



# Aligning Market Signals and Policy Incentives for Encouraging Low-Waste Process Innovation in Sustainable Green Manufacturing

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**Abstract-** Manufacturing firms are under growing pressure to improve environmental performance while maintaining operational efficiency, leading to increased adoption of low-waste process innovations. However, the environmental benefits generated within production systems are rarely transparent to external stakeholders, creating information gaps that hinder the effective market evaluation of sustainability-oriented practices. When environmental performance cannot be directly observed, the credibility of firms' sustainability claims becomes a central challenge for both consumers and institutions. This study proposes an analytical framework that explores how manufacturers, consumers, and institutional actors interact in sustainability-focused markets characterized by informational imperfections. The framework examines how economic instruments, assurance arrangements, and public policy measures collectively influence firms' incentives to undertake waste-reducing process improvements. While rising consumer awareness can stimulate demand for greener products, limited verification mechanisms may prompt firms to rely on indirect signaling strategies or engage in opportunistic behavior, potentially weakening market efficiency. Institutional design plays a pivotal role in addressing these challenges. In particular, the structure of subsidy programs and the degree of regulatory credibility shape the effectiveness of sustainability signals transmitted to the market. Well-calibrated policy tools—such as performance-linked incentives, certification support, or preferential procurement rules—can enhance signal reliability and align private decision-making with environmental objectives. The findings indicate that markets are better able to distinguish substantive environmental efforts from symbolic actions when institutional signals are credible and incentive schemes are properly targeted. Overall, the study underscores that meaningful sustainability signaling depends not only on firm-level innovation and consumer preferences, but also on the presence of supportive institutional mechanisms that reduce information asymmetry in modern manufacturing supply chains.

**Keywords:** Emission Reduction, Environmental Audits, Process Innovation, Asymmetric Information.

## I. Introduction

Climate change and environmental degradation have intensified global concern over carbon emissions generated by industrial production systems. According to the IPCC (2023), manufacturing and energy-related activities remain among the largest contributors to global greenhouse gas emissions, posing persistent challenges to achieving climate mitigation targets. Recent evidence further indicates that global CO<sub>2</sub> emissions continue to rise despite international commitments and policy interventions (International Energy Agency, 2022). These trends suggest that emission reduction in manufacturing remains a critical and unresolved global challenge. Addressing this issue therefore requires more than technological advancement alone and calls for a deeper understanding of firms' strategic responses to environmental regulation.

Manufacturers do not respond passively to environmental policies; rather, they strategically adjust prices, output, and emission-reduction efforts in anticipation of both regulatory actions and competitors' behavior. In competitive markets, firms internalize regulatory constraints as part of their strategic decision-making processes. Game-theoretic studies have shown that carbon policies fundamentally reshape firms' incentives, with equilibrium outcomes driven by strategic interaction effects rather than direct regulatory control (Zhao et al., 2024). Consequently, the effectiveness of environmental policy depends critically on how firms interpret and respond to regulatory signals. Governments therefore play a central role in shaping firms' environmental strategies through regulatory supervision, enforcement mechanisms, and incentive design. Existing research indicates that credible government intervention can significantly influence supply chain coordination and firms' emission-reduction decisions (Zhang et al., 2024). However, when regulatory signals are inconsistent or weak, firms may reduce their incentives to invest in long-term emission abatement, even in the presence of formal



regulation (Pun et al., 2025). These findings imply that government intervention functions not merely as an administrative constraint, but as a strategic signal that shapes firms' expectations and behavior.

A fundamental challenge in environmental regulation lies in the limited observability of firms' actual emission-reduction efforts. Governments and consumers often cannot directly verify abatement actions, creating opportunities for symbolic compliance or strategic misreporting. Liao et al. (2022) demonstrates that regulation under asymmetric information can induce moral hazard, thereby weakening the effectiveness of supervision and incentive mechanisms. As a result, information asymmetry plays a critical role in shaping firms' strategic incentives and regulatory outcomes. Although prior studies have extensively examined carbon emission reduction using game-theoretic approaches, many assume perfect observability of firms' actions. This assumption limits the ability of existing models to capture realistic regulatory environments characterized by uncertainty and imperfect enforcement. Li et al. (2023) argue that information asymmetry can significantly distort firms' responses to environmental policies, leading to inefficient regulatory outcomes. These limitations suggest that existing models may overestimate policy effectiveness and underscore the need for frameworks that explicitly incorporate informational constraints.

To address these shortcomings, recent research has increasingly adopted dynamic game-theoretic frameworks to analyze carbon emission reduction over time. Meng et al. (2022) show that differential game models effectively capture the intertemporal trade-offs between short-term profitability and long-term environmental performance by modeling regulators and firms as strategic actors whose decisions evolve dynamically. Building on this perspective, the present study develops a game-theoretic framework that explicitly incorporates asymmetric information in manufacturer–government interactions for carbon emission reduction. By comparing scenarios without intervention, with regulatory supervision, and with subsidy-based incentives, the analysis reveals how policy instruments interact with firms' strategic behavior. Evolutionary considerations further enrich the framework by capturing adaptive responses over time. Overall, this study contributes to a deeper understanding of carbon regulation by linking strategic interaction with informational constraints. The remainder of the paper is organized as follows. Section 2 reviews the related literature, Section 3 presents the model, Section 4 discusses the equilibrium results, and Section 5 concludes.

