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Subsidy Mechanisms for Product Carbon Footprint Assessment of Energy Storage Lithium Batteries

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Abstract

To address the high fixed entry cost, insufficient B2B procurement value of certification, and limited incentives for continued emission reduction in product carbon footprint (PCF) certification of energy-storage lithium batteries, this study develops a two-stage Stackelberg game between the government and a manufacturer. Four mechanisms are compared: no subsidy, a performance-based emission-reduction subsidy, a certification-cost subsidy, and a combined subsidy. The model characterizes equilibrium transitions among three manufacturer states: uncertified, compliance-certified, and excess reduction. The results show that, without subsidies, voluntary certification depends on the procurement value of certification, the minimum emission reduction required for certification, and the fixed certification cost. The performance subsidy exhibits dual thresholds for certification participation and emission-reduction intensity; unit product emission reduction increases only after the intensity threshold is exceeded. The certification-cost subsidy mainly relaxes the certification-entry constraint created by fixed costs, whereas the combined subsidy is advantageous when the fixed certification cost is high and a standalone performance subsidy is insufficient to induce participation. A higher certification procurement value broadens the range of voluntary certification, while higher emission-reduction costs, stricter certification thresholds, and larger fixed certification costs increase the need for policy intervention. A higher fiscal shadow cost suppresses the government's optimal total subsidy expenditure. Accordingly, PCF subsidy policy for energy-storage lithium batteries should distinguish the certification-entry stage from continued emission reduction after certification and strengthen coordination between subsidy mechanisms and B2B green procurement.

Keywords: Energy storage; Lithium battery; Product carbon footprint; Government subsidy



1. Introduction

Driven jointly by the development of product carbon footprint management systems and the evolution of global green trade rules, product carbon footprint assessment for energy-storage lithium batteries is shifting from a voluntary corporate practice toward a governance instrument that integrates procurement access, green trade, and continued emission reduction. In 2027, the EU Battery Regulation will enter full implementation, and high-carbon batteries will face market-access restrictions and may be unable to qualify for EU green procurement. In China, the Implementation Plan for Establishing a Carbon Footprint Management System identifies lithium batteries as a key product, and pilot certification for product carbon-footprint labels has also been extended to lithium batteries; the EU Battery Regulation (Regulation (EU) 2023/1542), meanwhile, incorporates carbon footprint declarations, performance classes, and threshold requirements into a phased implementation framework. Unlike green consumer products sold directly to end users, energy-storage lithium batteries are procured mainly in B2B settings by energy-storage system integrators, project investors and operators, energy companies, and related organizations. The market value of PCF information is therefore reflected primarily in certification-related benefits such as procurement access, tender evaluation, and green-procurement eligibility, rather than in a continuously paid premium proportional to unit emission reduction. At the same time, the long supply chains of energy-storage lithium batteries mean that PCF assessment and certification require firms to incur fixed costs for data collection, life-cycle accounting, and third-party verification, while actual emission reductions are also needed to satisfy the certification threshold. Firms therefore face two sequential decisions: whether to enter the certification system and, once certified, whether to continue reducing emissions beyond the minimum requirement. Designing government subsidy mechanisms that match these two decisions is thus of practical importance. On this basis, this paper constructs a two-stage Stackelberg game between the government and manufacturers to compare four mechanisms—no subsidy, emission-reduction performance subsidy, certification cost subsidy, and combined subsidy—and addresses three questions: When are firms willing to bear certification costs? What type of subsidy can drive firms to shift from compliance certification to beyond-compliance emission reduction? Under what budget and welfare conditions does a combined subsidy have implementation value? The contribution of this paper lies in separating the discrete procurement benefits brought by certification from the continuous emission reduction decisions made after certification, identifying participation thresholds and intensity thresholds, and accordingly defining the roles and applicable conditions of different subsidy instruments.

2. Literature Review

Research on entry into product carbon footprint certification, carbon information disclosure, B2B green procurement, life-cycle carbon footprints of energy-storage lithium batteries, and environmental subsidy design has established a substantial theoretical and empirical foundation. In line with the research questions addressed in this study, the literature can be organized into five streams: environmental certification and the economics of certification; carbon disclosure and corporate environmental behavior; B2B green procurement and supply-chain decarbonization; life-cycle carbon footprints and PCF policy for energy-storage lithium batteries; and environmental subsidies and firms' emission-reduction incentives.

2.1. Environmental Certification and the Economics of Certification

At its core, environmental certification converts environmental attributes that are difficult to observe directly into verifiable market information, while certification thresholds reshape firms' product design, pricing, and entry decisions. Using ENERGY STAR certification, Houde (2022) shows that firms strategically adjust around certification requirements and capture certification value through product differentiation and price premia, indicating that certification thresholds are not merely passive constraints but endogenously alter firm behavior. Li et al. (2024) further compare pass-fail certification

with precise-disclosure certification and find that more certification information does not necessarily generate higher social welfare; pass-fail certification has broad policy applicability in many settings. These studies provide a modeling basis for certification scenarios with clear compliance standards, but this does not imply that discrete certification can encompass all carbon disclosure or procurement systems.

Recent research has further revealed the tension between certification benefits and environmental performance. Houde (2026) found that coarse-grained certification may cause products to concentrate at the certification threshold and crowd out supply with higher environmental quality. Whereas Li et al. (2024) discuss the welfare comparison of certification schemes under different levels of information precision, Houde (2026) emphasizes the impact of certification information on product quality selection. Together, these two studies suggest that the policy value of certification depends on institutional design, and that the effectiveness of sustained emission reduction cannot be judged solely by certification coverage. Accordingly, this paper treats certification participation and post-certification emission reduction intensity as two outcomes that require separate explanations.

Certification adoption is jointly determined by entry costs and certification benefits. Zhao and Duan (2025) distinguish products with high marginal costs from those with high fixed development costs and show that cost structure materially changes firms' ecolabel adoption strategies; moreover, stricter certification standards do not always improve environmental outcomes. Margaret et al. (2024) show that the market value of ISO 14001 environmental management certification varies with the external institutional environment, indicating that certification can generate identifiable signaling and market value, but that these benefits are context dependent. Certification economics therefore needs to account jointly for fixed entry costs, certification thresholds, and post-certification market returns. Existing research has focused mainly on certification adoption, label design, and market value; relatively little attention has been paid to whether firms continue to increase verified abatement intensity after entering the certification system, or to how distinct government support instruments separately affect certification entry and subsequent abatement.

2.2. Carbon Disclosure and Corporate Environmental Behavior

Research on carbon disclosure shows that information transparency can affect firms' actual abatement behavior through peer benchmarking, investor pressure, and regulatory expectations. Using the U.S. mandatory greenhouse-gas reporting program, Tomar (2023) finds that firms' emissions fall significantly after emissions data become public, with peer benchmarking as an important mechanism, whereas measurement without public disclosure does not produce comparable effects. Using international CDP data, Cohen et al. (2023) find that institutional investors' demand for climate information increases firms' likelihood of disclosure, and disclosure is in turn associated with lower subsequent carbon emissions. Ramadorai and Zeni (2024) further show that firms' expectations of future climate regulation and reputational interactions across firms materially affect abatement behavior. Bratten et al. (2026), from a green-innovation perspective, document that mandatory environmental disclosure is associated with growth in climate-related patents and improvements in future environmental performance. Overall, carbon disclosure serves not only an informational role; through external monitoring, expectation formation, and technological innovation, it can also translate into real emission reductions.

