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Constraint by Rule or Incentive by Reward: Central-Local Game and Optimal Delegation for China's CCER Regulation

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Abstract

The 2024 relaunch of China's Certified Emission Reduction (CCER) program creates a dual-track carbon market, posing a key governance dilemma: how should the central government set the CCER offset rate when local governments possess private information on emissions but hold divergent policy goals? We model this challenge using a principal-agent framework featuring the central government, local governments, as well as abatement firms and CCER suppliers. Our core contribution is to derive and unify the optimal delegation mechanisms for two distinct institutional settings: "Greenfield" regions without policy history and "Brownfield" regions with established path dependence. We find that local governments' "status quo veto power", acquired from historical practice, drives a governance shift from *ex-ante* control (rules) to *ex-post* incentives (rewards). For Greenfield regions, the optimal policy is *partial discretion with a cap*, theoretically justifying China's national 5% limit. For Brownfield regions, this veto power necessitates a menu of contracts with financial rewards to manage information rents, explaining why some pilot regions maintain their original, higher standards. Our analysis also confirms the "double-edged sword" effect of CCERs, which lower costs but can dilute the carbon market's environmental effect by crowding out firms' internal abatement efforts. The optimal offset rate is shown to be sensitive to key economic and policy parameters.

1. Introduction

Emissions Trading Schemes (ETS) have become a cornerstone of climate policy worldwide. Since launching the world's largest national carbon market in 2021, China has continuously refined its operational mechanisms. In 2024, China relaunched its national Certified Emission Reduction (CCER) program to diversify market participants, lower compliance costs for regulated firms, and incentivize broader abatement actions. This move marks the market's transition to a dual-track system, driven by both a mandatory ETS and a voluntary CCER program. However, setting the CCER offset rate, the core parameter linking these two markets, is not merely a technical parameter but a profound governance challenge. The offset rate acts as a double-edged sword: too high, and it risks flooding the allowance market, depressing carbon prices, and weakening long-term abatement incentives; too low, and its cost-saving potential remains untapped.

Fundamentally, setting this rate is a focal point of complex game between central and local governments, representing a classic principal-agent problem in political economy. The central government prioritizes national abatement targets and long-term market stability. In contrast, local governments, driven by pressures for economic growth and vested local interests, may prefer higher offset rates to reduce short-term compliance costs. Their objectives are thus inherently misaligned. Compounding this problem is severe information asymmetry: local governments possess private information on crucial factors like regional emission levels and abatement potential, challenging the central government's ability to implement a uniform policy effectively.

This central-local governance dilemma manifests in two distinct forms in China's unique institutional evolution, presenting a theoretical puzzle. For Greenfield regions with no prior experience in CCER pilots, the central government designs policy on a blank slate. While possessing full agenda-setting power, it faces the challenge of designing a regulatory mechanism that both deters local opportunism and accommodates regional heterogeneity under severe information asymmetry. Is the uniform 5% national cap the optimal solution under these constraints? In contrast, for early pilot zones like Beijing, Guangdong, and Hubei, years of local market practice have created strong path dependence, forming institutional Brownfields. These regions previously allowed higher offset rates (e.g., up to 10%), which not only

shaped local policy preferences but also created entrenched interests. When the national 5% cap was introduced, these historical practices became a source of status quo veto power in their negotiations with the center. The central government can no longer simply impose its will; it must now address local demands for special policy treatment. This dynamic offers a potential explanation for why some pilot regions may continue to use or lobby for their higher, pre-existing standards even after the introduction of a national rule.

This paper, therefore, addresses a critical theoretical and practical challenge: how to design an incentive-compatible delegation mechanism that encourages local governments to reveal their private information and effectively implement policy, while keeping their actions aligned with the center's strategic goals. Existing literature has not adequately addressed this issue, lacking a unified framework that can explain both the Greenfield and Brownfield dilemmas. To this end, we ask two core questions: (1) In the government-firm interaction, what are the key economic determinants of the optimal CCER offset rate? How does the introduction of CCERs affect total abatement costs and environmental outcomes? (2) Under information asymmetry, how should the central government design optimal delegation and incentive mechanisms for Greenfield and Brownfield regions, respectively?

To systematically answer these questions, we develop a two-level game-theoretic model featuring the central government, local governments, and two types of firms: abatement firms and CCER suppliers. Our key methodological innovation is to systematically model these two distinct institutional settings. This distinction reveals that the status quo veto power, which local governments endogenously acquire from historical practice, is the fundamental reason forcing a shift in the central government's optimal governance strategy, from *ex-ante* control by rules to *ex-post* motivation by rewards.

Our analysis proceeds as follows. First, building on the classic work of Weitzman (1974), Krysiak (2008), and Shinkuma and Sugeta (2016), we construct a game-theoretic model of government-firm interaction under complete information to derive the optimal CCER offset rate and analyze its key determinants. This step not only formalizes the mechanism's double-edged sword effect but also establishes a key theoretical benchmark against which we will later analyze the central-local agency problem. Second, for the Greenfield scenario, we introduce information asymmetry and show how the central government can use a partial discretion with a cap contract to manage the trade-off between information extraction and policy drift. Third, we turn to the "Brownfield" scenario. Here, the status quo veto power compels the center to offer monetary rewards. We build an incentive-based delegation model to analyze the optimal contract, the resulting information rents, and the effectiveness of financial incentives. Through this analysis, we provide a unified framework for understanding central-local interactions and optimal policy design under different institutional histories.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the basic model. Section 4 solves for the optimal CCER offset rate under complete information and demonstrates its double-edged sword property. Sections 5 and 6 form the core of our analysis, examining the optimal delegation mechanisms for Greenfield and Brownfield regions, respectively. Section 7 provides a comparative analysis and presents our unifying theoretical framework. Section 8 concludes. All formal proofs are in the Appendix.

2. Literature Review

This study is situated at the intersection of three streams of literature: the economics of carbon offset mechanisms, environmental federalism, and the principal-agent theory of delegation. By engaging with these three bodies of work, we identify a critical theoretical disconnect and articulate our core contribution.

Carbon offset mechanisms serve as a key supplement to mandatory cap-and-trade systems, with the core economic principle being to enhance market cost-effectiveness. A broad consensus in theoretical and empirical literature suggests that introducing low-cost abatement credits, such as China's CCERs, can lower firms' compliance burdens and achieve macro-level emission targets at a lower societal cost (Wara & Victor, 2008). Recent studies provide multi-faceted evidence of these benefits. At the macro level, offsets can foster regional economic development, improve air quality, and promote urban greening (Cong et al., 2021; Yan et al., 2020; Zheng & Zhang, 2023). At the micro level, they effectively incentivize investment in renewable energy projects (Yang et al., 2022; Zhang & Liu, 2024). However, a core tension has always surrounded offset mechanisms: concerns over their environmental integrity. These concerns stem from two persistent problems. The first is the challenge of additionality, distinguishing genuinely additional abatement from free-riding on projects that were already economically viable. The second is information asymmetry in baseline setting, which can lead to the inflation or over-crediting of emission reductions (Schneider & Kollmuss, 2015). This inherent double-edged sword effect means that introducing CCERs can dilute the environmental effectiveness of the ETS and suppress carbon prices, a finding supported by numerous system dynamics and evolutionary game models (e.g., Ye et al., 2021; He et al., 2023; Liu & Wu, 2024; Wu et al., 2025). Consequently, research has naturally focused on mechanism

design, particularly on setting an optimal offset rate to balance cost-effectiveness and environmental integrity. Some game-theoretic models have begun to explore the determinants of the optimal rate, identifying its critical relationship with parameters like the total emissions cap (Li et al., 2019). Nevertheless, this literature has a fundamental limitation: it often operates under the assumption of a benevolent social planner, focusing on what the optimal policy is. It largely overlooks how such a policy can be implemented without distortion in a multi-level governance system rife with conflicting interests and asymmetric information.

Placing CCER regulation within China's governance context inevitably raises core questions from the political economy of environmental decentralization, specifically the optimal allocation of authority between central and local governments (Oates, 2002). The central-local relationship in China has long been characterized by policy implementation deviations (Ran, 2013), driven by misaligned objectives and information asymmetry. The central government prioritizes long-term, national environmental goals. In contrast, local governments face immense pressure to promote economic growth, giving them incentives to engage in opportunistic behavior to protect local industries (Kostka & Nahm, 2017). In the CCER context, local governments hold a significant informational advantage regarding the abatement potential and project quality within their jurisdictions. This creates a classic principal-agent relationship. Local governments might relax project approvals or authorize higher offset rates to lower compliance costs for local firms, thereby undermining national abatement targets. However, the existing literature on China's central-local environmental relations exhibits a clear problem of scale. Its focus and analytical tools are concentrated on macro-level, command-and-control, or fiscal instruments. For example, a large body of research examines the Central Environmental Inspection, a powerful top-down intervention, analyzing its deterrent effects on local government and firm behavior (e.g., Li et al., 2020; Feng et al., 2022; Cheng & Yu, 2023). Other important works explore how macro-institutional variables—such as promotion-based official incentives (e.g., Kahn et al., 2015), political connections (e.g., Zhang, 2017; Zhang et al., 2022), and fiscal pressures (e.g., He, 2006; Chen et al., 2018; Fei & Lin, 2021), shape the enforcement of local environmental regulations. In stark contrast to this macro-level focus, few studies drill down to the specific, technical, and market-based instrument of the CCER offset rate. This leaves a clear theoretical disconnect between the literature on CCER mechanism design (focused on optimality) and the literature on environmental governance (focused on enforcement of macro tools). A core objective of this paper is to bridge this disconnect by applying a mature central-local game-theoretic framework to a policy domain overlooked by previous research.