## II. Literature Review

### 2.1 Game Theory for Carbon Emissions

Game theory has become a central analytical framework for examining carbon emission reduction because it explicitly captures strategic interdependence among decision-makers operating under regulatory and competitive pressure. Early studies show that firms' emission-reduction and pricing decisions are not independent but are shaped by expectations regarding competitors' responses and market demand sensitivity (Cao et al., 2017). In carbon-regulated markets, such strategic anticipation determines whether regulatory policies lead to effective emission reduction or merely redistribute costs across firms (Li et al., 2021). These findings suggest that environmental policies must be evaluated within a strategic interaction framework rather than through isolated firm-level optimization.

To represent hierarchical decision environments common in environmental governance, many scholars adopt Stackelberg game structures. In these models, leaders—often governments or dominant firms—commit to policy or strategic variables first, while followers respond optimally. Peng et al. (2018) demonstrate that leadership structure significantly affects emission-reduction outcomes in vertically structured supply chains, indicating that the order of strategic moves plays a critical role in policy effectiveness. Beyond static leadership settings, dynamic considerations further enrich game-theoretic carbon research. Li et al. (2025) develop a differential game model of joint emission reduction, showing how firms balance short-term profitability against long-term environmental performance. Similarly, Chen et al. (2023) analyze emission-reduction decisions under cap-and-trade regulation and find that intertemporal coordination improves both economic and environmental outcomes. In construction supply chains, further show that dynamic game models better capture the persistence of emission-reduction incentives than static formulations.

Beyond assumptions of perfect rationality, evolutionary game theory has been introduced to analyze adaptive behavior in carbon regulation contexts. Chen and Hu (2018) employ an evolutionary framework to study governments and manufacturers' adaptive strategies under carbon taxes and subsidies, revealing that stable low-carbon equilibria emerge only when incentive alignment outweighs opportunistic behavior. This perspective provides important insights into gradual behavioral adjustment processes that static equilibrium models cannot capture. Recent research further extends game-theoretic analysis toward market-based mechanisms and computational settings. Wang et al. (2021) conceptualize pollution trading as a mathematical game, illustrating how trading rules and participation incentives shape strategic behavior. Meanwhile, Li et al. (2024) integrate Stackelberg games with algorithmic solution methods to address complex low-carbon decision environments, reflecting a broader shift toward hybrid analytical–computational frameworks.



Recent studies also incorporate demand-side factors into game-theoretic models by accounting for consumer environmental awareness. When demand is sensitive to perceived environmental performance, firms face a dual incentive structure involving both market competition and regulatory pressure. Differential and Stackelberg game models show that stronger consumer green preferences amplify firms' incentives to invest in emission reduction, even in the absence of stringent regulation (Ma et al., 2021). This stream of research highlights the importance of demand heterogeneity in shaping equilibrium outcomes and suggests that market forces may partially substitute for regulatory enforcement. Another important extension examines coordination and cooperation mechanisms among firms facing collective emission targets. Cooperative and coalition-based game models demonstrate that coordinated emission-reduction strategies can achieve Pareto improvements relative to non-cooperative equilibria, particularly when abatement technologies exhibit spillover effects. Jin et al. (2022) show that cooperative allocation of emission-reduction responsibility leads to more stable and efficient outcomes in regulated industries, indicating that cooperative game theory complements non-cooperative approaches by providing insights into responsibility sharing and cost allocation in carbon mitigation.

## 2.2 Government Interactions

A substantial body of literature focuses on strategic interactions between manufacturers and governments, emphasizing how regulatory authority shapes firms' environmental decisions. In these settings, governments influence firm behavior through supervision, emission standards, or policy commitments, while manufacturers respond strategically. Chen et al. (2020) show that government intervention reshapes equilibrium outcomes by altering firms' expectations regarding regulatory responses, particularly in supply-chain contexts. Regulatory credibility and consistency are repeatedly identified as key determinants of policy effectiveness. Zhang et al. (2024) demonstrate that when regulatory policies are perceived as unstable or subject to revision, firms adopt conservative emission-reduction strategies to hedge against uncertainty. Such strategic caution may weaken the intended environmental impact of regulation, even when formal policy targets are stringent. Information asymmetry further complicates manufacturer–government interactions. Zhu et al. (2024) show that when governments cannot perfectly observe firms' true emission-reduction effort, regulatory mechanisms may induce moral hazard and strategic misreporting. Under these conditions, firms may comply symbolically rather than substantively, reducing the effectiveness of environmental regulation.

