}(\boldsymbol{g}) \geq 0 \ (\beta_{in}), \ \forall i, \forall n, \tag{10c}$$

$$\bar{t}_\ell(\boldsymbol{g}) \geq 0 \ (\overline{\mu}_\ell), \ \forall \ell, \tag{10d}$$

$$\underline{t}_\ell(\boldsymbol{g}) \geq 0 \ (\underline{\mu}_\ell), \ \forall \ell, \tag{10e}$$

$$u(\boldsymbol{g}) = 0 \ (\theta). \tag{10f}$$

The solution to this maximization problem is equivalent to the outcome of a perfectly competitive electricity market under the fixed emissions target. Problem (10a)–(10f) is a single-level convex programming problem, and we derive the KKT conditions as follows:

$$\boldsymbol{0} \leq \boldsymbol{g} \perp \triangledown_{\boldsymbol{g}} sw(\boldsymbol{g}) + \lambda \triangledown_{\boldsymbol{g}} e(\boldsymbol{g}) + \triangledown_{\boldsymbol{g}} v(\boldsymbol{g}) \leq \boldsymbol{0} \tag{11a}$$

$$0 \leq \lambda \perp e(\boldsymbol{g}) \geq 0, \tag{11b}$$

$$0 \leq \beta_{in} \perp h_{in}(\boldsymbol{g}) \geq 0, \ \forall i, \forall n, \tag{11c}$$

$$0 \leq \overline{\mu}_\ell \perp \bar{t}_\ell(\boldsymbol{g}) \geq 0, \ \forall \ell, \tag{11d}$$

$$0 \leq \underline{\mu}_\ell \perp \underline{t}_\ell(\boldsymbol{g}) \geq 0, \ \forall \ell, \tag{11e}$$

$$u(\boldsymbol{g}) = 0 \text{ with } \theta \text{ u.r.s.}, \tag{11f}$$

where $\triangledown_{\boldsymbol{g}} v(\boldsymbol{g}) = \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} \beta_{in} \triangledown_{\boldsymbol{g}} h_{in}(\boldsymbol{g}) + \sum_{\ell \in \mathcal{L}} \Big( \overline{\mu}_\ell \triangledown_{\boldsymbol{g}} \bar{t}_\ell(\boldsymbol{g}) + \underline{\mu}_\ell \triangledown_{\boldsymbol{g}} \underline{t}_\ell(\boldsymbol{g}) \Big) + \theta \triangledown_{\boldsymbol{g}} u(\boldsymbol{g})$ and "u.r.s." denotes a variable that is unrestricted in sign.

## 3.4 State-by-State Performance-Based Policy (SP)

As mentioned in Subsection 3.1, we consider an environmental policymaker as an upper-level leader and an ISO as a lower-level follower. State-by-state performance-based policy can be represented by a bi-level optimization problem with heterogeneous rates $\boldsymbol{f}$ and distinct state-by-state regulation (6).

$$\text{SP:} \ \underset{\{\boldsymbol{f} \geq \boldsymbol{0}\} \cup \{\boldsymbol{g} \geq \boldsymbol{0}\}}{\text{Maximize}} \ sw(\boldsymbol{g}) \tag{12a}$$

$$\text{s.t. Eq. (10b)},$$

$$\underset{\boldsymbol{g} \geq \boldsymbol{0}}{\text{Maximize}} \ sw(\boldsymbol{g}) \tag{12b}$$

$$\text{s.t.} \ r_m(\boldsymbol{g}, f_m) \geq 0 \ (\rho_m), \ \forall m, \tag{12c}$$

$$\text{Eqs. (10c)–(10f)}.$$

Under SP, each state (node) is subject to an individually distinct performance-based policy. The lower-level problem (12b)–(12c) and (10c)–(10f) of the ISO yields the perfectly competitive outcome under SP. At the upper level, the environmental policymaker sets the optimal state-by-state rates $\boldsymbol{f} = (f_1, f_2, \ldots, f_N)^\top$ subject to the federal emissions target (10b) in addition to the lower-level problem that corresponds to the perfectly competitive outcome under SP. Note that SP is relatively flexible in that it includes $N$ decision variables regarding state-by-state rates $\boldsymbol{f}$. However, SP may result in relatively stringent regulation in that it includes $N$ state-by-state regulatory constraints as in Eq. (12c) corresponding to individual states. Those constraints are associated with a dual variable vector $\boldsymbol{\rho}$, i.e., possibly different $CO_2$ prices.

Since the lower-level problem is a convex programming problem, it may be replaced by its KKT conditions. Then the policymaker's bi-level problem may be re-cast as a mathematical program with equilibrium constraints (MPEC).

$$\text{SP}': \underset{\{\boldsymbol{f}\geq\mathbf{0}\}\cup\{\boldsymbol{g}\geq\mathbf{0}\}\cup\Psi}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{13a}$$

$$\text{s.t. Eq. (10b)},$$

$$\mathbf{0} \leq \boldsymbol{g} \perp \nabla_{\boldsymbol{g}} sw(\boldsymbol{g}) + \sum_{m\in\mathcal{N}} \rho_m \nabla_{\boldsymbol{g}}\, r_m(\boldsymbol{g}, f_m) + \nabla_{\boldsymbol{g}} v(\boldsymbol{g}) \leq \mathbf{0} \tag{13b}$$

$$0 \leq \rho_m \perp r_m(\boldsymbol{g}, f_m) \geq 0, \; \forall m, \tag{13c}$$

$$\text{Eqs. (11c)–(11f)},$$

where $\Psi = \left\{\boldsymbol{\rho}, \boldsymbol{\beta}, \overline{\boldsymbol{\mu}}, \underline{\boldsymbol{\mu}}, \theta\right\}$ is the set of dual variable vectors for the lower-level problem.

## 3.5 Regional Performance-Based Policy (RP)

Regional performance-based policy can be expressed by a bi-level optimization problem with a single (homogeneous) rate $f = f_1 = f_2 = \cdots = f_N$, i.e., (8), and regional regulation (7).

$$\text{RP}: \underset{\{\boldsymbol{f}\geq\mathbf{0}\}\cup\{\boldsymbol{g}\geq\mathbf{0}\}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{14a}$$

$$\text{s.t. Eq. (10b)},$$

$$\underset{\boldsymbol{g}\geq\mathbf{0}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{14b}$$

$$\text{s.t. } r(\boldsymbol{g}, \boldsymbol{f}) \geq 0 \; (\rho), \tag{14c}$$

$$f_m = f_N \; (\phi_m), \; \forall m \neq N, \tag{14d}$$

$$\text{Eqs. (10c)–(10f)}.$$

RP adopts aggregated regional regulation among all states. The lower-level problem (14b)–(14d) and (10c)–(10f) of the ISO yields the perfectly competitive outcome under RP. The environmental policymaker decides the homogeneous optimal rate $f$ at the upper level subject to the federal emissions target and the lower-level problem. As previously mentioned, this can be also regarded as an alliance of different states to develop a multi-state plan for averaging emissions rates in a region under a uniform standard. Note that RP is less flexible than SP in that RP virtually sets a single rate $f$ in a region. However, RP is milder than SP in terms of regulation since RP includes only a single regional regulatory constraint as in Eq. (14c) across all states. RP has a single dual variable, $\rho$, and, hence, a single $CO_2$ price.