However, lower emissions at the focal firm do not necessarily imply net reductions at the system level. Bartram et al. (2022), studying California's carbon-trading policy, show that some financially constrained firms shift output and emissions to other locations, suggesting that local environmental regulation may induce cross-jurisdictional regulatory arbitrage. At the supply-chain level, Song et al. (2023) find that lower in-house emissions at focal firms can coincide with higher supplier emissions, generating supply-chain carbon leakage. These studies indicate that the environmental effects of disclosure and regulation depend on accounting boundaries and firms' ability to reallocate production and supply-chain activities. Accordingly, this study treats production locations and supply-chain

boundaries as given, focuses on the focal manufacturer's verified unit abatement and certification decisions, and regards cross-regional and supply-chain carbon leakage as outside the model boundary and as an issue for subsequent discussion.

2.3. B2B Green Procurement and Supply-Chain Decarbonization

In B2B markets, environmental information derives value primarily from procurement access, supplier screening, and order allocation rather than from end consumers' continuous willingness to pay for each unit of emission reduction. From the perspective of supplier-audit information sharing, Ha et al. (2023) show that audit information changes manufacturers' sourcing choices between suppliers exposed to responsibility risk and alternative suppliers, indicating that third-party verified information can directly influence B2B procurement decisions. Based on a global manufacturing supply network, Diebel et al. (2024) find that suppliers' voluntary environmental disclosure is shaped by the market and sustainability institutional logics represented by their buyers; buyers can thus exert persistent influence on upstream environmental behavior through supply relationships.

Further, using panel data on manufacturing suppliers, Song et al. (2024) find that more extensive environmental disclosure by a supplier's customer base is significantly associated with lower supplier greenhouse-gas emissions, suggesting that downstream customers' environmental commitments can be transmitted upstream through signaling and procurement pressure. For energy storage lithium-ion battery transactions in which buyers primarily screen suppliers based on compliance status, this paper interprets the value of PCF certification as a B2B procurement response, including project eligibility, bidding evaluation, supplier assessment, and order opportunities. By contrast, procurement scenarios involving continuous premium payments for each additional unit of emission reduction do not fall within this simplified setting. On this basis, the present study uses B2B residual procurement demand and separates the procurement value of certification from actual post-certification abatement intensity, thereby identifying the distinct margins through which market-access incentives and continued-abatement incentives operate.

2.4. Life-Cycle Carbon Footprints of Energy-Storage Lithium Batteries and PCF Policy

Product carbon footprint accounting is intrinsically data intensive and requires substantial supply-chain coordination. From a transactional carbon-accounting perspective, Reichelstein (2024) argues that firm-level cradle-to-gate product carbon footprints require embodied emissions from suppliers to be passed along successive tiers while remaining verifiable. Berger et al. (2022) propose a digital battery-passport framework and emphasize that full life-cycle battery management relies on extensive data on products, sustainability, performance, and value-chain actors. These studies show that PCF assessment is not simply an informational label; it requires a set of up-front investments in data collection, system-boundary identification, emission-factor matching, supplier coordination, and third-party verification, providing a practical basis for treating certification cost as a fixed entry cost.

Carbon footprints of energy-storage lithium batteries also exhibit pronounced industry heterogeneity. In discussing European battery carbon-footprint rules, Peiseler et al. (2022) emphasize the importance of upstream materials and production processes. Degen et al. (2023) show that cell manufacturing is highly energy intensive and that energy demand varies substantially across battery chemistries and production processes. Combining cost accounting with life-cycle assessment, Gutsch and Leker (2024) find that the contributions of materials, manufacturing, and recycling to cost and environmental impacts differ markedly. Kallitsis et al. (2024) further show that material sourcing and production location can substantially alter the cradle-to-gate carbon footprint of lithium-ion batteries; Peiseler et al. (2024) identify material procurement as an important driver of both battery carbon-footprint levels and their distribution. From the perspective of industrial-scale recycling supply chains, Machala et al. (2025) show that recycling pathways and electricity sources likewise materially affect life-cycle environmental impacts.

With the phased implementation of the EU Battery Regulation, the Product Carbon Footprint (PCF) information and performance metrics for applicable batteries are gradually being aligned with market access requirements. Hansen et al. (2024) systematically reviewed the compliance requirements of the new EU Battery Regulation, noting that manufacturers must navigate multiple interrelated data, product, and environmental constraints. Liu et al. (2025) further quantified the impact of carbon footprint thresholds and recycled material requirements on China's lithium-ion battery industry, indicating that higher product carbon footprints may pose substantial barriers to EU market access. These studies provide a backdrop for analyzing procurement or market access scenarios involving carbon footprint threshold requirements; however, a distinction should still be made between carbon footprint declarations, accounting and certification, and low-carbon compliance requirements. This paper examines fixed certification costs, minimum certified emission reductions, and the value of B2B certified procurement under scenarios with explicit compliance requirements.

Studies from 2025 – 2026 further emphasize the importance of accounting adaptability for industrial energy storage applications. Bassi et al. (2025) proposed recommendations for carbon footprint calculation and verification methods for industrial batteries with a capacity greater than 2 kWh and without external energy storage, distinguishing between the system boundaries and functional units of industrial batteries; this report provides a technical basis for future policies but is not itself a mandatory regulation that has already taken effect. In a life cycle assessment of containerized energy storage systems, Jasper et al. (2026) found that ancillary components such as transformers and thermal management systems may constitute a non-negligible environmental burden. Consequently, emission reductions from battery cells or battery products cannot be directly equated with the net emission reductions of energy storage systems, and both certification costs and emission reduction costs should be interpreted within consistent product boundaries. While these studies have deepened the accounting basis, they do not directly address whether manufacturers should bear certification costs or how the government should allocate entry support and performance incentives.

2.5. Environmental Subsidies and Firms' Emission-Reduction Incentives

Recent research in environmental policy and operations management increasingly emphasizes that different subsidy instruments operate on different margins of firm decision making. Within a government-firm-user Stackelberg framework, Guo et al. (2022) show that the appropriate target of green-product subsidies should vary with technological effectiveness and agent heterogeneity, so no single subsidy scheme is uniformly optimal. Using a dynamic structural model of the solar industry, Gerarden (2023) further shows that adoption subsidies affect not only current demand but also long-run production costs through firm innovation. From the perspective of a budget-constrained regulator, Mohammadi et al. (2024) examine subsidies for clean-technology investment and show that up-front technology investment costs directly affect whether firms undertake clean-technology development.