## 2.3 Subsidy Policy

Subsidy policies are widely studied as instruments for encouraging carbon emission reduction by lowering firms' effective abatement costs. Game-theoretic analyses show that subsidies influence not only emission-reduction effort but also pricing and output decisions. Chen et al. (2024) demonstrate that subsidies can accelerate emission-reduction investment in the short run, but their long-term effectiveness depends on sustained policy commitment. Dynamic models further reveal diminishing returns to subsidy-based regulation. Chen et al. (2023) show that as carbon accumulates over time, the marginal effectiveness of subsidies declines, implying that increasing subsidy intensity alone may not guarantee sustained emission reduction. Huang et al. (2024) further demonstrate that coordinated subsidy schemes outperform decentralized approaches when firms face intertemporal trade-offs between profit and environmental performance. Subsidy effectiveness is also sensitive to information asymmetry. Sarkar et al. (2023) argue that when emission-reduction effort cannot be verified, subsidies may incentivize signaling behavior rather than genuine abatement. In such cases, public funds risk being inefficiently allocated, highlighting the need to combine subsidies with monitoring or credibility-enhancing mechanisms. Accordingly, subsidy policies are increasingly analyzed within multi-actor governance frameworks that involve governments, manufacturers, and third-party institutions. Tripartite evolutionary game models reveal that subsidy effectiveness depends not only on subsidy magnitude but also on supervision intensity and institutional coordination. Li et al. (2024) demonstrate that dual supervision mechanisms combined with subsidies can stabilize low-carbon strategies by discouraging opportunistic behavior. This line of research underscores that subsidy-based regulation is most effective when embedded within broader governance structures that address both incentive provision and strategic compliance.

## III. Methodology

Environmental improvement in manufacturing often takes place within internal production processes that are difficult for external parties to observe, making it challenging for consumers and policymakers to accurately assess a firm's true environmental performance. In such contexts, manufacturers typically possess private information regarding their actual emission-reduction activities, while market participants must rely on indirect indicators to form expectations about environmental responsibility. As a result, environmental effort becomes a strategic choice that is communicated rather than verified, influencing market demand through perception instead of direct measurement. Observable decisions—such as pricing or declared emission-reduction commitments—therefore function as signals that shape consumer beliefs under imperfect information. This

informational gap allows firms to strategically manage how environmental performance is perceived, even when the authenticity of such claims cannot be fully confirmed. The analytical setting considered in this study is applicable under several realistic market conditions. Consumers are assumed to exhibit positive environmental awareness while remaining unable to directly verify the accuracy of manufacturers' environmental claims, leading demand to depend on perceived rather than actual emission reduction. Regulatory authorities are assumed to operate through credibility enhancement rather than strict enforcement, reflecting institutional environments where trust-based supervision plays a dominant role. In such cases, regulatory involvement can be represented by a credibility parameter, with full supervision corresponding to a high-trust scenario ( $\delta = 1$ ). Furthermore, environmental initiatives are assumed to involve increasing marginal costs, ensuring that excessive signaling or effort is economically constrained. Subsidy mechanisms, when present, are standardized and not conditional on perfectly observed outcomes, making the framework particularly suitable for markets characterized by persistent information asymmetry.

Within this environment, market interactions unfold through a sequence of strategic decisions that jointly determine price setting, environmental signaling, and demand realization. Manufacturers first choose their pricing and declared emission-reduction effort to balance expected market benefits against the associated signaling and operational costs. Consumers then respond to these observable signals, forming demand based on expected environmental performance as reflected in the corresponding demand functions, such as  $D_M$ ,  $D_G$ , and  $D_S$  under different institutional settings. Government involvement, when introduced, does not directly alter production decisions but instead affects how strongly environmental claims influence demand, thereby reshaping consumer response rather than firm technology. This structure allows the framework to be applied to a wide range of practical situations, including reputation-based green branding, voluntary environmental disclosure, and policy initiatives aimed at strengthening market confidence in sustainability claims.

**Table 3.** 1 Notation that will be used

Notation	Description
$i = M, G, S$	Index for strategy M, G, S respectively
$\theta$	cost coefficients of carbon emitted manufacturers made
$D$	Demand market
$\alpha$	potential market size
$\xi$	price sensitivity coefficient of consumers
$\gamma$	the green performance coefficient of the consumer
$e$	Emission reduction effort
$\pi$	Profit
$c$	cost of product made
$\sigma$	subsidy sensitive factor for consumers
$\delta$	regulator trust on the manufacturer's reputation
$S$	initial subsidy from the regulator
<b>Decision variables</b>	
$p(e)$	price of the product
$s(e)$	subsidy from the regulator

To examine how alternative institutional arrangements influence strategic behavior under asymmetric information, three distinct environments are analyzed in this study. The first, referred to as Market Signalling Strategy, represents a baseline market setting in which firms operate without external intervention and demand is driven solely by consumer perception, as reflected in  $D_M$ . The second, denoted as Regulator Strategy, introduces supervisory oversight ( $\delta > 0$ ) that enhances the credibility of environmental claims, leading to an adjusted demand response captured by  $D_G$ . The third, labeled Subsidy Strategy, incorporates sales-based financial support that directly affects firm incentives while maintaining imperfect observability of environmental effort, resulting in demand  $D_S$ . Together, these three strategies provide a structured basis for comparing how market forces, institutional trust, and fiscal incentives interact to shape firm behavior and environmental outcomes in the presence of asymmetric information.