The lower-level problem may be replaced by its KKT conditions since it is a convex programming problem as in SP. Noting that $\sum_{m \neq N \in \mathcal{N}} \phi_m \nabla_{\boldsymbol{g}} (f_m - f_N) = 0$, the policymaker's bi-level problem may be re-cast as an MPEC as follows:

$$\text{RP}': \underset{\{\boldsymbol{f} \geq \boldsymbol{0}\} \cup \{\boldsymbol{g} \geq \boldsymbol{0}\} \cup \Phi}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{15a}$$

$$\text{s.t. Eq. (10b)},$$

$$\boldsymbol{0} \leq \boldsymbol{g} \perp \nabla_{\boldsymbol{g}} sw(\boldsymbol{g}) + \rho \nabla_{\boldsymbol{g}} r(\boldsymbol{g}, \boldsymbol{f}) + \nabla_{\boldsymbol{g}} v(\boldsymbol{g}) \leq \boldsymbol{0} \tag{15b}$$

$$0 \leq \rho \perp r(\boldsymbol{g}, \boldsymbol{f}) \geq 0, \tag{15c}$$

$$f_m = f_N \text{ with } \phi_m \text{ u.r.s.}, \; \forall m \neq N, \tag{15d}$$

$$\text{Eqs. (11c)–(11f)},$$

where $\Phi = \left\{\rho, \boldsymbol{\phi}, \boldsymbol{\beta}, \overline{\boldsymbol{\mu}}, \underline{\boldsymbol{\mu}}, \theta\right\}$ is the set of dual variable vectors for the lower-level problem.

### 3.6 Restrictive SP (RSP)

A modified and restrictive state-by-state performance-based policy (RSP) is introduced for analytical purposes. We consider a single (homogeneous) rate in SP by adding Eq. (14d) to the lower-level problem. Thus, RSP is more restricted than SP.

$$\text{RSP}: \underset{\{\boldsymbol{f} \geq \boldsymbol{0}\} \cup \{\boldsymbol{g} \geq \boldsymbol{0}\}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{16a}$$

$$\text{s.t. Eq. (10b)},$$

$$\underset{\boldsymbol{g} \geq \boldsymbol{0}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{16b}$$

$$\text{s.t.} \; r_m(\boldsymbol{g}, f_m) \geq 0 \; (\rho_m), \; \forall m, \tag{16c}$$

$$f_m = f_N \; (\phi_m), \; \forall m \neq N, \tag{16d}$$

$$\text{Eqs. (10c)–(10f)}.$$

The environmental policymaker's bi-level problem may be re-written as follows:

$$\text{RSP}': \underset{\{\boldsymbol{f} \geq \boldsymbol{0}\} \cup \{\boldsymbol{g} \geq \boldsymbol{0}\} \cup \bar{\Psi}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{17a}$$

$$\text{s.t. Eq. (10b)},$$

$$\boldsymbol{0} \leq \boldsymbol{g} \perp \nabla_{\boldsymbol{g}} sw(\boldsymbol{g}) + \sum_{m \in \mathcal{N}} \rho_m \nabla_{\boldsymbol{g}} r_m(\boldsymbol{g}, f_m) + \nabla_{\boldsymbol{g}} v(\boldsymbol{g}) \leq \boldsymbol{0} \tag{17b}$$

$$0 \leq \rho_m \perp r_m(\boldsymbol{g}, f_m) \geq 0, \; \forall m, \tag{17c}$$

$$f_m = f_N \text{ with } \phi_m \text{ u.r.s.}, \; \forall m \neq N, \tag{17d}$$

$$\text{Eqs. (11c)–(11f)},$$

where $\bar{\Psi} = \left\{ \boldsymbol{\rho}, \boldsymbol{\phi}, \boldsymbol{\beta}, \overline{\boldsymbol{\mu}}, \underline{\boldsymbol{\mu}}, \theta \right\}$ is the set of dual variable vectors for the lower-level problem.

### 3.7 Performance-Based Policy under Integrated Decision Maker (ISP, IRP)

Now suppose that the upper- and lower-level decision makers could be virtually integrated as one regulatory entity. This may be regarded as perfect coordination among different decision makers. As alluded to before, it may be difficult to achieve integration or perfect cooperation due to possible legal, institutional, or political barriers in reality. Nevertheless, it would be worth examining this case for comparison. In this case, there is no leader or follower, and the entire set of decisions would be made in a single-level problem. SP under integrated decision maker (ISP) can be represented as a single-level convex programming problem as follows:

$$\begin{aligned} \text{ISP: } & \underset{\{\boldsymbol{f} \geq \mathbf{0}\} \cup \{\boldsymbol{g} \geq \mathbf{0}\}}{\text{Maximize}} \; sw(\boldsymbol{g}) \\ & \text{s.t. Eq. (10b),} \\ & \quad\;\;\; \text{Eq. (12c),} \\ & \quad\;\;\; \text{Eqs. (10c)–(10f).} \end{aligned} \tag{18}$$

In the same vein, RP under integrated decision maker (IRP) can be written as a single-level convex programming problem as follows:

$$\begin{aligned} \text{IRP: } & \underset{\{\boldsymbol{f} \geq \mathbf{0}\} \cup \{\boldsymbol{g} \geq \mathbf{0}\}}{\text{Maximize}} \; sw(\boldsymbol{g}) \\ & \text{s.t. Eq. (10b),} \\ & \quad\;\;\; \text{Eqs. (14c)–(14d),} \\ & \quad\;\;\; \text{Eqs. (10c)–(10f).} \end{aligned} \tag{19}$$

# 4 Analytical Results

## 4.1 State-by-State or Regional Policy?

We assume that there exist optimal solutions for the bi-level problems of SP, RP, and RSP. The superscripts MP, SP, RP, RSP, ISP, and IRP are used for optimal values of and optimal solutions to individual problems.

Specifically, our focus is to compare distinct state-by-state policy and system-wide regional policy in terms of social welfare, that is, $sw^{SP}$ and $sw^{RP}$. We begin by showing several related results. SP and RSP are identical except that RSP has additional constraints (16d). Hence, the following is obvious.

**Lemma 1** *Social welfare under state-by-state policy is greater than or equal to that under restrictive state-by-state policy, i.e.,* $sw^{SP} \geq sw^{RSP}$.

We next compare $sw^{RP}$ and $sw^{RSP}$. The only difference between RP and RSP is whether it is regional regulation or state-by-state regulation, i.e., (14c) or (16c). The regional constraint (14c) is constructed by aggregating all the individual constraints in (16c). Vectors $\boldsymbol{g}, \boldsymbol{f}$ that are feasible in (16c) are always feasible in (14c), whereas the reverse is not necessarily true. Thus, we have the following order for social welfare.

**Lemma 2** *Social welfare under regional policy is greater than or equal to that under restrictive state-by-state policy, i.e.,* $sw^{RP} \geq sw^{RSP}$.

Moreover, we can show the following property of SP and RSP for interior solutions.

**Proposition 1** *Assume interior solutions with positive outputs, i.e.,* $\boldsymbol{g} > \boldsymbol{0}$. *Then,* $CO_2$ *prices are equalized among all states, i.e.,* $\rho_1 = \rho_2 = \cdots = \rho_N$ *holds, for SP and RSP.*

**Proof of Proposition 1**

Take any arbitrary producers $i, j \in \mathcal{I}$ and any arbitrary nodes $n, m \in \mathcal{N}$. Assume interior solutions $g_{inn}, g_{inm}, g_{jnn}, g_{jnm} > 0$. From Eq. (13b) or Eq. (17b), we obtain the following conditions:

$$b'_n - c'_{in} - \beta_{in} + \rho_n \left(f_n - E_{in}\right) = 0 \quad \text{(w.r.t. } g_{inn}\text{)}, \tag{20a}$$

$$b'_m - c'_{in} - \beta_{in} - \sum_{\ell \in \mathcal{L}} \left(PTDF_{\ell n} - PTDF_{\ell m}\right)\left(\overline{\mu}_\ell - \underline{\mu}_\ell\right) + \rho_m \left(f_m - E_{in}\right) = 0 \quad \text{(w.r.t. } g_{inm}\text{)}, \tag{20b}$$

$$b'_n - c'_{jn} - \beta_{jn} + \rho_n \left(f_n - E_{jn}\right) = 0 \quad \text{(w.r.t. } g_{jnn}\text{)}, \tag{20c}$$

$$b'_m - c'_{jn} - \beta_{jn} - \sum_{\ell \in \mathcal{L}} \left(PTDF_{\ell n} - PTDF_{\ell m}\right)\left(\overline{\mu}_\ell - \underline{\mu}_\ell\right) + \rho_m \left(f_m - E_{jn}\right) = 0 \quad \text{(w.r.t. } g_{jnm}\text{)}. \tag{20d}$$