Most closely related to the two subsidy instruments in this study is the distinction between investment support and operating support. Zhao et al. (2024) directly compare investment and operating subsidies for renewable electricity and find that the former operate by reducing the cost of technological improvement, whereas the latter incentivize firms by increasing marginal operating returns and expanding market demand, underscoring different transmission mechanisms for cost-side and marginal-return-side support. Campiglio et al. (2024) further argue that when clean innovation is constrained by financing costs, policies that directly narrow financing-cost differentials for clean technologies have independent value beyond carbon pricing and R&D subsidies. Comparing dynamic purchase subsidies and investment subsidies for electric vehicles, Kim (2026) likewise finds that optimal support is distinctly front-loaded and should phase down as the technology matures.

At the same time, the welfare effects of performance- or output-based subsidies are not monotonic. Comparing the welfare consequences of a broad set of climate taxes and fiscal spending policies, Hahn et al. (2026) find that some subsidies tied to actual clean-energy output deliver high value per dollar of public funds. Casey et al. (2026), however, show that whether clean-energy production subsidies reduce

emissions depends on substitution between clean and carbon-intensive energy and on demand elasticities; under some parameter configurations, such subsidies can even increase emissions and reduce welfare. Taken together, these studies indicate that subsidy design should not be evaluated solely by nominal subsidy intensity. Instead, it is necessary to identify whether a policy acts on fixed entry costs or marginal abatement returns and to assess fiscal expenditure and social-welfare conditions within a unified framework. Accordingly, this study models the certification-cost subsidy as an entry-oriented instrument that reduces the firm's fixed certification burden, and the performance-based emission-reduction subsidy as a marginal incentive tied to verified abatement and sales volume.

2.6. Literature Synthesis and Research Gaps

In summary, existing research provides important foundations for this study with respect to certification thresholds, certification costs, information disclosure, B2B procurement value, and differentiated subsidy design, but four gaps remain to be connected. First, certification economics primarily examines whether firms adopt certification and how certification standards should be designed, with insufficient attention to whether firms continue to undertake abatement beyond the certification threshold after entering the certification system. Second, research on carbon disclosure and green procurement shows that environmental information can influence firm behavior through investors, customers, and supply-chain relationships, but seldom distinguishes the discrete market-access value generated by certification from continuous post-certification abatement effort. Third, the battery PCF literature has documented the importance of material sourcing, production location, data quality, and regulatory thresholds, but focuses mainly on life-cycle accounting and compliance impacts, with limited analysis of how certification rules interact with firms' economic decisions and government incentives. Fourth, subsidy research recognizes that investment-, cost-, and operating-oriented support work through different incentive channels, yet has not fully characterized the sequential decision chain in a PCF setting: fixed certification cost, certification participation, and continued post-certification abatement. Based on the above research, this paper constructs a theoretical analysis framework of “certification costs—market value—policy incentives—corporate emission reduction decisions.” In this framework, certification costs determine the initial constraint on firms' entry into the PCF certification system; B2B procurement value determines the capacity to translate certification information into market returns; and subsidy policies influence firm behavior by reducing fixed certification costs or increasing the marginal returns to emission reduction. This framework connects environmental certification theory, information disclosure theory, and environmental policy incentive theory, and is used to explain the intrinsic mechanism by which firms transition from an uncertified state to compliance certification and beyond-compliance emission reduction.

3. Problem Description and Basic Assumptions

This study considers a two-stage Stackelberg game between the government and a representative manufacturer of energy-storage lithium batteries. The government is the leader and chooses the subsidy mechanism and subsidy intensity under a fiscal budget constraint to maximize social welfare. The manufacturer is the follower and, after observing government policy, decides whether to participate in product carbon footprint (PCF) certification and subsequently chooses output and unit product emission reduction. Because energy-storage lithium batteries are procured mainly in B2B settings by energy-storage system integrators, project investors and operators, energy companies, and related organizations, demand is interpreted here as the residual procurement demand faced by the focal manufacturer, conditional on competition from other suppliers, project procurement scale, and other procurement conditions.

Let the manufacturer's baseline unit product carbon footprint before additional emission-reduction measures be CF_0 , and let e denote the unit emission reduction achieved through measures such as green-electricity substitution, process energy conservation, low-carbon material procurement, and supply-

chain coordination. The unit product carbon footprint after emission reduction is therefore $CF = CF_0 - e$. Let $\overline{CF}$ denote the maximum unit product carbon footprint permitted for PCF certification, with $CF_0 > \overline{CF}$. To meet the certification standard, the firm must satisfy $CF \leq \overline{CF}$, which yields the minimum emission reduction required for certification, $e_0 = CF_0 - \overline{CF} > 0$. Define the certification-state variable $z = \begin{cases} 1, & e \geq e_0, \\ 0, & e < e_0. \end{cases}$ where $z = 1$ indicates that the product meets the PCF certification requirement and $z = 0$ indicates that it does not. If the firm does not participate in certification, it undertakes no additional verifiable emission-reduction measures, so $e = 0$.

Assume the inverse market demand function is $p = a - bq + \theta z$, where p is the transaction price, q is the residual procurement order volume obtained by the focal manufacturer, $a > 0$ is the baseline B2B residual procurement market size after accounting for competition from other suppliers, project procurement scale, and basic market conditions, $b > 0$ is the sensitivity of residual procurement demand to the transaction price, and $\theta \geq 0$ represents B2B buyers' procurement response to PCF certification, or equivalently, the procurement value of certification.

The manufacturer's unit production cost is c , with $a > c$. The emission-reduction effort cost is specified as $C_e(e) = \frac{k}{2}e^2$, where $k > 0$ is the emission-reduction cost coefficient. The quadratic form captures increasing marginal reduction costs as the firm moves from managerial improvements toward process retrofitting, green-electricity substitution, and low-carbon material replacement. The fixed cost of PCF assessment and certification is $F > 0$. It includes life-cycle data collection, system-boundary identification, emissions accounting, third-party verification, report preparation, and internal data governance. Because this cost does not vary continuously with current-period output, it mainly determines whether the firm enters the certification system.

The government uses two subsidy instruments. The first is a performance-based emission-reduction subsidy, paid according to verified unit emission reduction and sales volume, with subsidy coefficient $s \geq 0$. The second is a certification-cost subsidy, under which the government covers a proportion of the fixed certification cost, with subsidy ratio $0 \leq t \leq 1$. Only firms that meet the certification threshold and complete verification are eligible for policy support. Government subsidy expenditure is therefore $G = z(sq_e + tF)$. The subsidy budget ceiling is $\overline{B} > 0$, and policy implementation must satisfy $G \leq \overline{B}$. The analysis below compares four policy regimes: no subsidy (N), performance-based emission-reduction subsidy (S), certification-cost subsidy (T), and combined subsidy (H).