### 3.1 Market Signaling Strategy

The baseline setting is designed to represent a market environment in which environmental performance cannot be directly verified and no institutional intervention is present. Under this condition, the manufacturer operates purely based on market signals, and demand is formed through consumer perception rather than factual confirmation of emission reduction. The structure reflects a competitive tension between market expansion and cost containment, governed by several implicit constraints. Market potential, captured by the parameter  $\alpha$ , defines the upper bound of demand in the absence of price and environmental considerations, while the price sensitivity parameter  $\xi$  ensures that excessive pricing leads to demand contraction. At the same time, environmental signaling is assumed to be costly, with increasing marginal costs preventing unbounded

declarations of emission reduction effort. These constraints ensure that the baseline scenario yields economically meaningful outcomes and provides a stable benchmark for evaluating policy-driven alternatives.

$$D_M = \alpha - \xi p_M + \gamma e_M \quad (1)$$

Within this framework, baseline demand  $D_M$  is jointly determined by price decisions and the perceived environmental commitment of the manufacturer. The parameter  $\gamma$  reflects the degree of consumer environmental awareness, indicating how strongly declared emission-reduction effort influences purchasing behavior. A higher value of  $\gamma$  implies that consumers place greater weight on environmental considerations when making decisions, whereas lower values reduce the importance of such claims. Price enters demand through the coefficient  $\xi$ , capturing the trade-off between affordability and perceived quality. On the profit side, the unit production cost  $c$  directly affects the firm's pricing strategy by narrowing the feasible margin between price and cost. Although no subsidy is provided in this baseline setting, the parameter  $\sigma$  is retained to characterize the broader policy environment and serves as a reference for later analysis, highlighting the absence of demand-side financial support. Together, these parameters establish a clear relationship between market characteristics, consumer preferences, and the manufacturer's strategic choices.

$$\pi_M = (p_M - c)D_M - \theta(e_M)^2 \quad (2)$$

This baseline configuration reveals both beneficial and restrictive features inherent in a market governed solely by consumer perception. When the potential market size  $\alpha$  is large and environmental awareness  $\gamma$  is sufficiently strong, manufacturers may find it profitable to engage in environmental signaling even without external incentives. However, high price sensitivity  $\xi$  or elevated production costs  $c$  can limit the effectiveness of such strategies, shifting emphasis toward price competition rather than environmental differentiation. The lack of financial support, as reflected by the absence of  $\sigma$ -related effects, further constrains the firm's ability to leverage environmental claims to expand demand. As a result, outcomes under this setting depend critically on the interplay among market scale, consumer awareness, and cost structure, creating conditions where perceived environmental responsibility may or may not translate into tangible economic benefits. This makes the baseline case a necessary reference point for assessing how supervision and subsidy mechanisms alter incentives and market dynamics under asymmetric information.

$$\pi_M^* = \frac{\theta(\alpha - c\xi)^2}{-\gamma^2 + 4\theta\xi} \quad (3)$$

Solving the manufacturer's profit-maximization problem yields closed-form equilibrium solutions for the reported emission-reduction effort and product price. The equilibrium effort level is given by

$$e_M^* = \frac{-\alpha\gamma + c\gamma\xi}{\gamma^2 - 4\theta\xi} \quad (4)$$

which reflects the balance between demand expansion driven by consumer environmental awareness and the increasing marginal cost of signaling environmental performance. A higher value of  $\gamma$  strengthens the incentive to declare greater effort, while larger production cost  $c$  and price sensitivity  $\xi$  jointly weaken this incentive by raising the effective cost of sustaining environmental claims. The condition  $\gamma^2 - 4\theta\xi > 0$  guarantees profit concavity and ensures the existence of a unique interior equilibrium. Correspondingly, the equilibrium price is

$$p_M^* = \frac{c\gamma^2 - 2\alpha\theta - 2c\theta\xi}{\gamma^2 - 4\theta\xi} \quad (5)$$

indicating that pricing decisions internalize both production cost and effort-related expenses in the absence of institutional support.

Substituting  $p_M$  and  $e_M$  into the profit function yields the equilibrium profit  $\pi_M$ , which captures the net outcome of market-driven pricing and costly environmental signaling under asymmetric information. Because profit is endogenously determined by the joint choice of price and effort, its magnitude depends on the combined effects of market potential  $\alpha$ , consumer awareness  $\gamma$ , cost structure  $c$ , and effort cost intensity  $\theta$ . Importantly, the same concavity condition that governs price and effort also bounds equilibrium profit, preventing excessive pricing or unrestrained effort declarations from being privately optimal. As a result, Strategy M characterizes a purely market-based outcome in which environmental behavior emerges only when it enhances private profitability, thereby serving as a natural benchmark for evaluating how supervision and subsidy mechanisms reshape incentives and equilibrium outcomes in subsequent strategies.