Subtract Eqs. (20b) and (20d) from Eqs. (20a) and (20c), respectively. Further subtracting one equation from another yields:

$$\left(\rho_n - \rho_m\right)\left(E_{in} - E_{jn}\right) = 0. \tag{21}$$

For any arbitrary $E_{in} \neq E_{jn}$, $\rho_n = \rho_m$. □

When SP or RSP has interior solutions $\boldsymbol{g} > \boldsymbol{0}$ as an optimal portfolio of generation output among nodes and producers, this implies a uniform dual variable regarding Eq. (12c) or Eq. (16c), i.e., the $CO_2$ price. Even under state-by-state environmental regulation, producers can participate in a single power market and adjust their generation across different states. Producers can arbitrage away the $CO_2$ price differences, thereby leading to a uniform $CO_2$ price across states. Note that SP is more flexible than RSP in setting the regulated $CO_2$ emissions rates among nodes, which leads to Lemma 1.

Using Proposition 1, the relationship between RP and RSP can be shown. We are interested in the case in which $CO_2$ prices are positive, i.e., performance-based policies are in effect.

**Proposition 2** *Assume interior solutions with positive outputs, i.e.,* $\boldsymbol{g} > \boldsymbol{0}$*. Also assume positive* $CO_2$ *prices, i.e.,* $\boldsymbol{\rho} > \boldsymbol{0}$*. Then, social welfare under regional policy is equal to that under restrictive state-by-state policy, i.e.,* $sw^{RP} = sw^{RSP}$*.*

**Proof of Proposition 2**

By construction, $\bigtriangledown_{\boldsymbol{g}} r(\boldsymbol{g}, \boldsymbol{f}) = \bigtriangledown_{\boldsymbol{g}} \sum_{m \in \mathcal{N}} r_m(\boldsymbol{g}, f_m) = \sum_{m \in \mathcal{N}} \bigtriangledown_{\boldsymbol{g}} r_m(\boldsymbol{g}, f_m)$. From Proposition 1, $\rho_1 = \rho_2 = \cdots = \rho_N$ holds for RSP, and we obtain $\sum_{m \in \mathcal{N}} \rho_m \bigtriangledown_{\boldsymbol{g}} r_m(\boldsymbol{g}, f_m) = \rho \sum_{m \in \mathcal{N}} \bigtriangledown_{\boldsymbol{g}} r_m(\boldsymbol{g}, f_m) = \rho \bigtriangledown_{\boldsymbol{g}} r(\boldsymbol{g}, \boldsymbol{f})$ for condition (17b) of RSP. Thus, assuming interior solutions $\boldsymbol{g} > \boldsymbol{0}$, we have an equivalent condition for (15b) of RP and (17b) of RSP:

$$\bigtriangledown_{\boldsymbol{g}} sw(\boldsymbol{g}) + \rho \bigtriangledown_{\boldsymbol{g}} r(\boldsymbol{g}, \boldsymbol{f}) + \bigtriangledown_{\boldsymbol{g}} v(\boldsymbol{g}) = \boldsymbol{0}. \tag{22}$$

Eq. (22) is a necessary and sufficient condition for the lower-level convex programming problems of RP and RSP. Given the same $\boldsymbol{f}$ in the upper-level problems, consider the same solutions $\boldsymbol{g}^*$ in the lower-level problems of RP and RSP that satisfy Eq. (22). Assuming $\boldsymbol{\rho} > \boldsymbol{0}$, $\boldsymbol{g}^*$ satisfy the binding condition $r_m(\boldsymbol{g}^*, f_m) = 0, \forall m$ in Eq. (17c) of RSP. $\boldsymbol{g}^*$ also satisfy the binding condition $r(\boldsymbol{g}^*, \boldsymbol{f}) = \sum_{m \in \mathcal{N}} r_m(\boldsymbol{g}^*, f_m) = 0$ in Eq. (15c) of RP. Eqs. (11c)–(11f) and Eq. (15d) (or Eq. (17d)) are common for RP and RSP. Thus, the lower-level problems of RP and RSP have the same solutions $\boldsymbol{g}^*$ and $sw(\boldsymbol{g}^*)$ given the same $\boldsymbol{f}$ in the upper-level problems. Noting that the upper-level problems of RP and RSP have Eq. (10b) in common, we find the same solutions $\boldsymbol{f}^*, \boldsymbol{g}^*$, which yield $sw^{RP} = sw^{RSP}$. □

Under the assumptions of $\boldsymbol{g} > \boldsymbol{0}$ and $\boldsymbol{\rho} > \boldsymbol{0}$, Proposition 2 implies that RP can be regarded as a variant of SP in which a single (homogeneous) rate is furthermore imposed. Now we can compare $sw^{SP}$ and $sw^{RP}$.

**Proposition 3** *Assume interior solutions with positive outputs, i.e.,* $\boldsymbol{g} > \boldsymbol{0}$*. Also assume positive* $CO_2$ *prices, i.e.,* $\boldsymbol{\rho} > \boldsymbol{0}$*. Then, social welfare under state-by-state policy is greater than or equal to that under regional policy, i.e.,* $sw^{SP} \geq sw^{RP}$*.*

**Proof of Proposition 3**

$sw^{SP} \geq sw^{RSP} = sw^{RP}$ follows from Lemma 1 and Proposition 2. □

If we assume positive values of an optimal portfolio of generation output among nodes and producers and if we assume positive $CO_2$ prices with effective performance-based policies, Proposition 3 implies that distinct state-by-state policy would outperform broader regional policy in terms of social welfare. As previously mentioned, SP is a relatively tight regulation in that it includes $N$ state-by-state regulatory constraints corresponding to individual states. However, as alluded to in Proposition 1, producers can participate in a single power market and arbitrage away the $CO_2$ price differences by adjusting their generation across states. As a result, social welfare can be higher under state-by-state policy than under regional policy.

In a similar way as in Propositions 1–3, it can be shown that $sw^{ISP} \geq sw^{IRP}$ holds under integrated decision maker if we assume $\boldsymbol{g} > \mathbf{0}$ and $\boldsymbol{\rho} > \mathbf{0}$. The only difference in this discussion is whether it is a bi-level or single-level programming problem, and we do not show the details to save space. Again, the result implies that distinct state-by-state policy would outperform system-wide regional policy under an integrated decision maker.

## 4.2 Individual or Integrated Decision Maker?

We here compare the models which have a different structure of decision makers. Particularly, our focus is on the different degree of integration between the upper-level environmental policymaker and the lower-level ISO.

**Proposition 4** *Integrated decision making yields greater or equal social welfare compared to unintegrated decision making under the state-by-state policy, i.e.,* $sw^{ISP} \geq sw^{SP}$.