Under linear residual procurement demand, downstream buyer surplus is $CS = \frac{1}{2}bq^2$. Let $\eta \geq 0$ denote the social environmental benefit per unit of verified emission reduction; total environmental benefit is then $ER = \eta qez$. Subsidy expenditure entails a fiscal shadow cost with coefficient $\lambda \geq 0$. When $\lambda = 0$, the subsidy is only a transfer between the government and the firm; when $\lambda > 0$, public funds entail an opportunity or distortionary cost. Social welfare is uniformly defined as $SW = CS + \pi_M + ER - (1 + \lambda)G$, where π_M is manufacturer profit including subsidy income. Whether the firm ultimately participates in certification depends on whether its optimal profit in the certified state reaches the outside-option profit available in the uncertified state.

Table 1. Main Variables and Parameters

Symbol	Meaning	Setting
a	Baseline B2B residual procurement market size	$a > 0$, and $a > c$
b	Sensitivity of residual procurement demand to the transaction price	$b > 0$
θ	B2B buyers' procurement response to PCF certification, or equivalently, the procurement value of certification	$\theta \geq 0$
c	Manufacturer's unit production cost	$a > c$
k	Emission-reduction cost coefficient	$k > 0$
F	Fixed cost of PCF assessment and certification	$F > 0$
CF_0	Baseline unit product carbon footprint before additional emission-reduction measures	$CF_0 > \overline{CF}$
$\overline{CF}$	Maximum unit product carbon footprint permitted for PCF certification	Certification requirement: $CF \leq \overline{CF}$
e_0	Minimum emission reduction required for certification	$e_0 = CF_0 - \overline{CF} > 0$
η	Social environmental benefit per unit of verified emission reduction	$\eta \geq 0$
λ	Fiscal shadow cost coefficient of subsidy expenditure	$\lambda \geq 0$
$\overline{B}$	Government subsidy budget ceiling	$\overline{B} > 0$, and $G \leq \overline{B}$
s	Performance-based emission-reduction subsidy coefficient	$s \geq 0$
t	Certification-cost subsidy ratio	$0 \leq t \leq 1$
q	Residual procurement order volume (output) obtained by the manufacturer	Manufacturer decision variable
e	Unit product emission reduction	If certified, $e \geq e_0$; if uncertified, $e = 0$
z	Certification-state variable	$z \in \{0, 1\}$
p	Transaction price	$p = a - bq + \theta z$
CF	Unit product carbon footprint after emission reduction	$CF = CF_0 - e$
$C_e(e)$	Emission-reduction effort cost	$C_e(e) = \frac{k}{2}e^2$
G	Government subsidy expenditure	$G = z(sq + tF)$
CS	Downstream buyer surplus	$CS = \frac{1}{2}bq^2$
ER	Environmental benefit from verified emission reduction	$ER = \eta qez$
π_M	Manufacturer profit including subsidy income	Certified optimal profit must be no lower than the uncertified outside-option profit
SW	Social welfare	$SW = CS + \pi_M + ER - (1 + \lambda)G$

4. Model Formulation and Equilibrium Analysis

4.1. Basic Model

The sequence of the game is as follows. In Stage 1, the government announces the subsidy package (s, t) , the fiscal budget ceiling $\overline{B}$, and the carbon-footprint verification rules. In Stage 2, the manufacturer observes the policy and decides whether to participate in PCF certification. If it participates, it chooses output q and unit product emission reduction e , subject to $e \geq e_0$; if it does not participate, then $z = 0$ and $e = 0$. The market then determines the transaction price according to B2B residual procurement demand, and the government pays subsidies on the basis of verified sales, emission reduction, and fixed certification cost.

In the uncertified state, the manufacturer faces inverse demand $p = a - bq$; the optimal output and outside-option profit are $q^U = (a - c)/(2b)$ and $\pi^U = (a - c)^2/(4b)$, respectively. Importantly, q^U and π^U are not exogenously specified; rather, they are equilibrium outcomes endogenously determined by the B2B residual procurement demand faced by the manufacturer when it does not participate in PCF certification. After certification, the procurement response θ enters the demand side. For notational simplicity, let $A \equiv a + \theta - c > 0$. The manufacturer's decision problem in the certified state is then:

$$\max_{q,e} \pi^C = Aq - bq^2 + sqe - \frac{k}{2}e^2 - (1-t)F, \quad \text{s.t. } e \geq e_0.$$

Lemma 1. Manufacturer's optimal response under the certification threshold. If $0 \leq s < \sqrt{2bk}$, the profit function in the certified state is strictly concave and the manufacturer has a unique optimal response. The optimal unit emission reduction, output, and profit are, respectively:

$$e_C(s) = \begin{cases} e_0, & 0 \leq s \leq s_c, \\ \frac{sA}{2bk - s^2}, & s_c < s < \sqrt{2bk}, \end{cases}$$

$$q_C(s) = \begin{cases} \frac{A + se_0}{2b}, & 0 \leq s \leq s_c, \\ \frac{kA}{2bk - s^2}, & s_c < s < \sqrt{2bk}, \end{cases}$$

$$\hat{\pi}^C(s, t) = \begin{cases} \frac{(A + se_0)^2}{4b} - \frac{k}{2}e_0^2 - (1-t)F, & 0 \leq s \leq s_c, \\ \frac{kA^2}{2(2bk - s^2)} - (1-t)F, & s_c < s < \sqrt{2bk}. \end{cases}$$

Proof. The Hessian of the profit function is negative definite when $2bk - s^2 > 0$; it is therefore sufficient to compare the unconstrained interior solution with the certification threshold. Ignoring $e \geq e_0$, the first-order conditions yield $e^I = sA/(2bk - s^2)$. Setting $e^I = e_0$ gives the critical performance subsidy at which the firm switches from compliance certification to excess reduction: $s_c = \frac{-A + \sqrt{A^2 + 8bke_0^2}}{2e_0}$, $0 < s_c < \sqrt{2bk}$. The optimal unit emission reduction and output of a certified firm then follow. Substituting these decisions back into the profit function gives the optimal profit in the certified state. This completes the proof.

Lemma 1 shows that the certification threshold partitions the manufacturer's continuous emission-reduction decision into two regions. In the compliance-certification region, the firm is constrained at e_0 , and the performance subsidy mainly expands output by raising the per-unit operating return on certified products. Once the firm enters the excess-reduction region, the certification constraint ceases to bind and the performance subsidy affects both output and unit emission-reduction intensity. From the government's perspective, any subsidy scheme must simultaneously satisfy the manufacturer's participation constraint, the fiscal budget constraint $G \leq \bar{B}$, and the welfare-improvement condition relative to the uncertified state. The four policy mechanisms are compared below on this basis.

4.2. Equilibrium Analysis under Four Policy Regimes

No subsidy regime (N). Under no subsidy, $(s, t) = (0, 0)$ and $s = 0 < s_c$. Thus, once the firm becomes certified, it chooses only the minimum compliant emission reduction e_0 . In the certified state,

$q_N^C = \frac{A}{2b}$, and profit is $\pi_N^C = \frac{A^2}{4b} - \frac{k}{2}e_0^2 - F$. Comparing this with the uncertified profit π^U yields the maximum fixed certification cost that the firm can bear voluntarily $F_N^{\text{crit}} = \frac{A^2 - (a-c)^2}{4b} - \frac{k}{2}e_0^2$.