To bridge this disconnect, we employ the principal-agent theory of delegation as our core analytical tool. This theory studies how a principal (the central government) can design an optimal incentive contract to constrain an agent (a local government) with private information from acting opportunistically, thereby managing the trade-off between leveraging informational advantages and controlling agency costs (Holmström, 1984; Laffont & Tirole, 1993). It provides a powerful explanation for the goal divergence of local governments, whether it stems from regulatory capture by industry interests (Laffont & Tirole, 1991) or political lobbying by interest groups (Grossman & Helpman, 1994). Both can be parameterized as a misalignment of objectives in an agency model. Recent advances have embedded delegation within more complex two-level agency frameworks (principal–intermediate agent–agent), which align closely with our central-local-firm structure. These studies offer powerful tools for analyzing how information and incentives are transmitted and distorted within a hierarchy. They have progressed along two main dimensions. The first focuses on how the complexity of the regulatory task itself shapes the optimal contract. This line of work reveals that agency costs at the lower level (e.g., firms' adverse selection or moral hazard) travel up the hierarchy and determine the structure of the upper-level contract. For instance, the optimal delegation mechanism must endogenously account for downstream moral hazard in risk prevention (Hiriart & Martimort, 2012) or multiple informational asymmetries in firms' costs, technologies, and quality (Kundu & Nilssen, 2020, 2022). The common thread in these studies is their treatment of the intermediate agent (the local government) as a conduit for information and incentives, whose optimal discretion depends on the complexity of the downstream information it must handle. The second dimension shifts the focus from the task to the agent, exploring the sources of the intermediate agent's power and autonomy. While traditional models often assume a passive agent, recent research recognizes that local governments can be more assertive. This includes expanding their discretion beyond setting a single policy standard to choosing among different policy instruments (e.g., incomplete vs. complete contracts, or emissions taxes vs. cap-and-trade), which grants them more profound and differentiated authority (Lossa & Martimort, 2016; Fang et al., 2020). Further advancing this literature, some studies characterize the intermediate agent as a strong player with an independent outside option or status quo veto power, necessitating participation rents to ensure cooperation (Voss & Lingens, 2018; Wang et al., 2024).

However, these analyses typically treat such power as an exogenously given condition in settings distinct from our own, such as such as contract choice in monopoly regulation or the design of energy taxes. Our paper offers a more

nuanced perspective by investigating a context, China's CCER market, where this veto power is not a static attribute but an endogenous outcome of institutional path dependence. The historical reality of CCER pilot programs provides a compelling real-world laboratory: local governments, through their early policy practice, developed a credible status quo to leverage against the center's later attempts to impose a uniform national policy. This specific application is not merely a new setting; it is the key that allows us to move beyond a static analysis of strong agents. We model the transition from a weak to a strong agent, thereby providing a dynamic explanation for why the optimal delegation mechanism must fundamentally transform from one of power constraint to one of interest alignment through incentives.

3. The Basic Model

Our model features a three-tier hierarchy, a central government (principal), a local government (intermediate agent), and firms (agent), which creates a two-level agency problem. The central government designs a delegation contract to govern the local government, which holds private information on regional conditions. The local government, in turn, acts as a regulator, setting the CCER offset rate for two types of firms: abatement firms (demand) from sectors like power and steel and CCER suppliers (supply) from sectors like solar energy and forestry. We assume these firms interact within perfectly competitive ETS and CCER markets.

3.1. Firms' Cost and Information

To build our analytical framework, we first define the cost structures and information environment for the firms in the markets. Our approach follows the standard in environmental economics (e.g., Weitzman, 1974; Krysiak, 2008; Shinkuma & Sugeta, 2016) by specifying the cost functions for two types of market participants: abatement firms and CCER suppliers.

(1) Abatement Firms: Cost of Emission Reduction

We consider a region with $n_1 (n_1 \geq 2)$ heterogeneous firms, indexed by $i (i = 1,2, \dots, n_1)$ that are subject to emission constraints. These firms reduce their emissions by adopting abatement technologies or improving production processes. We specify the cost for firm i to achieve an abatement level a_i, denoted by $AC_i(a_i)$, as a quadratic function:

$$AC_i(a_i) = (c' + \theta_i)a_i + \frac{{a_i}^2}{2c''_i} \quad (1)$$

where c' is a positive constant representing the initial marginal abatement cost common to all firms. This can be interpreted as a foundational, technology-independent cost required for any abatement activity, such as for universal energy audits, management process adjustments, or basic compliance equipment. c''_i is a positive, firm-specific coefficient that determines the slope of the firm's marginal abatement cost curve. This parameter is the core source of firm heterogeneity in our model, reflecting differences in technological efficiency. A technologically advanced and efficient firm has a smaller $1/c''_i$, meaning its marginal cost increases more slowly, enabling it to achieve deep abatement at a lower additional cost. Conversely, a less advanced firm has a larger $1/c''_i$, its abatement potential is quickly exhausted, and its costs rise sharply. We assume that for the government, c''_i is drawn from a distribution with $E(c''_i) = c''$ and $E\left({c''_i}^2\right) = \varsigma^2 > 0$. This specification ensures the cost function is strictly convex, implying that marginal abatement costs are increasing. This feature captures the low-hanging fruit principle, where firms first implement low-cost abatement projects. As abatement targets deepen, firms must resort to more expensive technological upgrades and capital investments, causing the per-unit cost of further abatement to rise. This is a standard and widely accepted assumption in environmental economics.

θ_i is a random shock representing the source of cost uncertainty. As Weitzman (1974) noted, the true cost of abatement cannot be precisely known ex-ante. This uncertainty can arise from various factors, such as extreme weather events (e.g., droughts affecting hydropower, thus increasing the abatement burden on thermal power), sudden fluctuations in energy prices, disruptions in the supply chain for abatement equipment, or unforeseen challenges in deploying new technologies. Although θ_i is firm-specific, we assume it is drawn from a common distribution with $E(\theta_i) = 0$ and $E\left({\theta_i}^2\right) = \sigma^2 > 0$. This implies that, in the long run and on average, these shocks have no systematic upward or downward bias and merely cause fluctuations around the true cost. We also assume that θ_i and c''_i are mutually independent.

(2) CCER Suppliers: Development and Certification Costs

The other key agents in our model are CCER suppliers, such as operators of solar, wind, and forestry projects. These firms generate the supply of CCERs through project development, operation, and certification. We assume the cost for a CCER supplier $j(j = 1,2, \dots, n_2)$ to supply s_j units of offsets, denoted $SC_j(s_j)$, is quadratic:

$$SC_j(s_j) = \frac{{s_j}^2}{2m_j} \quad (2)$$

Here, the cost coefficient $m_j > 0$, which implies that the marginal cost of supply increases linearly with the quantity s_j. This key assumption is justified by several real-world constraints. First, developers prioritize the most cost-effective resources (e.g., sites with optimal wind or solar endowments). As these are exhausted, new supply must shift to higher-cost alternatives, driving up marginal costs. Second, expanding project scale often leads to managerial diseconomies of scale. Third, the stringent validation and verification process for CCERs creates high demand for a limited number of qualified third-party auditors (DOEs), increasing transaction costs. The parameter m_j represents the slope of the marginal supply curve and reflects the supplier's technological efficiency. For tractability, we assume all suppliers share a common expected cost parameter, $E(m_j) = m$. This simplification shifts our focus from firm-level competition to the aggregate supply elasticity of the CCER market and its interaction with the ETS.

3.2. The Regulatory Framework

We model a quantity-based Emissions Trading System (ETS). The regulator sets an aggregate emissions cap, Q, defined in tons of CO2 equivalent. We take Q as exogenous to focus on the optimal design of the CCER offset policy, though we later analyze the sensitivity of our results to the cap level. Consistent with the initial phase of many carbon markets, we assume the regulator distributes a portion of allowances for free to encourage participation. The impact of this free allocation is also examined in our comparative statics.

The CCER offset policy is implemented through a two-stage game. Stage 1: Policy Setting. The government sets the CCER offset limit, $\delta \in [0,1]$. This parameter defines the maximum portion of an abatement firm's compliance obligation that can be met with offsets. Stage 2: Firm Decisions. After observing δ, firms act. Abatement firms choose their abatement level a_i, and CCER suppliers choose their supply quantity s_j, incurring the cost $SC_j(s_j)$ as defined in Eq.(2).

3.3. Governments: Information, Objectives, and Incentives

We model a principal-agent relationship between the central government (the principal) and a local government (the agent). The framework is defined by information asymmetry, misaligned objectives, and the incentive mechanisms the principal employs.

(1) Local Government's Private Information

The local government (LG) is responsible for regional environmental supervision and is therefore better informed about local economic conditions than the central government (CG). We model this information asymmetry by assuming the LG has private information about the regional aggregate baseline emissions, E. This parameter E represents the LG's type and reflects the underlying regional abatement cost structure. The CG knows only the prior distribution of E over the support $[\underline{E}, \overline{E}]$, described by the cumulative distribution function (CDF) $F(E)$ and the probability density function (PDF) $f(E) > 0$. We make the standard assumption that the inverse hazard rate, $(1 - F(E))/f(E)$, is non-increasing, a common regularity condition in contract theory.

(2) Goal Misalignment

A key feature of our model is the misalignment of objectives between the two government levels. The CG, acting as a benevolent social planner, aims to minimize the total social cost, which is the sum of firms' net compliance costs and the environmental damages from residual emissions. In contrast, the LG's objective reflects a local bias. It places a lower weight on environmental damages compared to the CG, while placing a higher weight on the indirect benefits that a larger CCER market (driven by a higher offset rate, δ) can bring to the local economy. This divergence can stem from regulatory capture by local industrial interests or a political imperative to prioritize local economic growth over national environmental goals.

(3) Central Government's Incentive Mechanisms

To address the information asymmetry and goal misalignment, the CG designs an incentive mechanism, but the tools at its disposal differ critically depending on the region's policy history.