**Proof of Proposition 4**

Define the optimal value function of the lower-level problem (12b)–(12c) and (10c)–(10f) of the ISO for given $\boldsymbol{f} \geq \mathbf{0}$ in SP as follows:

$$z^{SP}(\boldsymbol{f}) = \max_{\boldsymbol{g} \geq \mathbf{0}} \big\{ sw(\boldsymbol{g}) \mid \text{Eqs. (12c), (10c)–(10f)} \big\}. \tag{23}$$

Then, the bi-level problem of the environmental policymaker in SP can be restated as follows:

$$\text{SP}'': \underset{\{\boldsymbol{f} \geq \mathbf{0}\} \cup \{\boldsymbol{g} \geq \mathbf{0}\}}{\text{Maximize}} \; sw(\boldsymbol{g}) \tag{24a}$$

$$\begin{aligned} \text{s.t. } & \text{Eq. (10b)}, \\ & \text{Eq. (12c)}, \\ & \text{Eqs. (10c)–(10f)}, \\ & sw(\boldsymbol{g}) \geq z^{SP}(\boldsymbol{f}). \end{aligned} \tag{24b}$$

Eqs. (10b), (12c), (10c)–(10f), and (24b) along with the non-negativity constraints of $\boldsymbol{f}$ and $\boldsymbol{g}$ constitute the inducible region.[9] Since the inducible region of SP$''$ is a subset of the feasible region of ISP, $sw^{ISP} \geq sw^{SP}$ holds. $\square$

Eq. (24b) is added to the problem of the environmental policymaker since it is not optimal if $sw(\boldsymbol{g}) < z^{SP}(\boldsymbol{f})$. On the other hand, Eq. (23) implies $sw(\boldsymbol{g}) \leq z^{SP}(\boldsymbol{f})$ and hence, $sw(\boldsymbol{g}) = z^{SP}(\boldsymbol{f})$ eventually holds for Eq. (24b) at the optimal solutions. Eq. (24b) is the source of the possible difference in social welfare between SP and ISP. The economic implication behind this is that individual regulatory authorities cannot coordinate their decision of environmental policy $\boldsymbol{f}$ and power output $\boldsymbol{g}$ in a separated structure of leader-follower decision makers. It should be noted that even if the objective function $sw(\boldsymbol{g})$ is the same for both SP and ISP, SP may result in lower social welfare due to lack of harmonization between decision makers.

We have similar results for IRP and RP.

**Proposition 5** *Integrated decision making yields greater or equal social welfare compared to unintegrated decision making under regional policy, i.e.,* $sw^{IRP} \geq sw^{RP}$.

**Proof of Proposition 5**

Define the optimal value function of the lower-level problem (14b)–(14d) and (10c)–(10f) of the ISO for given $\boldsymbol{f} \geq \mathbf{0}$ in RP as follows:

$$z^{RP}(\boldsymbol{f}) = \max_{\boldsymbol{g}\geq\mathbf{0}}\left\{sw(\boldsymbol{g}) \mid \text{Eqs. (14c), (14d), (10c)–(10f)}\right\}. \tag{25}$$

Then, the bi-level problem of the environmental policymaker in RP can be rewritten as follows:

$$\begin{aligned}
\text{RP}'':\ \underset{\{\boldsymbol{f}\geq\mathbf{0}\}\cup\{\boldsymbol{g}\geq\mathbf{0}\}}{\text{Maximize}}\ & sw(\boldsymbol{g}) && \text{(26a)}\\
\text{s.t. } & \text{Eq. (10b)},\\
& \text{Eqs. (14c), (14d)},\\
& \text{Eqs. (10c)–(10f)},\\
& sw(\boldsymbol{g}) \geq z^{RP}(\boldsymbol{f}). && \text{(26b)}
\end{aligned}$$

Eqs. (10b), (14c), (14d), (10c)–(10f), and (26b) along with the non-negativity constraints of $\boldsymbol{f}$ and $\boldsymbol{g}$ constitute the inducible region. Since the inducible region of RP$''$ is a subset of the feasible region of IRP, $sw^{IRP} \geq sw^{RP}$ holds. $\square$

Given those results, we can assess the value of harmonization among regulatory authorities.

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[9] The inducible region represents the set over which the upper-level leader may optimize (Bard, 1998).

**Definition 1** *The "value of policy coordination" is defined as:*

$V^{SP} = sw^{ISP} - sw^{SP} \geq 0,$

$V^{RP} = sw^{IRP} - sw^{RP} \geq 0.$

The "value of policy coordination" provides a measure for social welfare improvement when regulatory authorities can harmonize their decision. However, as mentioned before, coordination of regulatory decision makers may be difficult in reality because of legal, institutional, or political reasons. In this situation, the value of policy coordination assesses the loss in social welfare due to disharmonization.

Finally, we compare ISP and IRP with MP.

**Proposition 6** *Integrated decision making yields the same social welfare under state-by-state and regional policies, which is equal to social welfare under the mass-based policy, i.e.,* $sw^{ISP} = sw^{IRP} = sw^{MP}$.

**Proof of Proposition 6**

ISP, IRP, and MP have the same objective function, $sw(\boldsymbol{g})$, in common. ISP includes the same constraints (10b)–(10f) of MP and furthermore additional constraints (12c) along with $\boldsymbol{f} \geq \boldsymbol{0}$. Thus, $sw^{ISP} \leq sw^{MP}$ holds. Choose sufficiently large $\boldsymbol{f} > \boldsymbol{0}$ such that

$$r_m(\boldsymbol{g}, f_m) = \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} (f_m - E_{in})\, g_{inm} > 0 \ (\rho_m), \ \forall m.$$

Then, ISP can be regarded as a problem in which non-binding constraints are added to MP. Hence, $sw^{ISP} = sw^{MP}$. Similarly, IRP includes the same constraints (10b)–(10f) of MP and furthermore additional constraints (14c)–(14d) along with $\boldsymbol{f} \geq \boldsymbol{0}$. Thus, $sw^{IRP} \leq sw^{MP}$ holds. Choose sufficiently large $\boldsymbol{f} > \boldsymbol{0}$ such that

$$r(\boldsymbol{g}, \boldsymbol{f}) = \sum_{m \in \mathcal{N}} \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} (f_m - E_{in})\, g_{inm} > 0 \ (\rho),$$
$$f_m = f_N \ (\phi_m), \ \forall m \neq N.$$

Then, IRP can be regarded as a problem in which non-binding constraints are added to MP. Hence, $sw^{ISP} = sw^{IRP} = sw^{MP}$. □

The usual independence of irrelevant (inactive) constraints in single-level problems can be applied to ISP and IRP. Thus, if the upper- and lower-level decision makers could be virtually integrated as one regulatory entity, the outcome of MP would be achieved, thereby making performance-based environmental policies redundant. This finding would be counterintuitive since performance-based environmental policy is no longer needed under the coordination of policymakers. Perfect cooperation of policymakers is welfare enhancing, and it may even make some policy unnecessary.

# 5 Numerical Case Study

## 5.1 Assumptions and Data

In order to illustrate the theoretical properties of the analytical results in Section 4 and to derive intuition about performance-based policies, we implement the models for a stylized test network comprising three states (nodes). Herein, we assume that each node represents a state that is subject to its environmental regulation. Each state includes producers and consumers along with interconnections with the other two states by a single transmission line with a transmission capacity limit and corresponding PTDF.