Corollary 1. Certification participation threshold without subsidies. When $F \leq F_N^{\text{crit}}$, the manufacturer voluntarily participates in PCF certification and chooses (q_N^C, e_0) ; when $F > F_N^{\text{crit}}$, the manufacturer remains in the uncertified state $(q^U, 0)$.

Corollary 1 identifies whether the market alone can sustain certification. A higher B2B certification procurement value θ increases A , thereby increasing the fixed certification cost that the firm can bear. By contrast, a higher emission-reduction cost coefficient k or a larger minimum emission reduction required for certification e_0 narrows the region of voluntary certification. In particular, when $F_N^{\text{crit}} < 0$, even reducing the fixed certification cost to zero cannot generate a certified equilibrium because the incremental procurement benefit from certification is still insufficient to cover the real resource cost of the minimum compliant emission reduction.

Performance Subsidy Regime (S). The performance subsidy uses $(s, 0)$, and the government pays according to verified unit emission reduction and sales volume. If the manufacturer's participation threshold lies in the compliance-certification region, setting $\hat{\pi}^C(s, 0) = \pi^U$ gives $s_P^C = \frac{\sqrt{(a-c)^2 + 2bke_0^2 + 4bF} - A}{e_0}$. When $s_P^C \leq 0$, the participation constraint is already satisfied without subsidies, so the participation threshold is $s_P = 0$; when $0 < s_P^C \leq s_c$, $s_P = s_P^C$. If the firm still fails to satisfy the participation constraint at $s = s_c$, certification can occur only after it enters the excess-reduction region. In that case, the participation threshold is determined by $s_P^E = \sqrt{2bk - \frac{kA^2}{2(F+\pi^U)}}$, and the feasible root satisfying $s_P^E > s_c$ and $s_P^E < \sqrt{2bk}$ is selected. Thus, s_P determines whether the firm enters the certification system, whereas s_c determines whether a certified firm further raises unit emission-reduction intensity. The government's optimal performance subsidy satisfies

$$s_S^* \in \arg \max_{0 \leq s < \sqrt{2bk}} SW_S(s), \quad \text{s.t. } \hat{\pi}^C(s, 0) \geq \pi^U, \quad G_S(s) \leq \bar{B}, \quad SW_S(s) \geq SW^U.$$

Corollary 2. Dual-threshold incentive effect of the performance subsidy. If $s_P \leq s_c$, as the performance subsidy increases, the firm's equilibrium state changes sequentially from uncertified (U) to compliance-certified (C) and then to excess reduction (E). If $s_P > s_c$, the firm still fails to satisfy the participation constraint when the intensity threshold is reached, so the equilibrium may switch directly from the uncertified state to excess reduction, namely

$$\begin{cases} U \rightarrow C \rightarrow E, & s_P \leq s_c, \\ U \rightarrow E, & s_P > s_c. \end{cases}$$

Proof. By Lemma 1, the manufacturer's certification-participation constraint is $\hat{\pi}^C(s, 0) \geq \pi^U$, so s_P is the performance-subsidy threshold at which the participation constraint is first satisfied. Meanwhile, s_c is determined by $e_c(s_c) = e_0$. Hence, when $s_P \leq s_c$, $s < s_P$ corresponds to the uncertified state U, $s_P \leq s \leq s_c$ to the compliance-certified state C, and $s > s_c$ to the excess-reduction state E. When $s_P > s_c$, the firm is already in the region $s > s_c$ when the participation constraint is first satisfied; the equilibrium therefore switches directly from U to E.

From $e_c(s_c) = e_0$, the critical equation is

$$f(s_c, \theta, k, e_0) \equiv e_0 s_c^2 + A s_c - 2b k e_0 = 0, \quad A = a + \theta - c.$$

Because $\partial f / \partial s_c = 2e_0 s_c + A > 0$, implicit differentiation gives

$$\frac{\partial s_c}{\partial \theta} = -\frac{s_c}{2e_0 s_c + A} < 0, \quad \frac{\partial s_c}{\partial k} = \frac{2be_0}{2e_0 s_c + A} > 0, \quad \frac{\partial s_c}{\partial e_0} = \frac{2bk - s_c^2}{2e_0 s_c + A} > 0.$$

Since $s_c < \sqrt{2bk}$, the last derivative is positive. This proves the corollary.

This corollary shows that a performance subsidy does not continuously increase unit emission reduction from zero. In the compliance-certification interval $0 \leq s \leq s_c$, $e_c(s) = e_0$ remains unchanged, while $q_c(s)$ increases with s . Only when $s > s_c$ do output and unit emission reduction increase simultaneously. The threshold condition $e_0 s_c^2 + A s_c - 2bke_0 = 0$ further yields $\partial s_c / \partial \theta < 0$, $\partial s_c / \partial k > 0$, and $\partial s_c / \partial e_0 > 0$. Hence, a stronger B2B procurement response to certification allows the firm to enter the excess-reduction region earlier, whereas a higher emission-reduction cost or a stricter certification threshold raises the performance incentive required.

Certification-cost subsidy regime (T). The certification-cost subsidy uses $(0, t)$. Because $s = 0 < s_c$, this policy does not change the marginal return to emission reduction after certification. Once certified, the firm therefore continues to choose $q_T^C = A/(2b)$ and $e_T^C = e_0$. Define certified operating net return before deducting the fixed certification cost as $V_0 = \frac{A^2}{4b} - \frac{k}{2}e_0^2$. The minimum subsidy ratio required to induce the firm to enter the certification system is then

$$t_T^{\min} = \begin{cases} \text{infeasible}, & V_0 < \pi^U, \\ 1 - \frac{V_0 - \pi^U}{F}, & \pi^U \leq V_0 < \pi^U + F, \\ 0, & V_0 \geq \pi^U + F. \end{cases}$$

When $V_0 < \pi^U$, even if the government bears the entire fixed certification cost, certified operating return remains below the uncertified outside option, so a pure cost subsidy cannot induce entry. When $0 < t_T^{\min} \leq 1$, the cost subsidy can fill the fixed entry gap, but output and unit emission reduction after certification do not change. Government expenditure is $G_T = tF$. When $\lambda > 0$, once the firm has crossed the participation threshold, any further increase in t only raises the fiscal shadow cost. Accordingly, subject to the budget and welfare-improvement conditions, the subsidy that is optimal for implementation is $t_T^{\text{opt}} = t_T^{\min}$. When $\lambda = 0$, a higher t does not create additional shadow loss in social welfare, but there is still no need to exceed the minimum participation level.