Non-pilot Regions (No Policy History): In regions without a pre-existing offset policy, the CG can exercise direct authority. It offers a menu of contracts that designed to ex-ante restrict the LG's policy discretion, contingent on the

LG's reported type, $\{\delta(\hat{E})\}_{\hat{E}\in[\underline{E},\overline{E}]}$. This mechanism underscores the CG's role in preemptively defining the boundaries of permissible local action. A key feature of this *power-constraining mechanism* is a hard cap on the allowable offset rate.

Pilot Regions (Pilot Policy History): In regions with a pre-existing offset policy, the LG holds a *status quo veto power*. This power is rooted in vested local interests—including abatement firms and CCER project developers—that benefit from the established, often more lenient, rules. Any attempt by the CG to tighten the offset rate thus faces strong opposition. Consequently, the CG cannot unilaterally impose its preferred policy. It must deploy an *interest-incentivizing mechanism*, also offering a compensatory package $\{r(\hat{E})\}_{\hat{E}\in[\underline{E},\overline{E}]}$, such as fiscal transfers or technology subsidies, to induce the LG to abandon its status quo. This process gives rise to information rents.

(4) Objective Functions

The model features two primary categories of agents: private-sector firms (abatement firms and CCER suppliers) and government entities (local and central). Each operates with a distinct objective.

Firm-Level Objectives: An abatement firm seeks to minimize its total compliance cost (ETC_i). This cost function varies depending on the availability of CCERs. In a scenario without CCERs (subscript *nc*), the firm's cost is the sum of its abatement expenditure and its net spending in the ETS:

$$ETC_{i,nc}(a_i) = AC_i(a_i) + p_{ets}(e_i - a_i - q_i) \tag{3}$$

where $AC_i(a_i)$ is the abatement cost, p_{ets} is the carbon allowance price, e_i is the initial emission, a_i is the abatement, and q_i is the free allocation. In a scenario with CCERs (subscript *wc*), the firm can use CCERs for compliance, creating a cost-saving opportunity since they are priced lower than ETS allowances ($p_{ccer} < p_{ets}$). The total cost function now reflects the savings from this substitution:

$$ETC_{i,wc}(a_i) = AC_i(a_i) + p_{ets}(e_i - a_i - q_i - s_i) + p_{ccer}s_i \tag{4}$$

where s_i is the quantity of CCERs used. The formula shows the firm covers its compliance obligation $e_i - a_i - q_i$ by purchasing a mix of ETS allowances and cheaper CCERs.

A CCER supplier (e.g., a renewable energy project) aims to maximize its profit. This is equivalent to minimizing its net costs (CTC_j), defined as its generation costs minus its sales revenue:

$$CTC_j(s_j) = SC_j(s_j) - p_{ccer}s_j \tag{5}$$

where $SC_j(s_j)$ is the cost to generate s_j units of CCERs, and $p_{ccer}s_j$ is the revenue from their sale.

Government-Level Objectives： Government entities aim to minimize a social cost function that aggregates total compliance costs and the environmental damage from residual emissions. Their objectives differ based on their jurisdiction (central vs. local) and the region's policy history.

The CG's objective is to minimize the national social cost. For a non-pilot CCER region (subscript *np*), the CG's objective function is:

$$W_{CG,np}(\delta) = \sum_{i=1}^{n_1} AC_i\big(a_i(\delta)\big) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{CG}D\big(AE(\delta)\big) \tag{6}$$

For a CCER pilot region (subscript *wp*), where an incentive payment r is required to induce cooperation, this transfer is added to the social cost:

$$W_{CG,wp}(\delta) = \sum_{i=1}^{n_1} AC_i\big(a_i(\delta)\big) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{CG}D\big(AE(\delta)\big) + r \tag{7}$$

The LG's objectives are systematically biased relative to the CG's, reflecting its distinct local priorities. For a non-pilot CCER region, the LG's objective function is:

$$W_{LG,np}(\delta) = \sum_{i=1}^{n_1} AC_i\big(a_i(\delta)\big) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{LG}D\big(AE(\delta)\big) \tag{8}$$

For a CCER pilot region, the LG's utility is defined net of the incentive payment r it receives:

$$W_{LG,wp}(\delta, r) = W_{CG,pa}(\delta, r) - \Delta\alpha D\big(AE(\delta)\big) - (1+\beta)r = \sum_{i=1}^{n_1} AC_i\big(a_i(\delta)\big) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{LG}D\big(AE(\delta)\big) - \beta r \tag{9}$$

where $\alpha_{CG} > \alpha_{LG} > 0$ and $\Delta\alpha = \alpha_{CG} - \alpha_{LG} > 0$. This inequality captures the core goal misalignment between central and local governments. This assumption is grounded in the practical concerns over the environmental integrity of offset credits. The CG's higher α signifies that it places a greater premium on the environmental benefits from direct, verifiable emissions reductions within the ETS compared to those from CCERs. This is due to two well-documented problems.

First, regarding to CCER's additionality, some CCER projects might have been implemented anyway due to their own economic viability, meaning the emissions reductions are not truly additional and are simply free-riding on the mechanism. Second, in terms of CCER's quality and verification, deficiencies in accounting and regulatory oversight can lead to the issuance of low-quality or inflated credits, where one CCER does not represent one tonne of real, additional, and verifiable emission reduction. $\beta > 0$ represents the LG's bureaucratic self-interest, reflecting its preference for fiscal transfers. A higher β indicates that the LG values receiving direct payments more than reducing aggregate social costs.

4. The Central Government's Optimal CCER Offset Mechanism

This section analyzes the optimal design of the CCER offset mechanism, first establishing a benchmark case without CCERs to highlight the mechanism's dual effects.

4.1. Benchmark: The ETS-Only Market

We begin with a benchmark scenario where only an ETS exists. We solve the model using backward induction. An abatement firm i chooses its abatement level a_i to minimize its total compliance cost, given the market allowance price p_{ets} and its realized abatement cost uncertainty θ_i. The firm solves:

$$\min_{a_i} ETC_{i,nc}(a_i) = (c' + \theta_i)a_i + \frac{{a_i}^2}{2c''_i} + p_{ets}(e_i - a_i - q_i)$$

The first-order condition (FOC) with respect to a_i yields the firm's optimal abatement response: $a_i = (p_{ets} - c' - \theta_i)c''_i$. This shows that a firm's abatement level increases with the allowance price and decreases with its own marginal cost. We substitute the firm's optimal response into the market-clearing condition, which requires that total abatement equals the aggregate emissions cap: $\sum_{i=1}^{n_1} e_i - \sum_{i=1}^{n_1} a_i = \sum_{i=1}^{n_1} q_i$ (ie., $\sum_{i=1}^{n_1} a_i = E - Q$). This allows us to solve for the equilibrium abatement level for firm ($a_{i,nc}$), the market-clearing allowance price ($p_{ets,nc}$), and the aggregate emissions (AE_{nc}):

$$a_{i,nc} = \left[\frac{(E-Q)}{n_1 c''} - \theta_i\right] c''_i \tag{10}$$

$$p_{ets,nc} = \frac{(E-Q)}{n_1 c''} + c' \tag{11}$$

$$AE_{nc} = E - \sum_{i=1}^{n_1} a_{i,nc} = Q \tag{12}$$

The subscript *nc* denotes the *no-CCER* benchmark. As expected, the equilibrium ensures that each firm's marginal abatement cost equals the market allowance price. The equilibrium outcomes are driven by the sector-wide abatement target ($E - Q$): higher aggregate emissions (E) or a more stringent allowance (a smaller Q) increases pressure on the market, raising both the equilibrium allowance price and individual abatement levels.

4.2. The Optimal Offset Mechanism in a Dual-Market Setting

We first analyze a benchmark case under full information, where the central government can observe the aggregate baseline emissions E, directly regulate firms and thereby not require an incentive payment r to induce cooperation for LG. This allows us to isolate the policy effects of the CCER mechanism. Using backward induction, we solve for the market equilibrium. Given an ETS price p_{ets} and a CCER price p_{ccer}, an abatement firm i with cost parameter c', c''_i and realized cost shock θ_i chooses its abatement level a_i, and a CCER supplier j with cost parameter m_j chooses its supply quantity s_j. The cost-minimization problems for a representative firm i and supplier j are:

$$\min_{a_i} ETC_{i,wc}(a_i) = (c' + \theta_i)a_i + \frac{{a_i}^2}{2c''_i} + p_{ets}(e_i - a_i - q_i - s_i) + p_{ccer}\delta q_i$$

$$\min_{s_j} CTC_j(s_j) = SC_j(s_j) - p_{ccer}s_j$$

Solving the first-order conditions yields the firms' optimal responses: $p_{ets} = a_i/c''_i + c' + \theta_i$ and $p_{ccer} = s_j/m_j$. We substitute these into the market-clearing conditions for the ETS market ($\sum_{i=1}^{n_1} e_i - \sum_{i=1}^{n_1} a_i - \sum_{i=1}^{n_1} s_i = \sum_{i=1}^{n_1} q_i$) and the CCER market ($\sum_{i=1}^{n_1} s_i = \sum_{i=1}^{n_1} \delta q_i = \sum_{j=1}^{n_2} s_j$), which yields the following equilibrium outcomes as functions of the offset rate, δ:

$$a_{i,wc}(\delta) = \left[\frac{(E - \delta Q - Q)}{n_1 c''} - \theta_i\right] c''_i \tag{13}$$

$$p_{ets,wc}(\delta) = \frac{(E-\delta Q-Q)}{n_1 c''} + c' \tag{14}$$

$$s_{j,wc}(\delta) = \frac{m_j \delta Q}{n_2 m} \tag{15}$$

$$p_{ccer,wc}(\delta) = \frac{\delta Q}{n_2 m} \tag{16}$$

$$AE_{wc}(\delta) = E - \sum_{i=1}^{n_1} a_{i,wc} = \delta Q + Q \tag{17}$$

We assume $E > \delta Q + Q$ for $\delta \in [0,1]$ and $E > 2Q$ to ensure interior solutions. The central government's problem under full information is to choose the offset rate δ to minimize total social cost, which comprises firms' abatement costs, CCER suppliers' costs, and environmental damages:

$$\min_{\delta} W_{CG,wp}(\delta) = \sum_{i=1}^{n_1} AC_i\left(a_{i,wc}(\delta)\right) + \sum_{j=1}^{n_2} SC_j\left(s_{j,wc}(\delta)\right) + \alpha_{CG} D\big(AE(\delta)\big) \quad \textit{s.t. (13) - (17)}$$