We consider three producers and ten generators (power plants). In addition to the basic setup in Subsection 3.2, an index $h$ for an individual generator is introduced for our case study since producers may possess multiple generators at different locations. Let $H_{in}$ denote the set of generators owned by producer $i$ at state $n$. We assume that producer $i$'s generator $h$ located at state $n$ is characterized by a linear marginal cost function:

$$B^0_{inh} + B^1_{inh} \sum_{m \in \mathcal{N}} g_{inhm}, \tag{27}$$

where $B^0_{inh}$ and $B^1_{inh}$ are the intercept and slope, respectively. A linear marginal cost is commonly used by power engineers and energy economists to represent the production cost of a power plant (Chao and Peck, 1996; Grigg et al., 1999). A linear marginal cost implies a quadratic cost function for each generator:

$$c_{inh}\Big(\sum_{m \in \mathcal{N}} g_{inhm}\Big) = B^0_{inh} \sum_{m \in \mathcal{N}} g_{inhm} + \frac{B^1_{inh}}{2}\Big(\sum_{m \in \mathcal{N}} g_{inhm}\Big)^2. \tag{28}$$

We use Eq. (28) when calculating the social welfare function (1). Table 3 summarizes the characteristics of the ten generators, including their marginal cost parameters, $CO_2$ emission rate, generating capacity, ownership, and location. The data were used previously to study emission leakage in a proposed emission trading program faced by the California government (Chen et al., 2011). In particular, state 1 is designed to resemble California's power system mainly comprising natural gas plants with a stable $CO_2$ emission rate around 0.55 ton/MWh. State 2 is characterized by hydropower with almost zero variable production cost and zero emissions, representing a northwest state. In contrast, state 3 represents a southwest state primarily consisting of coal plants with higher emissions but lower production costs.

Each state $m$ is characterized by consumer willingness to pay with a linear inverse demand function:

$$P^0_m - \frac{P^0_m}{Q^0_m} \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} \sum_{h \in H_{in}} g_{inhm}, \tag{29}$$

Table 3: Generation profile

| Generator $h$ | $B^0_{inh}$ [\$/MWh] | $B^1_{inh}$ [\$/MWh$^2$] | CO$_2$ rate [t/MWh] | Capacity [MW] | Producer $i$ (Owner) | State/Node $n$ |
|---|---|---|---|---|---|---|
| 1 | 38 | 0.02 | 0.58 | 250 | 3 | 1 |
| 2 | 35.72 | 0.03 | 0.545 | 200 | 1 | 1 |
| 3 | 36.8 | 0.04 | 0.6 | 450 | 2 | 1 |
| 4 | 15.52 | 0.01 | 0.5 | 150 | 1 | 2 |
| 5 | 16.2 | 0.02 | 0.5 | 200 | 2 | 2 |
| 6 | 0 | 0.001 | 0 | 200 | 3 | 2 |
| 7 | 17.6 | 0.02 | 1.216 | 400 | 1 | 3 |
| 8 | 16.64 | 0.01 | 1.249 | 400 | 1 | 3 |
| 9 | 19.4 | 0.01 | 1.171 | 450 | 1 | 3 |
| 10 | 18.6 | 0.02 | 0.924 | 200 | 3 | 3 |

where $P^0_m$ and $-\frac{P^0_m}{Q^0_m}$ are the intercept and slope, respectively. $P^0_m$ denotes the maximal willingness-to-pay for electricity. In other words, the quantity demanded drops to zero when the power price exceeds $P^0_m$. The slope or $-\frac{P^0_m}{Q^0_m}$ gives the decline in benefit when the quantity demand reduces by one MWh. This demand representation is also consistent with the extant literature (Green and Newbery, 1992; Hobbs, 2001). Letting $d_m = \sum_{i\in\mathcal{I}}\sum_{n\in\mathcal{N}}\sum_{h\in H_{in}} g_{inhm}$ denote consumption at state $m$, gross consumer benefit can be expressed as a quadratic function:

$$b_m(d_m) = P^0_m d_m + \frac{P^0_m}{2Q^0_m} d^2_m. \tag{30}$$

Eq. (30) is substituted in the social welfare function (1). The data regarding demand are shown in Table 4, which is also from Chen et al. (2011). State 1 has a high vertical intercept, i.e., maximal willingness-to-pay, and also a large horizontal intercept, corresponding to our assumption of high power demand as in California. By contrast, northwest state 2 and southwest state 3 exhibit moderate electricity demand.

Table 4: Demand profile

| State/Node $m$ | $P^0_m$ [\$/MWh] | $Q^0_m$ [MWh] |
|---|---|---|
| 1 | 228 | 1400 |
| 2 | 93.12 | 540 |
| 3 | 111.6 | 840 |

Transmission lines 1, 2, and 3 connect states 1–2, 2–3, and 1–3, respectively. We further assume that each line has the same same physical characteristics with the resulting PTDF reported in Table 5. $PTDF_{\ell n}$ in Table 5 represents the increase in the power flow on line $\ell$ resulting from a unit increase in the net power injected at state $n$ (Schweppe et al., 2013).[10] A network of three nodes is the simplest one that allows us consider the effect of looped-flows in a power market, which is an important and a crucial aspect of the power sector. A network where each line has the same characteristics is also commonly used in the existing literature to illustrate the numerical outcomes of simulation models (Chao and Peck, 1996; Hobbs, 2001).[11] As our purpose is to illustrate the outcomes of various types of policy designs in Section 4, we believe that using the current data does not impair our ability to generalize our findings to other situations. A transmission capacity limit is given in Table 6.

Table 5: $PTDF_{\ell n}$

| Line $\ell$ | State/Node $n$<br>1 | <br>2 | <br>3 |
|---|---|---|---|
| 1 | 0.3333 | -0.3333 | 0 |
| 2 | 0.3333 | 0.6667 | 0 |
| 3 | -0.6667 | -0.3333 | 0 |

Table 6: Transmission capacity

| Line $\ell$ | Capacity [MW] |
|---|---|
| 1 | 255 |
| 2 | 120 |
| 3 | 30 |

### 5.2 Scenarios and Models

Our analysis considers six scenarios, differing by types of policies, while subjecting all of them to the same aggregate level of $CO_2$ emissions. Our experiment design allows us to bypass the concern of defining a marginal damage function to quantify damage caused by different level of $CO_2$ emissions across scenarios when assessing welfare. We summarize each scenario and corresponding model as follows:

(a) RSP is introduced for analytical purposes by making SP more restricted (see also (c)). We solve problem (17) in Subsection 3.6.

(b) RP allows for *explicit* permit trading across all the states under system-wide regional regulation (14c). The resulting problem (15) in Subsection 3.5 is an MPEC solved by FilterMPEC via NEOS sever (neos-server.org).

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[10] State 3 is set as the hub node, which can be regarded as a reference bus.

[11] See Cheng and Overbye (2005) for discussions of how to find PTDF matrix of a smaller equivalent network based on congestion zones.

(c) Under distinct state-by-state regulation (12c), SP allows for *implicit* trading of permits taking place through power sales across all the states. The resulting problem (13) in Subsection 3.4 is also an MPEC solved using FilterMPEC. CPP in the U.S. is an example of distinct state-by-state regulation where implicit permit trading through the power sector provides a means for generating companies in individual state to comply with the regulation. However, the implementation of CPP is placed on hold by the Trump administration, and its "deregulatory" decision is currently challenged by a number of states in the court.[12]

The aforementioned cases are grouped as "non-cooperative" scenarios as the government indirectly affects the sector's output decisions through its determination of policy parameters, i.e., performance standard. We also perform three additional "cooperative" scenarios, which are formulated as single-level problems as the government fully coordinates both the policy parameters and output decisions of the polluting sector.

(d) ISP allows the government to have direct control over the state-by-state performance standard as well as the outputs by generators. The resulting problem (18) in Subsection 3.7 is a nonlinear problem (NLP) and can be solved using commercial solvers (e.g., MINOS).

(e) IRP allows the government to have direct control over the regional performance standard as well as the outputs by generators. The resulting problem (19) in Subsection 3.7 is an NLP that can be solved by commercial solvers.