### 3.2 Government Strategy

The second strategic environment extends the baseline setting by incorporating regulatory supervision that modifies how environmental claims influence market demand, while preserving the same fundamental cost and pricing structure as in Strategy M.

$$D_G = \alpha - \xi p_G + (\gamma + \delta)e_G \quad (6)$$

The key difference lies in the presence of a trust mechanism, captured by the supervision parameter  $\delta$ , which strengthens the credibility of declared emission-reduction effort without imposing direct financial intervention. Market potential  $\alpha$  and price sensitivity  $\xi$  continue to govern the basic demand structure, ensuring that demand remains decreasing in price and positive within a feasible range. To guarantee meaningful outcomes, unit production cost  $c$  is assumed to satisfy  $c < 1$ , ensuring that positive margins can be sustained under reasonable pricing decisions. Regulatory supervision thus operates by reshaping consumer interpretation of environmental signals rather than altering the manufacturer's technological or cost constraints, reflecting policy environments where oversight enhances transparency rather than enforcement.

$$\pi_G = (p_G - c)D_G - \theta(e_G)^2 \quad (7)$$

The impact of this strategy depends critically on the magnitude of consumer environmental awareness  $\gamma$ , which is assumed to be non-negative ( $\gamma \geq 0$ ) and reflects the extent to which consumers value environmental responsibility. When  $\gamma$  increases, demand becomes more responsive to declared emission-reduction effort in both Strategy M and the Regulator Strategy; however, the presence of supervision amplifies this response by increasing the perceived reliability of environmental claims. Price sensitivity  $\xi$  continues to limit the firm's ability to raise prices, but under regulatory supervision, environmental differentiation can partially offset this constraint by sustaining demand at higher price levels. In contrast, parameters associated with monetary incentives, such as  $\sigma$ , remain inactive in this setting, implying that changes in subsidy-related conditions do not affect outcomes under this strategy. As a result, while both strategies respond to shifts in  $\gamma$  and  $\xi$ , regulatory supervision creates an environment in which environmental awareness plays a more decisive role in shaping demand.

Beyond parameter sensitivity, the Regulator Strategy introduces a distinct balance between market discipline and institutional influence. By enhancing the credibility of environmental claims, supervision encourages more disciplined signaling behavior, reducing the incentive to rely solely on aggressive pricing or exaggerated declarations. At the same time, the absence of direct financial support means that firms must still internalize the full cost of environmental signaling, maintaining a natural constraint on excessive claims. The effectiveness of this approach therefore depends on the stability of regulatory credibility and the consistency of consumer response. When institutional trust is sustained, supervision can guide market outcomes toward improved environmental performance without distorting cost structures; when trust weakens, its influence diminishes accordingly. This strategy thus illustrates how credibility-based governance can shape firm behavior under asymmetric information while preserving market-driven incentives.

$$e_G^* = -\frac{(\gamma + \delta)(\alpha - c\xi)}{\gamma^2 + 2\gamma\delta + \delta^2 - 4\theta\xi} \quad (8)$$

$$p_G^* = \frac{-2\alpha\theta + c(\gamma^2 + 2\gamma\delta + \delta^2 - 2\theta\xi)}{\gamma^2 + 2\gamma\delta + \delta^2 - 4\theta\xi} \quad (9)$$

$$\pi_G^* = \frac{\theta(\alpha - c\xi)^2}{-(\gamma + \delta)^2 + 4\theta\xi} \quad (10)$$

Relative to the baseline case, the introduction of supervision effectively amplifies consumer responsiveness to environmental claims through the term  $(\gamma + \delta)$ , reflecting the role of regulatory trust in enhancing the credibility of reported effort. This amplification raises the marginal return to effort, thereby increasing  $e_G^*$  whenever supervision intensity  $\delta$  is sufficiently large. At the same time, higher effort cost intensity  $\theta$  and price sensitivity  $\xi$  continue to restrict both effort and pricing flexibility, as reflected in the common denominator governing equilibrium existence. The profit expression shows that, although supervision can strengthen incentives for effort provision, it does not eliminate the fundamental cost burden associated with emission-reduction signaling, implying that profitability remains bounded by the same effective market surplus term  $(\alpha - c\xi)$ . Overall, Strategy G illustrates how supervision reshapes equilibrium behavior primarily by enhancing demand-side credibility rather than by directly altering cost structures.

### 3.3 Subsidy Strategy

The subsidy-based strategy extends the regulatory environment by introducing direct financial support to the manufacturer in the form of a sales subsidy, while maintaining the same informational limitations regarding environmental performance. Unlike the Regulator Strategy, which influences market outcomes solely through

credibility enhancement, this setting alters the manufacturer's revenue structure by increasing the effective margin earned from each unit sold.

$$D_s = \alpha - \xi p_s + (\gamma + \delta)e_s \quad (11)$$

The subsidy parameter  $s$  enters the profit formulation additively to the price–cost margin, reflecting a policy instrument designed to stimulate production and market participation rather than directly conditioning support on verified emission reduction. To ensure that the subsidy does not eliminate the firm's cost discipline, it is assumed that  $s \geq 0$  and  $p - c + s > 0$ , guaranteeing that the manufacturer remains profit-oriented rather than subsidy-dependent. This design captures policy environments where governments seek to encourage greener products through output-based incentives while accepting that environmental effort itself cannot be perfectly audited.

$$\pi_s = (p_s - c + s)D_s - \left(\frac{1}{2}\right)\theta(e_s)^2 + S \quad (12)$$

The demand structure under this strategy, denoted by  $D_s$ , retains the same fundamental components as in the previous settings, with market potential  $\alpha$ , price sensitivity  $\xi$ , and consumer environmental awareness  $\gamma$  jointly determining baseline purchasing behavior. Regulatory supervision continues to operate through the trust parameter  $\delta$ , strengthening the demand response to declared emission-reduction effort when  $\delta > 0$ . In this sense, the subsidy strategy does not replace supervision but complements it by simultaneously enhancing revenue incentives and perceived credibility. For demand to remain economically meaningful, standard feasibility conditions such as  $\alpha - \xi p_s > 0$  and  $\gamma \geq 0$  are implicitly required. These conditions ensure that demand reacts positively to environmental claims and negatively to excessive pricing, preserving consistency with consumer behavior in green markets.