Substituting the equilibrium outcomes into the objective function and solving the first-order condition, see Eq.(18), yields the optimal offset rate in the dual-market setting, δ_{wc}:

$$\frac{dW_{CG,wp}(\delta)}{d\delta} = \left[p_{ccer} - p_{ets} + \frac{\alpha(1+\delta)Q}{\gamma}\right] Q = \left[\frac{\delta Q}{n_2 m} - \frac{(E-\delta Q-Q-nc'c'')}{n_1 c''} + \frac{\alpha_{CG}(1+\delta)Q}{\gamma}\right] Q = 0 \tag{18}$$

$$\delta_{wc} = \frac{(E-Q+n_1 c' c'')/n_1 c'' Q - \alpha_{CG}/\gamma}{1/n_1 c'' + 1/n_2 m + \alpha_{CG}/\gamma} \tag{19}$$

The second-order condition, $d^2 W_{CG,wp}(\delta)/d\delta^2 > 0$, holds, ensuring this solution corresponds to a social cost minimum. An economically intuitive condition for an interior solution ($\delta_{wc} \in [0,1]$) to exist is that $p_{ccer} \leq p_{ets}$ and $c' \in [Q\alpha_{CG}/\gamma - (E-Q)/(n_1 c''), (2Q-E)/(n_1 c'') + Q/(n_2 m) + 2Q\alpha_{CG}/\gamma]$, which ensures that offsets provide a cost-effective compliance option.

This analysis leads to our first main result, which we present in Lemma 1. The proposition formally characterizes the determinants of the optimal offset rate. The formal proof can be seen in the appendix.

Lemma 1. *The optimal offset rate, δ_{wc}, increases with the aggregate baseline emissions E, the average initial marginal abatement cost c', and firms' average technological efficiency $1/c''$. It decreases with the initial allocation of free ETS allowances Q, the average marginal cost of CCER supply $(1/m)$, and the government's weighting of environmental damages (α).*

The rationale behind this proposition stems from the government's core objective of minimizing total social costs while adhering to an emissions cap. The positive relationship between δ_{wc} and the parameters E, c', and $1/c''$ reflects the mechanism's function as a cost-containment instrument. A higher baseline emissions level (E) implies a greater ex-ante reduction requirement, raising the marginal value of cost-effective compliance options. Similarly, a higher initial marginal cost (c') establishes a higher cost floor for internal abatement across all firms, making the relative cost advantage of external CCERs more pronounced. Crucially, $1/c''$ captures technological efficiency. A higher average value of $1/c''$ indicates that, on aggregate, firms face steeper marginal abatement cost curves. This implies that the marginal cost for emitters to achieve reductions through their own technological improvements, such as installing more advanced purification equipment or adopting cleaner energy sources, is relatively high. In this context, if the average supply cost of CCER projects is lower than the firms' own marginal abatement costs, allowing a higher CCER offset ratio can incentivize them to purchase more credits from the CCER market rather than investing heavily in high-cost technological retrofits. This is likewise a strategy adopted by the government to achieve emissions reductions with greater cost-effectiveness.

Conversely, parameters that reduce the systemic need for cost containment lead to a lower δ_{wc}. A larger allocation of free allowances (Q) directly alleviates the compliance burden on abatement firms, lowering the equilibrium carbon price and diminishing the marginal utility of a supplementary offset mechanism. Likewise, a higher marginal cost of CCER supply $(1/m)$ attenuates the cost advantage of offsets, reducing their attractiveness and prompting the regulator to restrict their use. Finally, the parameter α represents the regulator's commitment to environmental integrity. A

higher α indicates a greater aversion to the perceived risks of offsets, such as non-additionality or measurement errors, which could dilute the environmental stringency of the cap. To safeguard the integrity of the emissions target, a regulator with a strong environmental preference will set a more stringent offset rate.

In essence, architecting the optimal offset policy involves navigating a fundamental trade-off: leveraging the mechanism for cost-effectiveness (which favors a higher offset rate when ETS or abatement costs are high) versus maintaining market stability and safeguarding the environmental integrity of the emissions cap (which favor a lower rate). Proposition 1 formalizes how the optimal balance of this trade-off shifts in response to key economic and technological parameters.

4.3. Analysis of Cost Savings versus Environmental Target Dilution

Compared to a scenario without offsets, the total abatement costs (TAC) and environmental damages (D) under a cap-and-trade system with CCERs are given by equations (20) through (23).

$$TAC_{nc} = \sum_{i=1}^{n_1} AC_i(a_{i,nc}) = c'(E-Q) + \frac{(E-Q)^2}{2n_1c''} - \frac{{n_1}^2\sigma^2c''}{2} \tag{20}$$

$$TAC_{wc} = \sum_{i=1}^{n_1} AC_i\left(a_{i,wc}(\delta_{wc})\right) + \sum_{j=1}^{n_2} SC_j\left(s_{j,wc}(\delta_{wc})\right) = c'(E-\delta_{wc}Q-Q) + \frac{(E-\delta_{wc}Q-Q)^2}{2n_1c''} - \frac{{n_1}^2\sigma^2c''}{2} + \frac{\delta_{wc}^2Q^2}{2n_2m} \tag{21}$$

$$D(AE_{nc}) = \frac{Q^2}{2\gamma} \tag{22}$$

$$D(AE_{wc}) = \frac{(\delta_{wc}Q+Q)^2}{2\gamma} \tag{23}$$

The resulting cost savings from introducing offsets can be expressed as the difference in expected total abatement costs:

$$\Delta TAC = TAC_{nc} - TAC_{wc} = \delta_{wc}Q\{c' - [\frac{\delta_{wc}Q-2(E-Q)]}{2n_1c''} - \frac{\delta_cQ}{2n_2m}\} \tag{24}$$

The introduction of the CCER mechanism yields cost savings ($\Delta TAC > 0$) fundamentally because the marginal abatement cost of offset projects (e.g., renewables, forestry) is typically lower than the internal marginal abatement cost of regulated firms. As shown in equation (24), when a firm's internal MAC exceeds the marginal cost of procuring CCERs, the offset mechanism demonstrates its cost-effectiveness. CCERs thus provide a pathway to reduce the cost of each incremental unit of abatement.

Conversely, the model shows that introducing offsets increases the expected environmental damages ($\Delta D > 0$), as shown in equation (25):

$$\Delta D = D(AE_{nc}) - D(AE_{wc}) = -\frac{\delta_{wc}Q^2(2+\delta_{wc})}{2\gamma} < 0 \tag{25}$$

This mathematically embodies the environmental target dilution effect. Although firms fulfill their compliance obligations by purchasing CCERs, the actual environmental outcome may be inferior to what would have been achieved through internal abatement alone. The environmental effectiveness is thus discounted. This occurs because access to relatively inexpensive CCERs can disincentivize firms from investing in more substantive and reliable deep-abatement technologies. The term $\delta_{wc}Q$ in the model can thus be interpreted as the environmental loss attributable to this dilution effect.

Consequently, our analysis reveals the dual role, or double-edged sword, of the CCER mechanism, which presents a fundamental policy trade-off. We elaborate on the two effects and their policy implications below. The cost-effectiveness effect materializes when the marginal cost of offset supply is lower than a firm's composite marginal cost of internal abatement and allowance purchasing. By providing a cheaper compliance alternative, offsets lower the total social cost of achieving the emissions cap. The magnitude of this cost saving is a function of the offset limit (δ_{wc}), the CCER supply elasticity (m), the initial ETS reduction target ($E,\ Q$), and the number of participating firms ($n_1,\ n_2$). Conversely, the environmental target dilution effect arises from a crowding-out phenomenon. The availability of low-cost offsets disincentivizes firms from investing in more substantive, and often more reliable, internal abatement technologies. Although firms meet their nominal compliance obligations, the actual reduction in physical emissions may be less than what a pure cap-and-trade system would induce. This weakens the system's overall environmental integrity, a risk that grows with the offset limit. This inherent trade-off presents a critical challenge for regulators. The primary policy lever to

navigate this trade-off is the offset limit (δ). Its optimal setting must balance multiple, often conflicting, objectives. An excessively high limit can depress the allowance price and amplify the dilution effect, while an overly restrictive limit neuters the mechanism's cost-saving potential. Effective governance, therefore, requires not only a scientifically determined and dynamically adjusted offset limit but also robust institutional oversight to ensure the quality and additionality of offset projects, thereby striking a deliberate balance between economic efficiency and environmental goals.

Thus far, our analysis has assumed a central planner with complete information. We now relax this assumption and turn to a more realistic scenario characterized by asymmetric information, where the CG lacks complete information regarding regional baseline emissions E and must delegate authority to local governments that hold an informational advantage. Specifically, our model will distinguish between regions with and without pilot CCER programs. The key modeling distinction lies in the characterization of local governments, which possess varying degrees of influence or voice.

5. Optimal Delegation Mechanism for CCER Offset Regulation in Non-Pilot Regions

This section investigates the design of an optimal delegation mechanism for regions that have not piloted CCERs (non-pilot regions). The CG aims to design a menu of contracts, specifically, a menu of CCER offset rate, to elicit the LG's private information regarding its regional baseline emissions. Unlike in the full information benchmark, the LG's abatement preferences differ from those of the CG, creating an incentive for misrepresentation. By offering a designed delegation contract, the CG can induce the LG to reveal its true private information (or type), thereby enabling policy decisions that are better aligned with the optimal ones.