(f) MP case can be regarded as a traditional cap-and-trade policy with all the states subjected to an aggregate emissions cap. The resulting problem (10) in Subsection 3.3 is also an NLP. MP programs have been implemented in the U.S. or elsewhere for decades. Limiting the focus to programs based on greenhouse gases, there are two active ones in the U.S., i.e., the Regional Greenhouse Gas Initiative (RGGI) and the California AB32. RGGI is a joint effort initially led by ten states in the northeast U.S., targeted at regional $CO_2$ emissions from the power sector. Some empirical evidence suggests that the program has led to a meaningful emission reduction (Murray and Maniloff, 2015). On the other hand, the program under the California AB32 is applied to regulate greenhouse gas emissions from the whole economy. Its policy design was subject to contentious policy debates as its intention is to regulate emissions from imports as well (Chen et al., 2011). A detailed review of the existing emission trading systems can be found in Narassimhan et al. (2018).

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[12] `http://www.babstcalland.com/news-article/legal-battles-begin-on-trump-administrations-key-environmental-deregulatory-actions/`

## 5.3 Results

Table 7 reports the power output/sales by generators for scenarios (a)–(f). The condition laid out by Propositions 1–3, i.e., $\boldsymbol{g} > \mathbf{0}$, is satisfied although the detailed decomposition is not shown. Table 7 implies that RSP and RP essentially produce the same solutions and, moreover, ISP, IRP, and MP are equivalent. In what follows, we will discuss the equivalence in more detail. With this in mind, we now proceed to discuss the main results summarized in Tables 8–9.

Table 7: Results of generators' output by scenarios [MW]

| Generator\Scenario | RSP (a) | RP (b) | SP (c) | ISP (d) | IRP (e) | MP (f) |
|---|---|---|---|---|---|---|
| 1 | 200 | 200 | 200 | 200 | 200 | 200 |
| 2 | 150 | 150 | 150 | 150 | 150 | 150 |
| 3 | 61.4 | 61.4 | 61.5 | 69.6 | 69.6 | 69.6 |
| 4 | 110.0 | 110.0 | 126.5 | 189.5 | 189.5 | 189.5 |
| 5 | 91.2 | 91.2 | 69.2 | 21.4 | 21.4 | 21.4 |
| 6 | 441.5 | 441.5 | 450 | 395.9 | 395.9 | 395.9 |
| 7 | 200 | 200 | 200 | 200 | 200 | 200 |
| 8 | 250 | 250 | 250 | 250 | 250 | 250 |
| 9 | 200 | 200 | 200 | 200 | 200 | 200 |
| 10 | 200 | 200 | 200 | 200 | 200 | 200 |

Tables 8–9 report, respectively, the results from the cases without and with policy coordination, each column corresponding to one scenario from (a)–(f). The tables contain two panels with the top panel giving the market outcomes, i.e., the weighted prices, $CO_2$ emissions, and surplus measurements. The lower panel reports the prices, demand, and consumer surplus by state.

Several observations emerge from Tables 8-9 regarding the market outcomes. First, SP gives the optimal rates of 0.51, 0.71, and 0.83 ton/MWh for states 1–3, respectively, under the total emissions capped at 1,197.5 tons, representing roughly a 20% reduction from uncapped case. The resulting $CO_2$ permit price is uniform at \$44.2/ton for all the three states with $\boldsymbol{g} > \mathbf{0}$, which is in line with Proposition 1.[13] Second, the same total emissions can also result from the optimal rates of 0.63 ton/MWh in RP and RSP. The $CO_2$ prices under RP and RSP are both equal to \$33.0/ton as alluded to in Proposition 2. Third, we observe the cross-subsidy effect of the performance-based polices in RSP, RP,

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[13] Note that SP or RSP does not always guarantee an equal permit price. While the market allows for exploring power sales among states to equate the permit price, this sale option could be exhausted due to physical constraints or economic un-profitability, thereby leading to a divergence of permit prices. For example, transmission constraints or generating capacity might prevent power sales of low-emitting sources to a state at which the permit price is relatively high. It could also be the case that power sales at some states are zero because they are not profitable from an economic sense even if their production could lead to equating permit prices.

and SP, in which low-emission but high-cost power that determines the electricity prices is subsidised, thereby lowering the power prices by \$1.6–3.1/MWh, and inflating the power demand by 18–28 MW due to lower power prices when compared to those under MP. The inflated demand also increases demand for tradable permits and drives up the $CO_2$ prices by \$20–30/ton compared to MP. Finally, among cases in Table 8, the higher permit price (\$44.2/ton) under SP leads to higher electricity prices, thereby benefiting producers by roughly 9% compared to the RP and RSP scenarios.

Table 8: Results under non-cooperative policymakers

| Variable\Scenario | RSP | | | RP | | | SP | | |
|---|---|---|---|---|---|---|---|---|---|
| | (a) | | | (b) | | | (c) | | |
| Weighted Price [\$/MWh] | | | 47.8 | | | 47.8 | | | 49.3 |
| Total $CO_2$ [tons] | | | 1,197.5 | | | 1,197.5 | | | 1,197.5 |
| Consumer Surplus [\$] | | | 120,530.1 | | | 120,530.1 | | | 117,289.8 |
| Producer Surplus [\$] | | | 37,926.6 | | | 37,926.6 | | | 41,271.1 |
| Social Surplus [\$] | | | 158,456.7 | | | 158,456.7 | | | 158,561.0 |
| Variable\State | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| $CO_2$ Rate [ton/MWh] | 0.63 | 0.63 | 0.63 | | 0.63 | | 0.51 | 0.71 | 0.83 |
| Price [\$/MWh] | 53.5 | 44.8 | 38.2 | 53.5 | 44.8 | 38.2 | 57.7 | 44.8 | 36.1 |
| Demand [MW] | 1071.5 | 280 | 552.6 | 1071.5 | 280 | 552.6 | 1080.0 | 280.0 | 547.2 |
| $CO_2$ Price [\$/ton] | 33.0 | 33.0 | 33.0 | | 33.0 | | 44.2 | 44.2 | 44.2 |
| Consumer Surplus [k\$] | 93.48 | 6.76 | 20.29 | 93.48 | 6.76 | 20.29 | 89.09 | 6.76 | 21.44 |

Table 9: Results under cooperative policymakers

| Variable\Scenario | ISP | | | IRP | | | MP | | |
|---|---|---|---|---|---|---|---|---|---|
| | (d) | | | (e) | | | (f) | | |
| Weighted Price [\$/MWh] | | | 50.9 | | | 50.9 | | | 50.9 |
| Total $CO_2$ [tons] | | | 1,197.5 | | | 1,197.5 | | | 1,197.5 |
| Consumer Surplus [\$] | | | 114,063.6 | | | 114,063.6 | | | 114,063.6 |
| Producer Surplus [\$] | | | 44,681.8 | | | 44,681.8 | | | 44,681.8 |
| Social Surplus [\$] | | | 158,745.4 | | | 158,745.4 | | | 158,745.4 |
| Variable\State | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| $CO_2$ Rate [ton/MWh] | 1.08 | 0.15 | 0.59 | | 0.87 | | N/A | N/A | N/A |
| Price [\$/MWh] | 60.9 | 44.82 | 35.81 | 60.9 | 44.82 | 35.81 | 60.9 | 44.8 | 35.7 |
| Demand [MW] | 1025.8 | 280 | 570.4 | 1025.8 | 280 | 570.4 | 1025.8 | 280 | 570.4 |
| $CO_2$ Price [\$/ton] | 13.8 | 13.8 | 13.8 | | 13.8 | | | 13.8 | |
| Consumer Surplus [k\$] | 85.69 | 6.76 | 21.61 | 85.69 | 6.76 | 21.61 | 85.69 | 6.76 | 21.61 |