Corollary 3. Participation-threshold effect of the certification-cost subsidy. Once the firm participates in certification, $\frac{\partial q_c}{\partial t} = 0$ and $\frac{\partial e_c}{\partial t} = 0$, while $\frac{\partial \hat{\pi}^c}{\partial t} = 0 = F > 0$. If $\lambda > 0$, the marginal effect of an additional increase in the cost subsidy on social welfare is $\frac{\partial SW^c}{\partial t} = -\lambda F < 0$. The certification-cost subsidy is therefore a typical entry-margin instrument: it should be set just high enough to cross the participation threshold rather than expanded universally after the firm has become stably certified.

Combined Subsidy Regime (H). The combined subsidy simultaneously uses the performance subsidy and the certification-cost subsidy (s, t) . For a given s , define the optimal certified operating return before deducting the fixed certification cost actually borne by the firm as $V(s) \equiv \hat{\pi}^C(s, 0) + F$. When $V(s) < \pi^U$, even $t = 1$ cannot induce the firm to enter the certification system. When $V(s) \geq \pi^U$, the minimum certification-cost subsidy ratio required is $t_{\min}(s) = \left[1 - \frac{V(s) - \pi^U}{F}\right]_0^1$. Here, $[\cdot]_0^1$ denotes truncation of the result to the interval $[0, 1]$. In the region $0 < t_{\min}(s) < 1$, because $V'(s) > 0$, a higher performance subsidy reduces the fixed-cost subsidy required to close the certification-entry gap. The two instruments are therefore substitutes on the participation margin, but they are not equivalent on the

emission-reduction intensity margin: t changes only the fixed-cost burden, whereas only $s > s_c$ can move the firm from minimum compliant emission reduction to excess reduction.

Fiscal expenditure under the combined subsidy is $G_H(s, t) = sq_C(s)e_C(s) + tF$. For a given s , increasing t does not change q_C or e_C , so the government chooses the minimum necessary $t = t_{\min}(s)$ among feasible schemes. The original two-dimensional policy problem can therefore be reduced to a one-dimensional optimization over s :

$$s_H^* \in \arg \max_{0 \leq s < \sqrt{2bk}} SW_H(s, t_{\min}(s)),$$

s. t. $V(s) \geq \pi^U$, $G_H(s, t_{\min}(s)) \leq \bar{B}$, and $SW_H(s, t_{\min}(s)) \geq SW^U$, with $t_H^* = t_{\min}(s_H^*)$ in the optimum.

Corollary 4. Conditional advantage of the combined subsidy). If, at a given performance intensity s , $V(s) - F < \pi^U \leq V(s)$, a pure performance subsidy is still insufficient to induce certification, but the combined subsidy can fill the fixed entry gap through $t \geq t_{\min}(s)$. Furthermore, when $s > s_c$, the combined subsidy yields $e_H = e_C(s) > e_0 = e_T$, and thus provides an excess-reduction incentive relative to the pure certification-cost subsidy. Conversely, if $V(s) - F \geq \pi^U$, then $t_{\min}(s) = 0$; the combined mechanism collapses to a pure performance subsidy, and additional fixed-cost support only increases firm profit and fiscal expenditure.

Proof. Since $V(s) \equiv \hat{\pi}^C(s, 0) + F$, the manufacturer's optimal certified profit under the combined subsidy can be written as

$$\hat{\pi}^C(s, t) = V(s) - (1 - t)F.$$

In the interior region $0 < t_{\min}(s) < 1$, the minimum certification-cost subsidy follows from imposing the participation constraint with equality:

$$t_{\min}(s) = 1 - \frac{V(s) - \pi^U}{F}, \quad \frac{dt_{\min}(s)}{ds} = -\frac{V'(s)}{F} < 0.$$

By the envelope theorem, $V'(s) = q_C(s)e_C(s) > 0$. Conversely, for a given t , the binding participation constraint can be written as $V(s(t)) = \pi^U + (1 - t)F$. Because $V(s)$ is strictly increasing,

$$s(t) = V^{-1}(\pi^U + (1 - t)F), \quad \frac{ds(t)}{dt} = -\frac{F}{V'(s)} < 0.$$

Thus, the two subsidies are substitutes on the certification-participation margin. When $V(s) - F < \pi^U \leq V(s)$, $t = 0$ is insufficient to satisfy the participation constraint, whereas $t \geq t_{\min}(s)$ fills the fixed entry gap; if, in addition, $s > s_c$, then $e_H = e_C(s) > e_0 = e_T$. When $V(s) - F \geq \pi^U$, $t_{\min}(s) = 0$, so the combined subsidy reduces to the pure performance subsidy. This proves the corollary.

Table 2. Comparison of Equilibrium Outcomes under the Four Subsidy Mechanisms

Indicator	No subsidy (N)	Performance subsidy (S)	Certification-cost subsidy (T)	Combined subsidy (H)
Policy combination	(0,0)	(s, 0)	(0, t)	(s, t)
Possible equilibrium states	U / C	U / C / E	U / C	U / C / E
Participation threshold	$F \leq F_N^{\text{crit}}$	$s \geq s_p$	$t \geq t_T^{\text{min}}$	$t \geq t_{\text{min}}(s)$
Unit emission reduction after certification	e_0	$e_c(s)$	e_0	$e_c(s)$
Output after certification	$\frac{A}{2b}$	$q_c(s)$	$\frac{A}{2b}$	$q_c(s)$
Government expenditure	0	$sq_c e_c$	tF	$sq_c e_c + tF$
Core role	Market-driven voluntary certification	Participation and intensity incentives	Entry support for certification	Dual-margin support for entry and intensity

Table 2 shows which emission-reduction state each subsidy instrument can induce, but it does not by itself indicate whether the policy is worth implementing. From the government's perspective, a subsidy mechanism is executable only when the firm is willing to participate, the fiscal budget can accommodate the expenditure, and social welfare improves relative to the uncertified benchmark. The policy boundaries are therefore compared below from three perspectives: the participation constraint, the budget constraint, and the fiscal shadow cost.

Corollary 5. Executable welfare-improvement condition for subsidy policy. For any subsidy mechanism $j \in \{S, T, H\}$, the policy can constitute an executable Stackelberg equilibrium and outperform the uncertified benchmark only if all of the following conditions are satisfied: $\hat{\pi}_j \geq \pi^U$, $G_j \leq \bar{B}$, $SW_j \geq SW^U$.

The three conditions in Corollary 5 form a three-stage screen for policy executability. First, firm profit must be no lower than the uncertified outside option; otherwise, the subsidy scheme will not be adopted by the firm. Second, subsidy expenditure must not exceed the fiscal budget. Third, the B2B buyer surplus and environmental benefits generated by certification must be sufficient to cover emission-reduction costs, the real resource cost of fixed certification, and the fiscal shadow cost. An increase in firm profit is therefore only a necessary condition and cannot be equated directly with policy effectiveness.