First, we consider a scenario where the LG in a non-pilot region is granted full discretion over its CCER offset rate. Based on the analysis in Section 4.2, its optimization problem is as follows:

$$\min_{\delta} W_{LG,np}(\delta) = \min_{\delta} \left[\sum_{i=1}^{n_1} AC_i\big(a_i(\delta)\big) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{LG} D\big(AE(\delta)\big)\right] \; s.t. (13) - (17)$$

By substituting the constraints into the objective function, we derive the optimal offset rate, δ_{LG}, through the first-order condition in Eq.(26):

$$\left[\frac{\delta Q}{n_2 m} - \frac{E-\delta Q-Q+nc'c''}{n_1 c''} + \frac{\alpha_{LG}(1+\delta)Q}{\gamma}\right]Q = 0 \tag{26}$$

$$\delta_{LG} = \frac{(E-Q+n_1 c'c'')/n_1 c''Q - \alpha_{LG}/\gamma}{1/n_1 c'' + 1/n_2 m + \alpha_{LG}/\gamma} \tag{27}$$

Because the LG's objective function assigns a lower weight to environmental damages compared to the central planner, $\partial\delta/\partial\alpha < 0$ implies that the LG will opt for a higher offset rate than the socially optimal one, i.e., $\delta_{LG} > \delta_{CG} = \delta_{wc}$.

To induce truthful reporting, contingent on the LG's reported information $\widehat{E} \in [\underline{E}, \overline{E}]$, the CG must offer a screening contract $\{\delta(\widehat{E})\}_{\widehat{E}\in[\underline{E},\overline{E}]}$ that satisfies the incentive compatibility (IC) constraint as follow:

$$E \in arg\min_{\widehat{E}} \; W_{LG,np}\big(E,\widehat{E}\big) = \sum_{i=1}^{n_1}\left[(c'+\theta_i)a_i(E,\delta(\widehat{E})) + \frac{a_i(E,\delta(\widehat{E}))^2}{2c''_i}\right] + \sum_{j=1}^{n_2}\frac{s_j(\delta(\widehat{E}))^2}{2m_j} + \alpha_{LG}\frac{(\delta(\widehat{E})Q+Q)^2}{2\gamma} \tag{28}$$

The standard revealed preferences arguments indicate that $\delta(E)$ is weakly increasing in E, i.e., $\delta'(E) \geq 0$ and almost everywhere differentiable. And the first-order condition for truth-telling can be obtained as:

$$\delta'(E)\left[\frac{\delta(E)Q}{n_2 m} - \frac{E-\delta(E)Q-Q+nc'c''}{n_1 c''} + \frac{\alpha_{LG}(1+\delta(E))Q}{\gamma}\right]Q = 0 \tag{29}$$

The analysis reveals that the optimal contract takes a specific structural form. The CCER offset rate is either at the discretion of the LG or is set to a fixed level, independent of the reported baseline emissions $\widehat{E}$. The CG can satisfy the incentive compatibility constraint by imposing an upper bound on the discretionary offset rate. This structure is optimal because a LG with a low true baseline (low-type) has an incentive to mimic a high-type to secure a higher offset rate, which further reduces its abatement costs at the expense of diluting the environmental target.

Consequently, the optimal delegation mechanism takes the form of a capped delegation rule, i.e., $\delta(E) = \min\{\delta_{LG}(E^*), \delta_{LG}(E)\}$. Here, the threshold offset rate $\delta_{LG}(E^*)$, which corresponds to a threshold baseline emissions level E^*, is a decision variable for the CG. If the LG's preferred offset rate based on its report is below this threshold, it retains discretion. Otherwise, its choice is constrained by the cap, effectively forfeiting full discretion. Under this framework, the CG's problem is to determine the optimal threshold baseline E^* that maximizes its expected objective function

$W_{CG,np}$. This leads to the following optimization problem for the CG in the non-pilot region under asymmetric information:

$$\min_{E^*} \int_{\underline{E}}^{E^*} \begin{matrix}\sum_{i=1}^{n_1}[(c'+\theta_i)a_i(E,\delta_{LG}(E)) + \frac{a_i(E,\delta_{LG}(E))^2}{2c''_i}] \\ +\sum_{j=1}^{n_2}\frac{s_j(\delta_{LG}(E))^2}{2m_j} + \frac{\alpha_{CG}(\delta_{LG}(E)Q+Q)^2}{2\gamma}\end{matrix} dF(E) + \int_{E^*}^{\overline{E}} \begin{matrix}\sum_{i=1}^{n_1}[(c'+\theta_i)a_i(E,\delta_{LG}(E^*)) + \frac{a_i(E,\delta_{LG}(E^*))^2}{2c''_i}] \\ +\sum_{j=1}^{n_2}\frac{s_j(\delta_{LG}(E^*))^2}{2m_j} + \frac{\alpha_{CG}(\delta_{LG}(E^*)Q+Q)^2}{2\gamma}\end{matrix} dF(E)$$

The solution to this optimization problem under asymmetric information is summarized in Proposition 1 below.

Proposition 1. *For a non-pilot CCER region with asymmetric information on baseline emissions E, the optimal delegation contract offered by the central government for setting the CCER offset rate is a capped delegation rule, implemented as follows:*

$$\delta_{A,np}(E) = \begin{cases}\delta_{LG}(E) & if \quad E \le E^*_{na} \\ \delta_{LG}(E^*_{np}) & if \quad E > E^*_{na}\end{cases} \tag{30}$$

where the local government has partial discretion, and the threshold for baseline emissions, E^*_{np}, is determined by:

$$\frac{\int_{E^*_{np}}^{\bar{E}} EdF(E)}{1-F(E^*_{np})} - E^*_{np} = n_1 c'' Q(\alpha_{CG} - \alpha_{LG})(1+\delta_{LG}(E^*_{np}))/\gamma \tag{31}$$

Thereby, the cap of CCER offset rate $\delta_{LG}(E^*_{np})$ is

$$\delta_{LG}(E^*_{np}) = \frac{(E^*_{np} - Q + n_1 c'c'')/n_1 c''Q - \alpha_{LG}/\gamma}{1/n_1 c'' + 1/n_2 m + \alpha_{LG}/\gamma} \tag{32}$$

For offset regulation in non-pilot CCER regions, Proposition 1 reveals the optimal delegation mechanism under conditions of asymmetric information and potential goal misalignment. The optimal mechanism is neither full delegation nor full control, but rather a conditional, screening-based partial delegation mechanism.

The core of this mechanism is to establish a threshold E^*_{np} for baseline emissions, which effectively screens LGs based on their private information (i.e., their different levels of baseline emissions). The existence of this threshold represents the CG's strategy to elicit the LG's true (or partially true) information at a minimal incentive cost and to calibrate the degree of delegation accordingly. LGs reporting a baseline below the threshold are granted discretion over their offset rates, whereas those reporting above it face a binding cap. This structure is a classic incentive mechanism designed to align the agent's (the LG's) actions with the principal's (the CG's) overall objectives. The determination of this cap reveals how the principal delegates authority to the agent, striking a balance between leveraging the agent's private information and controlling deviations from the central objective. Granting such partial discretion is an effective channel for eliciting and utilizing this private information.

Under full delegation, however, a LG might be tempted to set an excessively high offset rate to lower its abatement costs and alleviate local economic pressures, thereby deviating from the CG's ideal policy. To incentivize the LG to act in a manner more aligned with the central objective (given that the agent possesses private information but has misaligned goals), the CG can implement a cap, $\delta_{LG}(E^*_{np})$, to achieve this balance. This cap is intrinsically linked to the threshold, implying that the discretionary space granted to LG is differentiated by their type. Specifically, the mechanism allows a LG to select its CCER offset rate within the interval $[\delta_{LG}(\underline{E}), \delta_{LG}(E^*_{np})]$. Once the chosen rate hits this upper bound, in other words, when its baseline emissions are sufficiently high to reach or exceed E^*_{np}, the optimal regulatory outcome from the CG's perspective is the cap itself, $\delta_{LG}(E^*_{np})$, as depicted in Figure 1.

This optimal delegation mechanism finds a parallel in practice. According to the Administrative Measures for Carbon Emissions Trading (Trial), entities in China's national carbon market are permitted to use CCERs to offset up to 5% of their verified emissions for the year. The CG places great importance on the overall effectiveness of the carbon market and the effective control of shocks to the carbon allowance (CEA) price. An excessively high offset ratio would allow a large volume of low-cost CCERs to flood the market, which could significantly depress the carbon price and weaken the incentive for firms to invest in abatement technologies and pursue deeper reductions. Therefore, the CG does not want CCERs to excessively dilute the market's abatement function. For LGs focused on economic development, this 5% limit provides greater flexibility and lower compliance costs. From the CG's perspective, this ensures CCERs play a supplementary, not a dominant, role. This can be seen as a prudent, risk-averse strategy adopted in the face of uncertainty, akin to prudently setting the scope of delegation under incomplete information.