Table 10: Values of policy coordination under $-20\%$ case

| Variable\Scenario | RP | SP |
|---|---|---|
| Values of Policy Coordination [\$] | 288.7 | 184.4 |
| Relative Values of Policy Coordination [%] | 0.18 | 0.12 |

Next, we demonstrate the implications regarding social surplus in Section 4. First, as in Lemmas 1 and 2, social surplus under SP and RP is greater than that of RSP. Second, since both conditions identified by Proposition 2, i.e., interior solutions ($\boldsymbol{g} > \mathbf{0}$) and positive $CO_2$ prices ($\boldsymbol{\rho} > \mathbf{0}$), are satisfied, RP and RSP yield the same social surplus of $158,456.7. Third, we further observe, consistent with Proposition 3, that social surplus of $158,561.0 under SP is greater than that of RP. Fourth, as indicated in Propositions 4–5, policy coordination increases social surplus, with an incremental gain of $288.7 and $184.4 for RP and SP (Table 10), respectively. In a relative sense, it is equal to 0.18% and 0.12% increases in social surplus for RP and SP, respectively, which is a marginal gain in this case study. Finally, consistent with Proposition 6, social surpluses for coordination cases, ISP and IRP, are on par with that of MP, suggesting that mass-based regulation remains more efficient when holding the total emissions to be the same across those cases. In the single-level problem of MP, the $CO_2$ price is obtained as $\lambda =$\$13.8/ton. It turns out that the single-level problems of ISP and IRP yield the same $CO_2$ price $\lambda =$\$13.8/ton, whereas $\boldsymbol{\rho} = \mathbf{0}$. This is because performance-based policies become redundant in both ISP and IRP as discussed in Proposition 6.[14]

As shown in Tables 8 and 9, producers earn less profits under performance-based policies, SP, RP, and RSP, when compared to a mass-based policy, MP (and equivalently ISP and IRP). Table 9 shows producer surplus in which the initial permits are assumed to be grandfathered to producers. However if we assume that the initial permits are auctioned under mass-based policy, the economic rent of $16,525.5 ($13.8/ton×1,197.5 tons) is transferred from producers to the regulatory authority, leaving $28,156.3 for producer surplus, while social surplus remains unchanged. On the other hand, performance-based policies are inherently revenue neutral since these schemes involve transfers of wealth only among producers, particularly from high-emitting to low-emitting plants, by means of tradable permits.[15]

## 5.4 Policy Discussion

Focusing on the effect of policy coordination, we report the outcomes of a sensitivity analysis when the emissions are capped at 30% below the baseline or 1,047.8 tons in Table 11. Similar to the previous observation in Subsection 5.3, social surplus under SP is greater than that of RP as alluded to in Proposition 3. When compared to the first-best policy, i.e., MP (and equivalently ISP and IRP), the decrease in social surplus is $691.5 and $201.6 for RP and SP, respectively. This implies that the flexibility of allowing each state to have an individually distinct rate in the SP case renders a much-needed nimbleness

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[14] Note that in the bi-level problems of SP, RP, and RSP, $CO_2$ prices consist of only $\boldsymbol{\rho}$, which is a dual variable in the lower-level problem.

[15] If the emission rate of a generating unit is greater than the performance standard, it needs to pay a cost, effectively a tax, to cover its emissions. By contrast, when a generator's emission rate is less than the performance standard, it can receive a revenue, effectively a subsidy that lowers its production cost. This mechanism is in contrast to mass-based policy with an auction, where all the generators need to purchase allowances that could offset their total carbon emissions (Zhang et al., 2018; Fischer et al., 2018).

so that the state-by-state policy results in a more compatible performance with the most efficient MP case. Moreover, from the perspective of integrated decision making, the result suggests that policy coordination increases social surplus by \$691.5 and \$201.6, or 0.44% and 0.13%, for RP and SP, respectively. Interestingly, under a comparatively tighter cap ($-30\%$), the effect of policy coordination on social surplus is more impactful in the RP case (0.44%) than in the SP case (0.13%). When comparing it to Table 10, tightening the emission cap from 20% to 30% has a significantly larger impact on the RP case (from 0.18% to 0.44%) than the SP case (from 0.12% to 0.13%). It is worth noting that the tighter the emissions cap is, the larger is the value of policy coordination, and it is more so for RP.

Table 11: Values of policy coordination under $-30\%$ case

| Variable\Scenario | RP | SP |
|---|---|---|
| Values of Policy Coordination [\$] | 691.5 | 201.6 |
| Relative Values of Policy Coordination [%] | 0.44 | 0.13 |

Overall, our recommendation for policymakers is to adopt localized heterogenous regulation, namely SP, if the government is elected to implement performance-based policies. The advantage of SP over RP is prominent under tighter environmental regulation, particularly because of its flexibility to tailor heterogenous performance rates among states. However, the government might need to opt for less efficient system-wide homogenous regulation, i.e., RP, for some political reasons. Our analysis demonstrates that even on that occasion, policy coordination between the environmental authority and the system operator of the power system can improve social welfare. This indicates that coordination is an important aspect of the policy design for performance-based policies. Of course, the fact that performance-based policies entail the notion of wealth transfer among agents or states in an economy implying that policymakers might have a specific policy goal that goes beyond sole consideration of economic efficiency. Whether this consideration is politically motivated is beyond what we can or want to fathom in this paper. Nevertheless, carefully orchestrated coordination, if not perfect, is likely to produce more efficient economic outcomes while maintaining intended policy goals.

# 6 Conclusion

The separation of regulatory powers between environmental and economic agencies is commonly observed in many countries. Although these distinct regulators may have the same goal of improving social welfare, they may not be able to fully cooperate with each other due to legal, institutional, or political reasons. Different degrees of cooperation among policymakers might provide each party with different incentives, thereby affecting the overall welfare outcome. Moreover, different jurisdictional coverage of regulation would also have an impact on social welfare. Even within one country, regulatory instruments such as tax and environmental standards can be set on a state-by-state, regional, or national basis.

In this paper, we examined non-cooperation between policymakers and the jurisdictional scope of regulation in the context of performance-based environmental policy. Our work was motivated by Clean Power Plan (CPP) in the U.S., in which the Environmental Protection Agency (EPA) has authority to establish a distinct emissions rate standard for each state. Focusing on performance-based environmental policy, we developed a unified bi-level programming framework to analyze issues for both non-cooperative policymakers and regulatory jurisdiction. We argue that integration or perfect coordination of policymakers, i.e., environmental authority and the ISO in this case, leads to improvement in social welfare. We further found that as a result of full cooperation between policymakers, performance-based environmental policy becomes redundant, which eventually leads to mass-based environmental policy. This finding would be counterintuitive since performance-based environmental policy is not necessary under full cooperation of policymakers. We also found that heterogenous state-by-state regulation yields greater social welfare than broader homogenous regional regulation under mild conditions (i.e., positive sales and positive $CO_2$ prices). This is because even under state-by-state environmental regulation, producers competing in a regional power market can arbitrage away the $CO_2$ price differences by adjusting their generation across states. We conclude that localized heterogenous regulation can be superior to system-wide homogenous regulation. This feature becomes more salient under stricter environmental policies. However, inferior homogenous regional regulation could be sometimes more feasible for politicians possibly because advocates of fairness might oppose heterogenous treatment among states. Even in such undesired instances, there is still room for improving economic efficiency by harmonized decision making of distinct policymakers.

We point out several caveats of this study. First, we assume that producers participate in a perfectly competitive electricity and $CO_2$ credit markets. However, some large producers may exert market power to manipulate power and $CO_2$ prices in those markets. The issue of market power would be a relevant direction for future research to investigate the impact of price manipulation on the welfare outcome. Second, the focus of our analysis is on the short-term decisions and operations in the market. Thus, we do not consider long-term investment decisions in power plant capacity. Another interesting research direction would be to incorporate investment decisions in generation capacity in the long run under different environmental regulatory frameworks. Third, regional performance-based policy in this study can be also regarded as an alliance of different states to develop a multi-state plan for averaging emissions standards across states. Yet, states could have conflicts of interest, and each state may react in a strategic manner by considering only its own interests. We will leave these considerations to future work.