From the manufacturer's perspective, the inclusion of the subsidy modifies the trade-off between pricing, environmental signaling, and cost. A higher subsidy rate  $s$  relaxes the effective constraint imposed by the unit production cost  $c$ , allowing the firm to sustain competitive pricing even when signaling higher levels of emission reduction. However, the convex cost associated with declared effort, governed by the parameter  $\theta$ , continues to impose increasing marginal costs, ensuring that environmental signaling remains economically bounded. In particular, for interior solutions to exist, it is required that  $\theta > 0$ , preventing unrestrained expansion of declared effort. This structure reflects the reality that, although subsidies can offset part of the financial burden, environmental initiatives still require organizational, technological, and managerial resources that cannot be scaled indefinitely at low cost.

The interaction between key parameters reveals how the subsidy strategy reshapes incentives relative to the previous settings. When consumer environmental awareness  $\gamma$  is relatively low, the subsidy may primarily stimulate demand through price competitiveness rather than environmental differentiation. Conversely, when  $\gamma$  is sufficiently large, the combined effect of supervision ( $\delta > 0$ ) and subsidy  $s$  amplifies the demand response to declared emission-reduction effort, making environmental signaling a more attractive strategic lever. Price sensitivity  $\xi$  continues to constrain excessive price increases, but the subsidy effectively softens this constraint by allowing the firm to maintain demand at lower consumer prices. In contrast to the Regulator Strategy, this setting introduces a direct fiscal channel through which government policy influences firm behavior, making outcomes more sensitive to subsidy magnitude than to changes in trust alone.

$$e_s^* = -\frac{(\gamma+\delta)(\alpha+(-c+s)\xi)}{\gamma^2+2\gamma\delta+\delta^2-2\theta\xi} \quad (13)$$

$$p_s^* = \frac{-\alpha\theta+c(\gamma^2+2\gamma\delta+\delta^2-\theta\xi)-s(\gamma^2+2\gamma\delta+\delta^2-\theta\xi)}{\gamma^2+2\gamma\delta+\delta^2-2\theta\xi} \quad (14)$$

$$\pi_s^* = S - \frac{\theta(\alpha+(-c+s)\xi)^2}{2(\gamma+\delta)^2-4\theta\xi} \quad (15)$$

Compared with regulatory supervision alone, the introduction of a per-unit subsidy  $s$  directly modifies the effective cost term entering both demand and pricing decisions, thereby relaxing the cost constraint faced by the manufacturer. This effect increases the marginal return to effort through the adjusted surplus component  $\alpha+(-c+s)\xi$ , implying that higher subsidies can induce stronger effort provision even when production costs or price sensitivity are relatively high. At the same time, the supervision-related credibility term  $(\gamma+\delta)$  continues to amplify demand responsiveness, indicating that subsidies are most effective when combined with credible oversight. The profit expression shows that subsidy support partially offsets the cost of effort provision, but profitability remains bounded by effort cost intensity  $\theta$  and demand curvature, highlighting that financial incentives enhance but do not fully replace market discipline. Overall, Strategy  $S$  demonstrates how incentive-based regulation reshapes equilibrium behavior by jointly lowering effective costs and strengthening demand-side responsiveness under asymmetric information.

## IV. Results

Building on the analytical formulations developed in Chapter 3, this chapter examines how the equilibrium outcomes differ across the three strategic environments. The focus is placed on the comparative behavior of key decision variables as fundamental parameters vary, allowing for a systematic assessment of how market conditions and policy instruments shape strategic choices under asymmetric information. To facilitate this comparison, the results are organized along three dimensions that are central to the manufacturer's decision-making process: product pricing, profit performance, and declared emission-reduction effort. The following subsection begins by comparing equilibrium prices across strategies, providing a foundation for understanding how subsequent differences in profitability and effort emerge under alternative institutional settings.

### 4.1 Price Comparison

The equilibrium pricing behavior under the three strategic environments illustrated in Figure 4.1 as the emission-reduction cost parameter  $\theta$  varies. A clear differentiation emerges among the manufacturer-only strategy, the regulator-supervised strategy, and the subsidy-based strategy. In the absence of policy intervention, the equilibrium price  $p_M$  remains relatively stable across the range of  $\theta$ , indicating that cost pressure associated with emission reduction is only weakly transmitted to market prices when environmental claims rely solely on consumer perception. By contrast, prices under regulatory supervision, denoted by  $p_G$ , exhibit a moderate downward trend as  $\theta$  increases. This pattern reflects the role of supervision in strengthening the credibility of environmental claims, which allows manufacturers to maintain demand without relying excessively on higher prices. The subsidy-based price  $p_S$  shows the most pronounced decline, particularly at higher values of  $\theta$ , highlighting the ability of sales subsidies to absorb part of the cost burden and reduce price pass-through to consumers.