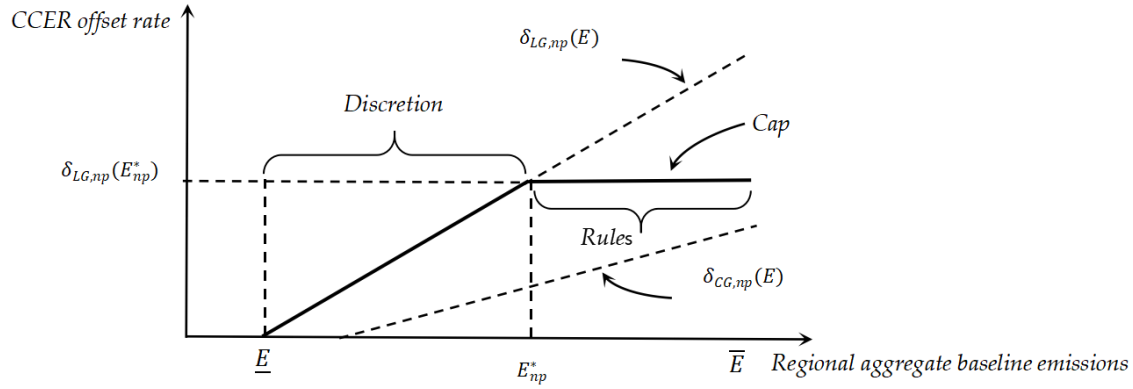


Figure 1. *The optimal delegation contracts offered by the CG for setting the CCER offset rate in a non-pilot region.*

6. Optimal Delegation Mechanism for Offset Regulation in Pilot Regions

This section analyzes the optimal delegation mechanism from the perspectives of both symmetric and asymmetric information. Specifically, we investigate how the CG should design the offset rate standard for a LG that, having already piloted CCER policies in regions like Beijing, Hubei, Guangdong, and Shenzhen, exhibits policy path dependence and possesses significant bargaining power.

6.1. The Benchmark Case: Symmetric Information in Pilot Regions

This subsection examines the benchmark case where the CG has complete information about the pilot region's baseline emissions, E. Since these regions have a history of implementing offset policies, we assume their policy preferences have stabilized. Thus, we can re-examine the LG's optimization problem from Eq.(9) but introduce a fixed incentive payment r. The LG's problem is:

$$\min_{\delta} W_{LG,wp}(E,\delta,r) = \min_{\delta} \left(\sum_{i=1}^{n_1} AC_i(a_i(E,\delta)) + \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + \alpha_{LG} D(AE(\delta)) - \beta r\right) \quad s.t.\,(13)-(17)$$

Substituting the constraints into the objective function, we derive the optimal offset rate δ_{LG} from the first-order condition, and its form is same as Eq.(27). We use $W^f_{LG,wp}$ to denote the utility level the LG obtains by implementing its optimal policy δ_{LG}, where the superscript f signifies that the policy choice is flexible for LG. In this scenario, the CG provides no additional reward, as follows:

$$W^f_{LG,wp}(E) = W_{LG,wp}(E,\delta_{LG}(E),r) \tag{33}$$

where

$$W^f_{LG,wp}{}'(E) = \frac{\partial W_{LG,wp}(E,\delta_{LG}(E),0)}{\partial E} + \underbrace{\frac{\partial W_{LG,wp}(E,\delta_{LG}(E),0)}{\partial \delta}}_{=0}\delta_{LG}{}'(E) = \sum_{i=1}^{n_1} \frac{dAC_i(a_i(E,\delta_{LG}(E)))}{da_i}\frac{\partial a_i(E,\delta_{LG}(E))}{dE} = \frac{E-\delta_{LG}Q-Q}{n_1 c''} + c' > 0 \tag{34}$$

Next, we analyze the relationship between the two levels of government. The objective is to design a contract for a pilot region. Given that pilot regions already have experience with offset policies, we can assume they have a preferred offset rate δ_{LG}. To induce the LG to adopt a policy closer to the CG's ideal, the CG can offer an incentive reward. The contract takes the form of a menu (δ, r), from which the LG makes a selection to accept or reject. By accepting this contract, the LG forgoes its own preferred policy choice in the pilot period and in return receives an incentive reward, r, for its compliance. Above the outside option, i.e., $W^f_{LG,wp}(E)$, the saving rent value of this contract to the LG is:

$$R(E,\delta,r) = W^f_{LG,wp}(E) - W_{LG,wp}(E,\delta,r) = W^f_{LG,wp}(E) - \sum_{i=1}^{n_1} AC_i(a_i(E,\delta)) - \sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) - \alpha_{LG} D(AE(\delta)) + \beta r \tag{35}$$

We then use this rent expression to reformulate the CG's objective function. First, we express the reward r as a function of the other variables and substitute it into the CG's objective function in Eq.(7). The problem can then be restated as minimizing $W_{CG,wp}(E,\delta,r)$:

$$\min_{\delta} W_{CG,wp}(E,\delta,r) = \min_{\delta} \{(1+\beta^{-1})\sum_{i=1}^{n_1} AC_i(a_i(E,\delta)) + (1+\beta^{-1})\sum_{j=1}^{n_2} SC_j\left(s_j(\delta)\right) + (\alpha_{CG} + \beta^{-1}\alpha_{LG})D(AE(\delta)) + \beta^{-1}[R(E,\delta,r) - W^f_{LG,wp}(E)]\}$$

$$s.t.\, R(E,\delta,r) \geq 0 \tag{36}$$

To solve this constrained optimization problem, we construct the Lagrangian function $L_{S,wp}$ as shown in Eq.(37). By differentiating $L_{S,wp}$ with respect to the offset rate δ and setting the result to zero, we obtain the first-order condition (FOC) given by Eq.(38):

$$L_{S,wp}(E,\delta,R(\delta),\lambda) = W_{CG,wp}(E,\delta,r) + \lambda(-R(\delta)) \tag{37}$$

$$\frac{dL_{S,wp}(E,\delta,R(\delta),\lambda)}{d\delta} = \frac{\partial L_{S,wp}}{\partial \delta} + \frac{\partial L_{S,wp}}{\partial R}\underbrace{R'(\delta)}_{=0} = Q[(1+\frac{1}{\beta})(\frac{1}{n_2 m}+\frac{1}{n_1 c''})\delta Q + \frac{(\alpha_{CG}+\frac{\alpha_{LG}}{\beta})(1+\delta)Q}{\gamma} - (1+\frac{1}{\beta})(\frac{E-Q}{n_1 c''}+c')] = 0 \tag{38}$$

Solving this first-order condition for δ yields the optimal offset rate under the CG's policy, $\delta_{S,wp}$:

$$\delta_{S,wp} = \frac{(E-Q+n_1 c' c'')/n_1 c'' Q - (\alpha_{LG}+\beta\alpha_{CG})/\gamma(1+\beta)}{1/n_1 c'' + 1/n_2 m + (\alpha_{LG}+\beta\alpha_{CG})/\gamma(1+\beta)} \tag{39}$$

Given that $\alpha_{LG} < (\alpha_{LG}+\beta\alpha_{CG})/(1+\beta) < \alpha_{CG}$, it follows that $\delta_{LG} > \delta_{S,wp} > \delta_{CG}$.

This analysis shows that even in a pilot region with complete information, the CG must offer a sufficiently high offset rate, higher than its own ideal rate δ_{CG}, to induce the LG to adopt it. This is because participation is voluntary, and adoption can only be incentivized by offering a sufficiently attractive reward. The optimal offset rate $\delta_{S,wp}$ maximizes the joint surplus of the two levels of government. The effectiveness of this reward mechanism is amplified by the LG's sensitivity to it, captured by the parameter β. A larger β indicates that the LG places greater weight on the reward, making the incentive tool more potent. Consequently, by offering a carefully calibrated reward, the CG can more easily induce the LG to deviate from its myopic optimum. This scenario presents a key distinction for the subsequent analysis. Under complete information, since all information is public, the LG's outside option (its reservation utility R) is independent of its type (i.e., its private information E). Mathematically, this means its derivative with respect to E is zero ($R'(\delta) = 0$), as shown in the first-order condition Eq.(38). Therefore, the complexities of incentive compatibility do not arise. However, under incomplete information, R becomes dependent on the LG's private information. This term ($R'(\delta)$) will no longer be zero, representing the critical trade-off between information rent and efficiency, which becomes central to the analysis, as detailed in the next subsection.

6.2. Optimal Delegation under Asymmetric Information in Pilot Regions

We now analyze the case where the CG lacks complete information about the pilot region's baseline emissions, E, which represents the LG's type. Applying the Revelation Principle, we can restrict our attention to direct revelation mechanisms. The CG designs a contract menu $\{\delta(\hat{E}), r(\hat{E})\}_{\hat{E}\in[\underline{E},\overline{E}]}$, contingent on the LG's reported type $\hat{E}$. Upon accepting the contract, a LG of type E reports $\hat{E}$ to minimize its total cost.

The incentive compatibility constraint requires that truth-telling is optimal for the LG:

$$E \in \arg\min_{\hat{E}} W_{LG,wp}\big(E,\delta(\hat{E}),r(\hat{E})\big) \tag{40}$$

where

$$\frac{\partial W_{LG,wp}(E,\delta(\hat{E}),r(\hat{E}))}{\partial \delta}\delta'(\hat{E}) + \underbrace{\frac{\partial W_{LG,wp}(E,\delta(\hat{E}),r(\hat{E}))}{\partial r}}_{=\beta} r'(\hat{E})\Bigg|_{\hat{E}=E} = 0 \tag{41}$$

If the LG rejects the CG's contract, it reverts to its preferred policy from the pilot period, yielding a reservation utility of $W^f_{LG,wp}(E)$. The information rent, $R(E)$, which the LG earns by participating in the mechanism, is thus:

$$R(E) = W^f_{LG,wp}(E) - W_{LG,wp}(E,\delta(E),r(E)) \tag{42}$$

The derivative of the information rent with respect to the LG's type E is:

$$R'(E) = W^f_{LG,wp}{}'(E) - \frac{\partial W_{LG,wp}(E,\delta(E),r(E))}{\partial E} - \underbrace{(\frac{\partial W_{LG,wp}(E,\delta(E),r(E))}{\partial \delta}\delta'(E) + \beta r'(E))}_{=0} = \frac{E-\delta_{LG}Q-Q}{n_1 c''} - \frac{E-\delta Q-Q}{n_1 c''} \tag{43}$$

Eq.(43) is the standard envelope theorem result for an incentive-compatible mechanism. It shows that to induce the LG to reveal its type truthfully, the information rent must vary with its type E. The LG is no longer driven by a single motive to over-report its emissions. Instead, the incentive compatibility condition reflects two conflicting motivations for misrepresentation.