Corollary 6. Suppressive effect of the fiscal shadow cost on optimal expenditure. Include the no-subsidy state and all feasible subsidy schemes in the government's choice set. Let ω denote a specific policy mechanism and its parameters, and let $\tilde{SW}(\omega)$ denote social welfare excluding the fiscal shadow cost. Then $SW_\lambda(\omega) = \tilde{SW}(\omega) - \lambda G(\omega)$. Suppose $\lambda_2 > \lambda_1 \geq 0$, with corresponding globally optimal policies ω_2 and ω_1 . Adding the two optimality inequalities gives $(\lambda_2 - \lambda_1)[G(\omega_1) - G(\omega_2)] \geq 0$.

Because $\lambda_2 - \lambda_1 > 0$, optimality directly implies $G(\omega_2) \leq G(\omega_1)$. Thus, the higher the opportunity cost of public funds, the lower, in the weak sense, the total fiscal subsidy expenditure associated with the government's globally optimal policy. This result concerns optimal total expenditure and does not require s and t to decrease monotonically one by one. Because the two instruments are substitutes on the certification-participation margin, tighter fiscal constraints may cause the government to reallocate spending between them. A more robust policy implication is to provide only the minimum

support needed to cross the participation threshold and to reduce fixed-cost subsidies that no longer generate additional emission reductions after firms have entered the certification system.

In summary, this study addresses three main questions: whether the firm enters the certification system, whether it undertakes excess emission reduction after certification, and whether the corresponding fiscal expenditure is affordable. The no-subsidy regime N identifies the boundary of market-driven voluntary certification. The performance subsidy S affects both certification participation and emission-reduction intensity, but it directly raises unit emission reduction only after s_c is exceeded. The certification-cost subsidy T mainly fills the fixed entry gap. Subject to the budget constraint, the combined subsidy H assigns distinct roles to an entry backstop and an intensity incentive. The following analysis varies key parameters to further examine these mechanism boundaries and their policy implications.

5. Comparative Analysis

Based on the model's equilibrium results, this section takes key parameters — certification procurement value, emission reduction costs and certification thresholds, fiscal shadow costs, and fixed certification costs—as a starting point to examine the equilibrium performance of four mechanisms—no subsidy, emission-reduction performance subsidy, certification cost subsidy, and combined subsidy—under variations in these parameters. It further identifies the differences among these policies in terms of certification entry, beyond-compliance emission reduction, and fiscal feasibility, thereby providing a basis for selecting subsidy mechanisms under different scenarios.

5.1. Certification Procurement Value and Manufacturer Emission-Reduction State

To examine how changes in the B2B procurement environment affect the firm's certification state, all other parameters are held constant and the benchmark policy intensities are fixed at S: $(s, t) = (0.35, 0)$, T: $(s, t) = (0, 0.419)$, and H: $(s, t) = (0.35, 0.140)$. The certification procurement value θ is allowed to vary over $[0, 30]$. Figure 1 reports the actual equilibrium unit emission reduction under the four mechanisms.

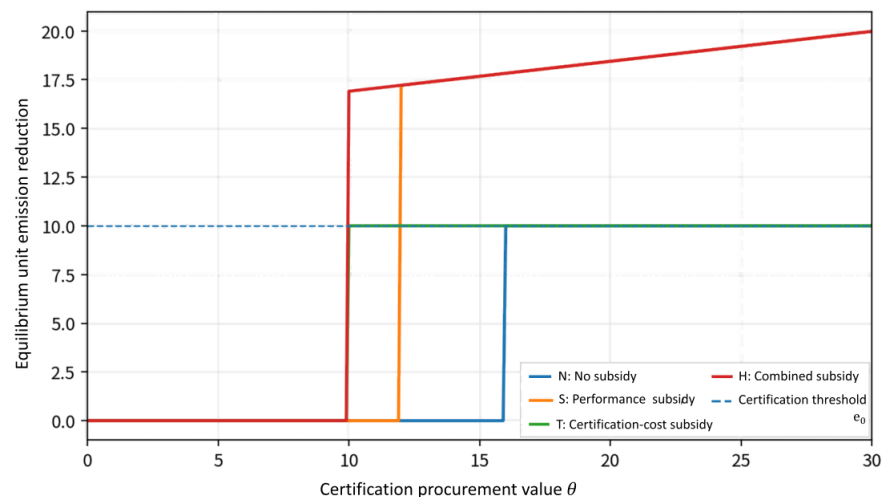


Figure 1: Effect of Certification Procurement Value on the Emission-Reduction Decision

Figure 1 shows that, at the given policy intensities, the participation thresholds across the four scenarios approximately satisfy $\theta_T \approx \theta_H < \theta_S < \theta_N$, consistent with Corollaries 1 and 2. A higher certification procurement value expands the range of certification costs that the firm can absorb on its own and lowers the participation threshold under the performance subsidy. Meanwhile, once certification occurs under regimes T and N, unit emission reduction remains at e_0 . Under regimes S and H, where $s_0 > s_c$, crossing the participation threshold leads directly to the excess-reduction state. Thus,

θ mainly affects the market-return side of whether certification is worthwhile, whereas whether s_c exceeds s_p determines the post-certification emission-reduction intensity.

The above results reflect the distinction between the decision to enter certification and the choice of post-certification effort. An increase in procurement value raises the operating profit from certification and relaxes the participation constraint; however, in the absence of performance-based subsidies, additional emission reductions beyond compliance no longer increase certification returns, so the optimal effort remains at the certification lower bound. This aligns with the direction of Song et al. (2024) regarding the impact of downstream environmental information on supplier behavior, and also echoes Houde's (2026) conclusion on certification-threshold clustering. Unlike the former study, which examines firms' overall emissions, this paper confines the procurement response to the discrete benefits generated by certification status, thereby explaining why procurement incentives promote participation but do not necessarily lead to beyond-compliance emission reductions. Therefore, green procurement and subsidies should separately assess certification participation and per-unit emission reductions; if a contract continuously pays a premium for additional emission reductions, the demand specification must be expanded before the equilibrium can be re-evaluated.

5.2. Dual-Threshold Effects of Emission-Reduction Cost and the Certification Threshold

To further examine how the emission-reduction cost and the certification threshold affect the two performance-subsidy thresholds, Figure 2 holds $\theta = 10$ and $F = 800$ constant, lets k vary over $[0.5, 2.5]$, and calculates the intensity threshold s_c for $e_0 = 8, 10, 12$. The participation threshold s_p under the benchmark $e_0 = 10$ and the benchmark performance subsidy $s_0 = 0.35$ are also shown.