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## References

Jose Miguel Abito, Christopher R. Knittel, Konstantinos Metaxoglou, and Andre Trindade. Separate markets for externalities: Regional versus state-by-state regulation of a global pollutant. Wharton School, University of Pennsylvania, 2017.

Thomas Aronsson and Olof Johansson-Stenman. Keeping up with the Joneses, the Smiths and the Tanakas: On international tax coordination and social comparisons. *Journal of Public Economics*, 131:71–86, 2015.

Jonathan F. Bard. *Practical bilevel optimization: applications and algorithms.* Kluwer Academic Publishers, 1998.

David P. Baron. Noncooperative regulation of a nonlocalized externality. *RAND Journal of Economics*, 16:553–568, 1985.

Dallas Burtraw, Karen Palmer, Anthony Paul, and Sophie Pan. A proximate mirror: greenhouse gas rules and strategic behavior under the us clean air act. *Environmental and Resource Economics*, 62(2):217–241, 2015.

James B. Bushnell, Stephen P. Holland, Jonathan E. Hughes, and Christopher R. Knittel. Strategic policy choice in state-level regulation: The EPA's Clean Power Plan. *American Economic Journal: Economic Policy*, 9(2):57–90, 2017.

Arthur J. Caplan and Emilson C.D. Silva. Federal acid rain games. *Journal of Urban Economics*, 46(1):25–52, 1999.

Hung-Po Chao and Stephen Peck. A market mechanism for electric power transmission. *Journal of Regulatory Economics*, 10(1):25–59, 1996.

Yihsu Chen, B. F. Hobbs, S. Leyffer, and T. Munson. Leader-follower equilibria for electric power and NOx allowances markets. *Computational Management Science*, 3 (4):307–330, 2006.

Yihsu Chen, Andrew L. Liu, and Benjamin F. Hobbs. Economic and emissions implications of load-based, source-based, and first-seller emissions trading programs under California AB32. *Operations Research*, 59(3):696–712, 2011.

Xu Cheng and Thomas J Overbye. PTDF-based power system equivalents. *IEEE Transactions on Power Systems*, 20(4):1868–1876, 2005.

Stephen E. Chick, Sameer Hasija, and Javad Nasiry. Information elicitation and influenza vaccine production. *Operations Research*, 65(1):75–96, 2016.

Coral Davenport and Alissa J. Rubin. Trump signs executive order unwinding Obama climate policies. *The New York Times*, 2017.

Victor DeMiguel and Huifu Xu. A stochastic multiple-leader Stackelberg model: Analysis, computation, and application. *Operations Research*, 57(5):1220–1235, 2009.

Stephan Dempe. *Foundations of bilevel programming*. Kluwer Academic Publishers, 2002.

Carolyn Fischer, Biao Mao, and Daniel Shawhan. Trade between mass-and rate-based regulatory regimes: Bad for emissions? *Energy Economics*, 73:326–336, 2018.

Richard J. Green and David M. Newbery. Competition in the British electricity spot market. *Journal of Political Economy*, 100(5):929–953, 1992.

Cliff Grigg et al. The IEEE reliability test system-1996: A report prepared by the reliability test system task force of the application of probability methods subcommittee. *IEEE Transactions on Power Systems*, 14(3):1010–1020, 1999.

Benjamin F. Hobbs. Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. *IEEE Transactions on Power Systems*, 16(2): 194–202, 2001.

Stephen P. Holland. Emissions taxes versus intensity standards: Second-best environmental policies with incomplete regulation. *Journal of Environmental Economics and Management*, 63(3):375–387, 2012.

Stephen P. Holland, Jonathan E. Hughes, and Christopher R. Knittel. Greenhouse gas reductions under low carbon fuel standards? *American Economic Journal: Economic Policy*, 1(1):106–146, 2009.

Stephen P. Holland, Jonathan E. Hughes, Christopher R. Knittel, and Nathan C. Parker. Some inconvenient truths about climate change policy: The distributional impacts of transportation policies. *Review of Economics and Statistics*, 97(5):1052–1069, 2015.

Steffen Jørgensen and Georges Zaccour. Price subsidies and guaranteed buys of a new technology. *European Journal of Operational Research*, 114(2):338–345, 1999.

James Landis. Report on regulatory agencies to the President-Elect. US Government Printing Office, Washington, DC, 1960.

Arik Levinson. Environmental regulatory competition: A status report and some new evidence. *National Tax Journal*, 56(1):91–106, 2003.

Ngo Van Long. Pollution control: A differential game approach. *Annals of Operations Research*, 37(1):283–296, 1992.

David Martimort. Renegotiation design with multiple regulators. *Journal of Economic Theory*, 88(2):261–293, 1999.

Brian C. Murray and Peter T. Maniloff. Why have greenhouse emissions in RGGI states declined? An econometric attribution to economic, energy market, and policy factors. *Energy Economics*, 51:518–589, 2015.

Easwaran Narassimhan, Kelly S. Gallagher, Stefan Koester, and Julio Rivera Alejo. Carbon pricing in practice: a review of existing emissions trading systems. *Climate Policy*, 18(8):967–991, 2018.

Reinhard Neck. Dynamic games of fiscal and monetary policies for Austria. *Annals of Operations Research*, 88:233–249, 1999.

Wallace E. Oates and Robert M. Schwab. Economic competition among jurisdictions: efficiency enhancing or distortion inducing? *Journal of Public Economics*, 35(3):333–354, 1988.

Wallace E. Oates and Robert M. Schwab. The theory of regulatory federalism: The case of environmental management. In *The Economics of Environmental Regulation.* (W. E. Oates, Ed.), Edward Elgar, 1996.

Karen L. Palmer and Anthony C. Paul. A primer on comprehensive policy options for states to comply with the Clean Power Plan. Resources for the Future Discussion Paper 15-15, 2015.

Sam Peltzman and T. Nicolaus Tideman. Local versus national pollution control: Note. *American Economic Review*, 62(5):959–963, 1972.

Martin T. Ross and Brian C. Murray. What is the fuel of the future? Prospects under the clean power plan. *Energy Economics*, 60:451–459, 2016.

Fred C. Schweppe, Michael C. Caramanis, Richard D. Tabors, and Roger E. Bohn. *Spot pricing of electricity*. Springer Science & Business Media, 2013.

Hanif D. Sherali. A multiple leader Stackelberg model and analysis. *Operations Research*, 32(2):390–404, 1984.

Hanif D. Sherali, Allen L. Soyster, and Frederic H. Murphy. Stackelberg-Nash-Cournot equilibria: characterizations and computations. *Operations Research*, 31(2):253–276, 1983.

Afzal S. Siddiqui, Makoto Tanaka, and Yihsu Chen. Are targets for renewable portfolio standards too low? The impact of market structure on energy policy. *European Journal of Operational Research*, 250(1):328–341, 2016.

Heinrich von Stackelberg. *The theory of the market economy*. Oxford University Press, 1952.

Jerome L. Stein. The 1971 report of the President's Council of Economic Advisers: Microeconomic aspects of public policy. *American Economic Review*, 61(4):531–537, 1971.

Richard Wolf. U.S. Supreme Court blocks Obama's Clean Power Plan. *USA Today*, 2016.

Duan Zhang, Yihsu Chen, and Makoto Tanaka. On the effectiveness of tradable performance-based standards. *Energy Economics*, 74:456–469, 2018.