First, as previously discussed, the LG has an incentive to over-report its baseline emissions E. A higher reported E would justify a higher offset rate δ, thereby lowering its abatement costs. To counteract this tendency, the contract must ensure that the information rent decreases as the reported emissions $\widehat{E}$ increase. This makes over-reporting less attractive for low-type governments (those with small E), as reflected in the second term of Eq.(43).

However, a countervailing incentive also exists. The LG's outside option (reservation utility) is also a function of its type E. Specifically, a lower E leads to a lower self-determined offset rate $\delta_{LG}(E)$ and consequently a lower reservation cost (i.e., its outside option is more attractive). This creates an incentive for the LG to under-report its type E. By pretending its outside option is better than it is, it can demand higher compensation (rent) from the CG for participating in the contract. This effect, captured by the first term in Eq.(43), implies that rent should increase with the reported emissions $\widehat{E}$ to reward high-type governments (those with large E) for revealing their less favorable outside options.

Given that $\alpha_{CG} > \alpha_{LG}$, which implies $\delta_{LG,wp} > \delta_{S,wp} > \delta_{CG,wp}$, any accepted contract involves a downward adjustment of the offset rate for LG. In this context, the incentive to over-report emissions to secure a higher offset rate dominates the incentive to under-report. Consequently, the information rent $R(E)$ is ultimately a decreasing function of the LG's type E.

Under the participation and incentive compatibility constraints, the CG's problem for a pilot region under asymmetric information is:

$$\min_{\delta} W_{CG,wp}(E,\delta,r) = \min_{\delta} [(1+\tfrac{1}{\beta})\textstyle\sum_{i=1}^{n_1} AC_i(a_i(E,\delta)) + (1+\tfrac{1}{\beta})\sum_{j=1}^{n_2} SC_j\big(s_j(\delta)\big) + (\alpha_{CG} + \tfrac{1}{\beta}\alpha_{LG})D(AE(\delta)) + \tfrac{1}{\beta}(R(E,\delta,r) - W^f_{LG,wp}(E))] \quad s.t.\,(36)\ and\ (43)$$

To solve this problem, we apply optimal control theory, following established methods (Seierstad and Sydsaeter, 1987; Hartl et al., 1995). We first formulate the Hamiltonian function to satisfy the incentive compatibility constraint, then consider the Kuhn-Tucker conditions for the remaining constraints. As results, we can get the optimal offset rate, i.e., $\delta_{A,wp}$, where the subscript represents asymmetry information, through the first-order condition of the resulting Lagrangian function, as follows:

$$L_{A,wp}(E,\delta,R,\mu,\lambda) = W_{CG,wp}(E,\delta,R)f(E) + \mu R'(E) + \lambda(-R(E)) = [(1+\tfrac{1}{\beta})(\textstyle\sum_{i=1}^{n_1} AC_i(a_i(E,\delta(E))) + \sum_{j=1}^{n_2} SC_j\big(s_j(\delta(E))\big)) + (\alpha_{CG} + \tfrac{1}{\beta}\alpha_{LG})D(AE(\delta(E))) + \tfrac{1}{\beta}(R(E,\delta(E),r) - W^f_{LG,wp}(E))]f(E) + \tfrac{\mu(\delta-\delta_{LG})Q}{n_1 c''} - \lambda R(E) \tag{44}$$

$$\frac{\partial L_{A,wp}(E,\delta,R,\mu,\lambda)}{\partial \delta} = [(1+\tfrac{1}{\beta})(\textstyle\sum_{i=1}^{n_1} \frac{dAC_i(a_i(E,\delta(E)))}{da_i}\frac{\partial a_i(E,\delta(E))}{\partial \delta} + \sum_{j=1}^{n_2} \frac{dSC_j\big(s_j(\delta(E))\big)}{ds_j}\frac{ds_j(\delta(E))}{d\delta}) + (\alpha_{CG} + \tfrac{1}{\beta}\alpha_{LG})\frac{dD(AE(\delta(E)))}{dAE}\frac{dAE(\delta(E))}{d\delta}]f(E) + \frac{\mu Q}{n_1 c''} \tag{45}$$

$$\delta_{A,wp} = \frac{(E - Q + n_1 c' c'')/n_1 c'' Q - (\alpha_{LG} + \beta\alpha_{CG})/\gamma(1+\beta) - \mu(E)\beta/(1+\beta)n_1 c'' Q f(E)}{1/n_1 c'' + 1/n_2 m + (\alpha_{LG} + \beta\alpha_{CG})/\gamma(1+\beta)} \tag{46}$$

From this formulation, we observe a crucial trade-off for pilot regions under asymmetric information. To ensure truthful revelation, the CG must concede information rents to the LG, which is achieved by implementing a distorted CCER offset rate policy. The term $\mu(E)$ represents the co-state variable, or shadow price, associated with the information rent dynamics. It captures the marginal cost to the CG of ensuring truthful revelation. In this adverse selection context, where the LG has an incentive to misreport its type to reduce its costs, information rents represent a direct cost to the principal. Therefore, we can anticipate that $\mu(E)$ will be negative. Under this premise, $-\mu(E)$ is a positive term reflecting the marginal cost of incentive provision. The expression for $\delta_{A,wp}$ (Eq.46) then reveals a crucial insight. A larger incentive cost (a more negative $\mu(E)$) compels the CG to set a higher offset rate $\delta_{A,wp}$. This constitutes a classic trade-off between efficiency and rent extraction: the principal optimally distorts the policy allocation upwards (closer to the agent's preference) to economize on costly information rents. We will formally derive the expression for $\mu(E)$ and verify its sign in Proposition 4.

To solve the principal-agent model, we employ the optimal control method. For tractability, we assume that the LG's type, E, is uniformly distributed on the interval $[\underline{E}, \overline{E}]$. The cumulative distribution function is thus $F(E) = (E - \underline{E})/(\overline{E} - \underline{E})$, and the corresponding probability density function is $f(E) = 1/(\overline{E} - \underline{E})$. We now characterize the optimal contract in Proposition 2.

Proposition 2. *For a pilot CCER region with asymmetric information on baseline emissions E, the optimal delegation contract offered by the central government for setting the CCER offset rate is a partial delegation or no delegation rule, implemented as follows:*

Define $\xi = \frac{\beta(\alpha_{CG}-\alpha_{LG})/\gamma}{1/n_1c'' + 1/n_2m + \alpha_{LG}/\gamma}$, *where* ξ *falls within* $(0,1)$ *due to* $\alpha_{CG} > \alpha_{LG}$ *and to ensure an interior solution.*

a) If $0 < \xi < (\overline{E} - \underline{E})/(\overline{E} + n_1c'c'' + n_1c''Q/n_2m)$, *the optimal contract grants partial discretion to the local government:*

$$\delta_{A,wp}(E) = \begin{cases} \delta_{A1}(E) & if \quad E \le E^*_{wp} \\ \delta_{LG}(E) & if \quad E > E^*_{wp} \end{cases} \tag{47}$$

$$R'_A(E) \begin{cases} < 0 & if \quad E \le E^*_{wp} \\ = 0 & if \quad E > E^*_{wp} \end{cases} \tag{48}$$

where the threshold $E^*_{wp} = \frac{\underline{E} + (c' + Q/n_2m)n_1c''\xi}{1-\xi}$ *and* $\delta_{A1}(E)$ *is defined as:*

$$\delta_{A1}(E) = \frac{(E - Q + n_1c'c'')/n_1c''Q - (\alpha_{LG} + \beta\alpha_{CG})/\gamma(1+\beta) + (E-\underline{E})/(1+\beta)n_1c''Q}{1/n_1c'' + 1/n_2m + (\alpha_{LG} + \beta\alpha_{CG})/\gamma(1+\beta)} \tag{49}$$

For $E \le E^*_{wp}$, *the central government incentivizes a compromise, resulting in an offset rate* $\delta_{A1}(E)$ *that is lower than the local government's preferred rate but higher than the first-best rate, i.e.,* $\delta_{LG}(E) \ge \delta_{A1}(E) > \delta_{S,wp}(E) > \delta_{CG}(E)$.

b) If $(\overline{E} - \underline{E})/(\overline{E} + n_1c'c'' + n_1c''Q/n_2m) \le \xi < 1$, *the local government has no discretion, where*

$$\delta_{A,wp}(E) = \delta_{A1}(E) \quad for \quad E \in [\underline{E}, \overline{E}] \tag{50}$$

$$R'_A(E) = 0 \quad for \quad E \in [\underline{E}, \overline{E}] \tag{51}$$

We now discuss the intuition behind Proposition 2. As illustrated in Figure 2, the LG has an incentive to over-report its type E to secure a higher offset rate and thus lower its abatement costs. To counter this adverse selection problem, the CG's optimal strategy is to offer a distorted delegation contract that concedes information rents for truthful revelation.

The need to pay these rents causes the optimal offset rate $\delta_{A,wp}(E)$ to be distorted upwards relative to the first-best solution $\delta_{S,wp}(E)$. This policy reflects the classic trade-off between allocative efficiency and rent extraction under asymmetric information. The magnitude of this distortion increases with E and vanishes for the lowest type, $\underline{E}$. This "no distortion at the bottom" result is a standard feature in screening models.

The threshold E^*_{wp} determines whether it is worthwhile for the CG to pay information rents to screen different types. When$0 < \xi <$.., the adverse selection problem is sufficiently severe. For efficient types ($E \le E^*_{wp}$), the CG offers a menu of reward contracts to induce separation and approaching to efficient policy, but it pools all inefficient types ($E > E^*_{wp}$) by granting discretion ($\delta_{LG}(E)$) that leaves them with no rent. At this point, the LG's participation constraint is binding. In contrast, when ξ is large, the incentive instrument proves to be highly effective. Consequently, the cost for the CG to steer the LG away from its preferred policy is not substantial. In this scenario, the participation constraint is no longer binding for any type of LG. The CG can thus eliminate the LG's policy discretion entirely and impose a compromised policy across all types ($\delta_{LG}(E) \ge \delta_{A1}(E) > \delta_{S,wp}(E)$).