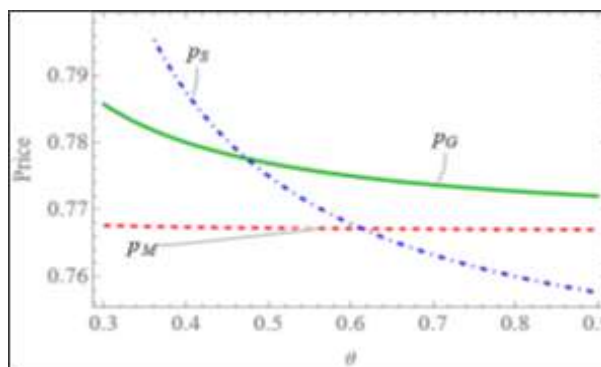


Figure 4.1 Price comparison on  $\theta$

The observed pricing patterns reveal distinct economic mechanisms underlying each strategy. Under *Strategy M*, the manufacturer faces the full cost of emission-reduction signaling while lacking institutional support, leading to conservative pricing adjustments that prioritize margin stability. Under *Strategy G*, supervision enhances perceived environmental value, partially compensating for rising costs and enabling more flexible pricing decisions. However, because no direct financial transfer is provided, price reductions remain limited. In contrast, *Strategy S* directly relaxes the effective marginal cost through subsidies, allowing firms to lower prices more aggressively without sacrificing profitability. As a result, consumers benefit from lower prices, while the policy instrument indirectly mitigates the negative demand effects associated with higher emission-reduction costs. These differences underscore how alternative policy instruments redistribute cost burdens between manufacturers and consumers.

From a broader perspective, the price comparison highlights how policy design influences market accessibility under asymmetric information. When emission-reduction costs rise, reliance on market-based credibility alone may not be sufficient to prevent price increases that discourage consumption. Regulatory supervision improves price stability by enhancing trust, but its effect remains constrained by cost considerations. Subsidies, on the other hand, directly intervene in the pricing mechanism, offering a more immediate means of sustaining affordability. This comparison suggests that subsidy-based policies are more effective in shielding consumers from cost escalation, while supervision-based approaches primarily operate through reputational and demand-side channels.

### 4.2 Profit Comparison

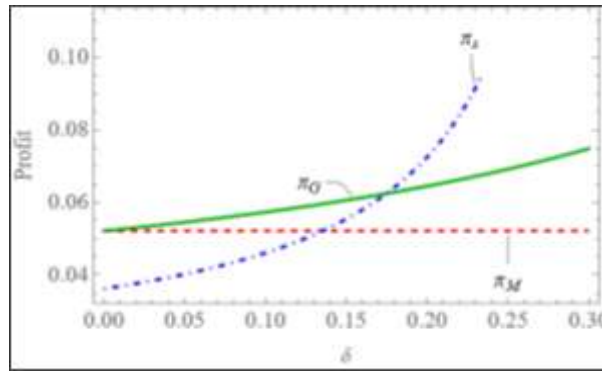


Figure 4.2 Profit comparison on  $\delta$

Figure 4.2 presents the equilibrium profit outcomes for the manufacturer under the three strategies as the level of regulatory trust  $\delta$  increases. The baseline profit  $\pi_M$  remains constant across all values of  $\delta$ , reflecting the absence of institutional interaction in the manufacturer-only strategy. In contrast, profits under regulatory supervision,  $\pi_G$ , increase steadily with  $\delta$ , indicating that enhanced credibility improves market response and revenue generation even without direct financial support. The most notable pattern emerges under the subsidy strategy, where  $\pi_S$  rises sharply as  $\delta$  increases, eventually surpassing both  $\pi_M$  and  $\pi_G$  by a substantial margin. This nonlinear growth highlights the complementary relationship between trust-based supervision and financial incentives.

The differing profit trajectories reveal how institutional credibility interacts with firm incentives under asymmetric information. Under *Strategy G*, increased trust strengthens the effectiveness of environmental signaling, translating into higher demand and improved profitability. However, because firms continue to bear the full cost of emission-reduction effort, profit growth remains moderate. Under *Strategy S*, subsidies directly enhance the firm's revenue structure, and when combined with higher trust levels, they significantly magnify the returns to environmental signaling. In this setting, credibility not only boosts demand but also increases the marginal benefit of each subsidized unit sold, producing an accelerating profit effect as  $\delta$  rises. This contrasts sharply with the baseline case, where profits are insulated from institutional dynamics and remain insensitive to changes in trust.

These results emphasize the importance of aligning policy instruments with informational conditions. Supervision alone improves profitability only as consumers respond to enhanced credibility, while subsidies become substantially more effective when trust is sufficiently high. The interaction between  $\delta$  and  $\pi_S$  suggests that fiscal support without credibility may yield limited returns, whereas combining financial incentives with trust-based governance can significantly strengthen firm performance. This finding highlights a key policy insight: under asymmetric information, profitability outcomes depend not only on the magnitude of support but also on the perceived reliability of environmental claims.