Our findings are consistent with observed policies. In 2021, the Ministry of Ecology and Environment of China (CMEE) issued the Measures for the Administration of Carbon Emissions Trading (Trial), stipulating that the national offset ratio for compliance cannot exceed 5% of the required carbon emission allowances. This is a uniform rule. However, several pilot markets, launched since 2013, had already established their own rules with higher caps. For instance, the pilot markets in Beijing, Tianjin, Guangdong, and Hubei set the cap at 10%, while Chongqing set it at 8%. Following the launch of the national ETS in 2021, some pilot regions continued to use their original, higher offset rates. Our model provides a political economy explanation for this phenomenon. The rationale is that these pilot regions, likely characterized by higher baseline emission levels (a high E in our model), face significant pressure to reduce abatement costs. From a national perspective, the CG aims to ensure the overall effectiveness of the ETS and thus offers an incentive scheme to induce compromise. However, it is plausible that these LGs, prioritizing local economic development, found the compromise (e.g., accepting the national 5% rate) too costly and chose instead to retain their preferred, more lenient discretionary policies.

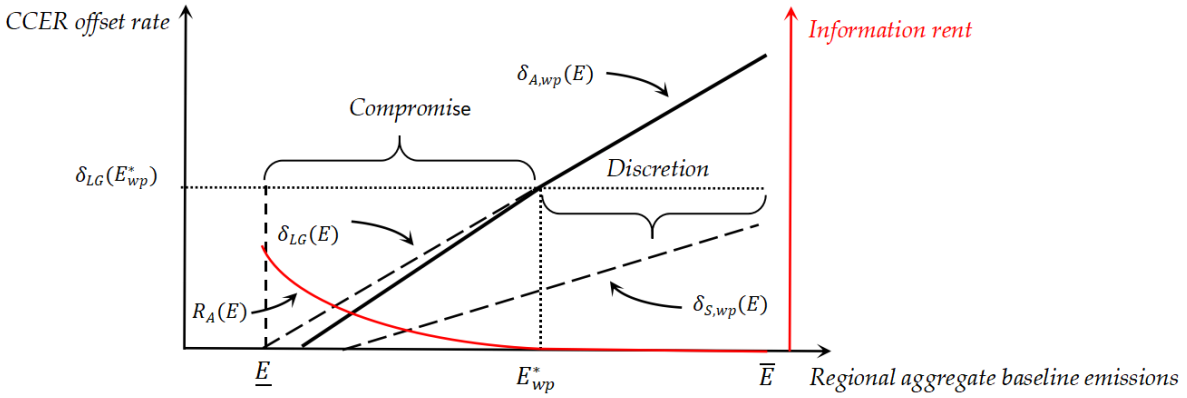


Figure 2. *The optimal delegation contracts offered by the CG for setting the CCER offset rate in a pilot region.*

7. Comparative Analysis and A Unifying Framework: Optimal Delegation under Institutional Path Dependence

Our preceding analyses for pilot-naïve and pilot-experienced regions reveal two distinct optimal delegation schemes. This contrast raises a more fundamental question. One is what are the underlying institutional logics driving these different delegation modes, and the other is what determines the choice between them. This section addresses this core issue by developing a unifying theoretical framework to deepen our understanding of principal-agent dynamics within the context of institutional evolution.

We begin by systematically comparing the optimal mechanisms under both scenarios, highlighting their differences in design, efficiency loss, and rent distribution. In the pilot-naïve setting, the optimal arrangement is an ex-ante power constraint, manifesting as a policy cap linked to the LG's private information. While the LG reports its private information, its policy discretion is directly curtailed by this cap. In sharp contrast, for pilot-experienced regions, the CG cannot unilaterally impose constraints due to the LG's powerful outside option, which is rooted in its historical implementation experience. The optimal strategy shifts to offering a menu of contracts−a policy-incentive bundle $(\delta(E), r(E))$. Here, the reward $r(E)$ functions as a monetary transfer, essentially an ex-post incentive provision. The CG must purchase the LG's cooperation by offering a contract that exceeds the value of its outside option and by adjusting the policy accordingly.

This divergence in mechanism design directly leads to different forms of efficiency loss under asymmetric information. In the non-pilot regime, the core tension is between leveraging local information and controlling policy deviation. The CG manages this risk by imposing a policy cap. This creates a classic distortion, i.e., high-type regions are inefficiently capped, sacrificing informational value, while lower-type regions are allowed some deviation. Agency costs are thus the sum of these distortion and deviation costs. The pilot regime shifts the problem to one of rent extraction. A strong outside option forces the CG to offer incentive payments, creating information rents, i.e., the surplus utility agents receive. These rents, which must be contingent on private information to ensure truth-telling, generate agency costs of a different nature, including the welfare loss from policy distortions designed to reduce these payments, plus the rents themselves, which represent a transfer of social welfare.

To conceptualize these findings more broadly, we introduce the concepts of Greenfield and Brownfield settings. Greenfield refers to a scenario where the principal designs a mechanism for a new initiative, possessing significant design authority. Brownfield, conversely, describes a situation with a pre-existing institutional reality, where the agent has established a status quo policy and a set of vested interests through historical practice. This history effectively grants the agent a status quo veto power, which translates into a powerful, endogenously formed reservation utility. The core distinction lies in the agent's outside option. In a Greenfield setting, it is often exogenously given and normalized to a low level. In a Brownfield setting, it is endogenously created by the agent's own past actions, generating a much higher and type-dependent reservation utility. This analytical lens clarifies our core theoretical argument.

Proposition 3. *The optimal delegation choice depends on the presence of a status quo veto power. (a) In a Greenfield setting, absent a historical precedent, the optimal mechanism is an ex-ante power constraint. (b) In a Brownfield setting, where the agent holds veto power, the optimal mechanism becomes an ex-post incentive scheme, which effectively buys out the agent's cooperation with a transfer payment.*

This framework offers significant generalizability. It not only unifies the specific CCER policy contexts examined in this paper but can also illuminate a wide range of policy reforms and institutional changes. Consider the initial phase of China's economic reforms in the 1980s. The CG established Special Economic Zones (SEZs) on what was essentially "blank slate" territory, a classic Greenfield approach. The policies granted to these zones were a form of delegated authority, but they were strictly defined and limited by the CG. Over several decades, these zones developed into powerful local economies with established practices and significant political clout, forming their own valuable outside options. Any subsequent reform affecting these areas must contend with this reality, shifting the dynamic toward a Brownfield model. A CG initiative to, for instance, unify national tax policy would have to buy in these powerful regions through fiscal transfers or other policy concessions.

A parallel can be drawn to the evolution of Medicaid in the United States. The original Medicaid legislation of 1965 was a Greenfield initiative, creating a new federal-state partnership. States could opt-in to receive federal matching funds. The initial terms, though negotiable, were fundamentally set by the federal government. Decades later, the Affordable Care Act (ACA) of 2010 sought to expand Medicaid. By this point, the existing Medicaid program was a deeply entrenched Brownfield reality. The Supreme Court's ruling effectively gave states a status quo veto power over the expansion. The federal government could not compel participation, and it had to incentivize it by offering to cover 100% of the expansion costs initially, which is a clear example of using ex-post transfers to buy out a powerful status quo.

These examples from diverse domains underscore a central insight from our framework. Any theory of delegation must account for its position in the institutional life cycle. In the creative Greenfield phase, the principal can rely on authority and constraints. In the reform Brownfield phase, where the agent's outside option is a formidable legacy of the past, the principal must rely on negotiation and inducement. The framework we propose provides a powerful lens for understanding this critical distinction.

8. Conclusions

This paper addresses a fundamental challenge in public administration, i.e., how to optimally delegate regulatory authority when historical context creates path dependence. Focusing on China's CCER policy, we develop a unified framework that demonstrates how the optimal mode of delegation fundamentally depends on whether local governments have acquired a status quo veto power through past practice. Our primary contribution is to formalize and distinguish between two governance paradigms, including a greenfield regime, where delegation is a problem of constraining authority, and a brownfield regime, where it becomes a problem of interest exchange.

The core mechanism driving our results is the endogenously formed reservation utility of the agent. In greenfield areas, where local governments lack a strong outside option, the central authority optimally employs ex-ante controls, such as a policy cap, to balance information utilization with risk mitigation. This provides a theoretical rationale for the observed use of uniform caps in new regulatory domains. In brownfield areas, however, historical practice grants local governments a credible threat to revert to the status quo. This forces the principal to shift to ex-post incentive reward contracts and pay information rents over the reservation utility. Critically, this framework provides a game-theoretic explanation for the seemingly puzzling phenomenon of some pilot regions rationally maintaining higher standards than the national mandate, a result driven by the high costs of incentivizing high-type agents to relinquish their advantageous positions.

Our work extends classical principal-agent theory by endogenizing the agent's reservation utility, transforming it from a standard exogenous constant into a type-dependent variable shaped by institutional history. This greenfield versus brownfield distinction offers a generalizable analytical tool for studying institutional change, reform deadlocks, and the strategic design of policies in contexts marked by path dependence. The framework is applicable beyond environmental regulation to areas such as financial supervision, industrial policy, and corporate governance where legacy systems influence current negotiations.

Finally, our analysis is conducted within single period model, which naturally points to a key direction for future research. Since institutional path dependence is an inherently dynamic process, a multi-period model could explore how an agent's veto power evolves. This raises a profound question about intertemporal commitment, regarding does granting greater discretion in the short term, while informationally efficient, inadvertently strengthen an agent's long-term bargaining power and lead to higher future rents? Investigating this dynamic trade-off would offer deeper insights into the strategic challenges of implementing phased reforms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of data availability

All data generated or analysed during this study are included in this published article.

Declaration of ethics

This article does not contain any studies with human participants performed by any of the authors.

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