#### 4.3 Effort comparison

Figure 3 depicts how declared emission-reduction effort varies across strategies as consumer price sensitivity  $\xi$  increases. A common downward trend is observed in all three cases, indicating that stronger price sensitivity weakens the attractiveness of environmental signaling. However, the extent to which effort declines differs considerably across strategies. The manufacturer-only strategy consistently yields the lowest effort level, with  $e_M$  declining sharply as consumers place greater emphasis on price. This outcome reflects the limited incentive to maintain strong environmental claims when signaling costs are fully internalized and no external support is available.

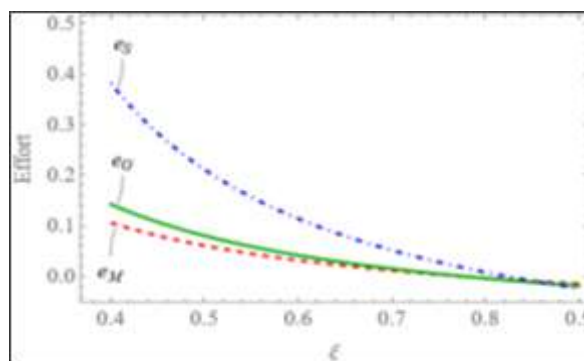


Figure 4.3 Effort comparison on  $\xi$



When regulatory supervision is present, the decline in effort becomes noticeably less pronounced. Under the Regulator Strategy,  $e_G$  remains above the baseline level across the entire range of  $\xi$ , suggesting that enhanced credibility partially shields environmental signaling from the disciplining effect of price sensitivity. Even as consumers become more price-focused, supervision sustains the perceived value of environmental claims, allowing firms to maintain a higher level of declared effort relative to the manufacturer-only case. This stabilizing effect, however, remains constrained by the absence of financial incentives, leading effort to continue declining as  $\xi$  increases.

The highest and most resilient effort levels are observed under the subsidy strategy. Throughout the parameter range,  $e_S$  exceeds both  $e_M$  and  $e_G$ , and its rate of decline with respect to  $\xi$  is substantially slower. The presence of subsidies reduces the financial burden associated with environmental signaling, enabling firms to sustain stronger declared efforts even when market conditions favor price competition. From an informational perspective, this pattern highlights how subsidies can reinforce signaling incentives under asymmetric information, encouraging firms to project stronger environmental commitment despite increasing consumer price sensitivity. Together, these results illustrate how policy support reshapes the balance between market discipline and environmental signaling, leading to distinct effort outcomes across institutional settings.

## V. Conclusion

This study develops a game-theoretic framework to examine carbon emission reduction strategies in manufacturing markets characterized by asymmetric information. By modeling environmental effort as a declared signal rather than a directly verifiable action, the analysis captures a key institutional challenge faced by regulators and consumers in sustainability-oriented markets. The framework integrates market signaling, regulatory supervision, and subsidy-based incentives to evaluate how different governance mechanisms shape pricing behavior, profitability, and emission-reduction effort under imperfect observability.

The analytical results reveal that market-driven environmental signaling alone is generally insufficient to induce high levels of emission-reduction effort when signaling costs are significant and consumers remain price sensitive. In the baseline setting, manufacturers engage in environmental signaling only when consumer environmental awareness and market potential are sufficiently strong, highlighting the limited effectiveness of voluntary action under asymmetric information. This outcome underscores the vulnerability of purely market-based mechanisms to cost pressure and credibility constraints.

Introducing regulatory supervision alters this outcome by enhancing the credibility of environmental claims. The results show that trust-based oversight amplifies consumer responsiveness to declared effort, thereby strengthening incentives for environmental signaling without directly intervening in firms' cost structures. However, while supervision improves both effort provision and profitability relative to the baseline, its effectiveness remains bounded by the absence of financial support, particularly when emission-reduction costs are high.

Subsidy-based regulation further reshapes equilibrium behavior by directly relaxing firms' effective cost constraints. When combined with supervisory credibility, subsidies generate the strongest incentives for both environmental effort and market expansion. The analysis demonstrates that subsidies are most effective when institutional trust is sufficiently high, indicating that fiscal incentives and credibility mechanisms function as complementary rather than substitutive policy tools. Nevertheless, because subsidies are linked to sales rather than verified effort, their effectiveness ultimately depends on the alignment between financial incentives and perceived environmental performance.

From a policy perspective, the findings suggest that addressing asymmetric information is central to the success of carbon regulation in manufacturing. Supervision mechanisms enhance the informational content of environmental signals, while subsidies influence firms' economic trade-offs. Policies that rely on a single instrument may produce limited or unstable outcomes, whereas integrated approaches that combine credibility enhancement with targeted incentives are more likely to sustain low-carbon behavior. These insights highlight the importance of institutional design in aligning market signals with environmental objectives.

Several limitations of this study suggest avenues for future research. First, the model abstracts from dynamic adjustment and learning effects that may influence long-term regulatory outcomes. Second, actual emission-reduction effort is not endogenously verified, reflecting realistic constraints but limiting welfare analysis. Future work could extend the framework to dynamic or multi-period settings, incorporate third-party verification mechanisms, or examine competition among multiple manufacturers. Despite these limitations, the present study contributes to the literature by demonstrating how asymmetric information fundamentally shapes the effectiveness of market signals and policy instruments in sustainable manufacturing.



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