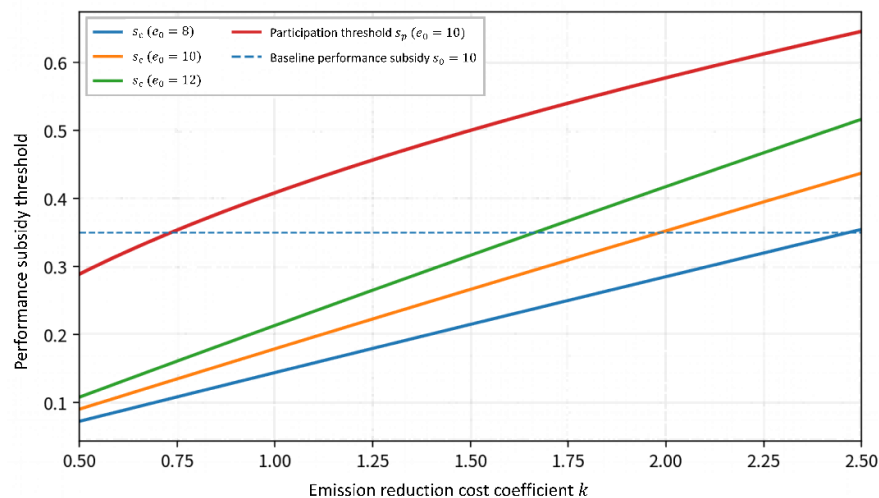


Figure 2: Effects of Emission-Reduction Cost and the Certification Threshold on Performance-Subsidy Thresholds

Figure 2 shows that s_c increases with k , and, for a given k , a higher minimum emission reduction required for certification e_0 implies a higher s_c . As the emission-reduction cost rises further, the participation threshold s_p also increases. The firm therefore finds it more difficult both to move from compliance certification to excess reduction and to cross the certification-participation threshold in the first place. This result indicates that a stringent carbon-footprint threshold can translate into sustained excess reduction only when accompanied by lower emission-reduction costs or stronger performance incentives. If the certification standard is tightened without a simultaneous improvement in the firm's emission-reduction technology, policy first confronts higher participation and intensity thresholds.

The dual thresholds arise from two types of constraints: the participation threshold requires that certification profits reach the level of the outside option without certification, while the intensity threshold corresponds to the minimum emission reduction constraint shifting from a binding constraint

to a slack one. When the former is higher than the latter, a firm can choose beyond-compliance emission reduction upon initial entry. Compared with the conclusion of Zhao et al. (2024) that operational subsidies improve marginal returns, the effort response in this paper is piecewise, because the model simultaneously introduces a fixed entry cost and a certification floor. Raising the threshold also increases the compliance burden, which echoes Zhao and Duan's (2025) conclusion that stricter labeling standards do not necessarily improve overall environmental outcomes; however, this paper explains this effect through participation constraints rather than firm competition. Therefore, policies should allocate support according to the actual binding constraints and complement standard adjustments with technological cost reductions; an increase in sales by certified firms cannot be directly interpreted as an increase in per-unit emission reduction intensity.

5.3. Fiscal Shadow Cost and Optimal Fiscal Expenditure

5.4.

To verify Corollary 6, for each λ , the uncertified state and all executable policies under N, S, T, and H are included in the government's choice set, and the government maximizes social welfare subject to the manufacturer's participation constraint and the budget constraint. Because the feasible policy set does not change with λ , the government's objective can be interpreted as a trade-off between fiscal expenditure G and welfare gains excluding the shadow cost. Figure 3 reports the fiscal expenditure and social welfare associated with the globally optimal policy for $\lambda \in [0, 2.5]$.

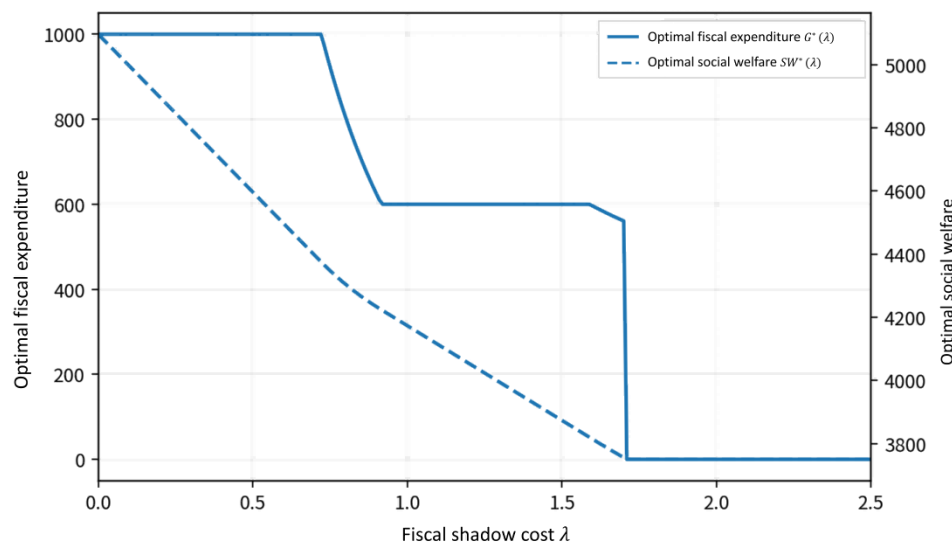


Figure 3: Effect of Fiscal Shadow Cost on Optimal Fiscal Expenditure and Social Welfare

Figure 3 shows that when the fiscal shadow cost is low, the government is willing to choose a relatively high performance intensity near the budget constraint to obtain greater environmental benefits and B2B buyer surplus, and optimal fiscal expenditure approaches the budget ceiling $\bar{B}$. As λ increases, the optimal policy gradually shifts from a high-expenditure performance incentive to a low-expenditure scheme close to the firm's participation threshold. When λ rises further, the net welfare generated by any certification subsidy is insufficient to cover the fiscal opportunity cost, and the government's optimal choice returns to the uncertified benchmark. Optimal total fiscal expenditure weakly decreases throughout this process, consistent with Corollary 6. It should be emphasized that policy parameters s and t may substitute for one another; the numerical result therefore verifies the decline in optimal total fiscal expenditure rather than requiring each subsidy parameter to decrease monotonically.

Optimal total expenditure weakly decreases with the fiscal shadow cost, reflecting the government's reweighting of expenditure costs within the same set of feasible policies; since the two types of instruments are substitutes for one another, the parameters for individual subsidies need not decrease separately. This is consistent with the approach taken by Hahn et al. (2026), who emphasize the value of public funds in climate policy; however, this paper presents the optimal choice relationship within the

model and does not estimate the return on funds for actual policies. Casey et al. (2026) further demonstrate that energy substitution and demand response affect the net emission reduction effects of subsidies; this paper limits environmental benefits to verified emission reductions within established product boundaries and does not account for all emission changes resulting from output expansion and supply chain shifts. Therefore, welfare improvements must be examined jointly with participation and budgetary constraints, and the verified emission reduction gains in the model cannot be directly taken as evidence of net emission reductions from energy storage systems.

5.5. Fixed Certification Cost and the Executability of Subsidy Mechanisms

Fixed certification costs directly determine whether a firm needs the government to bear part of its entry costs. Holding other benchmark parameters constant, we separately examine the pure certification cost subsidy T , the pure performance subsidy S , and the combined subsidy HH under $s_0 = 0.35$, where the minimum intensity of the pure performance subsidy is determined by the participation threshold s_p specified in Section 4.2, and the minimum fixed-cost subsidy for the combined subsidy is determined by $t_{\min}(s_0)$.

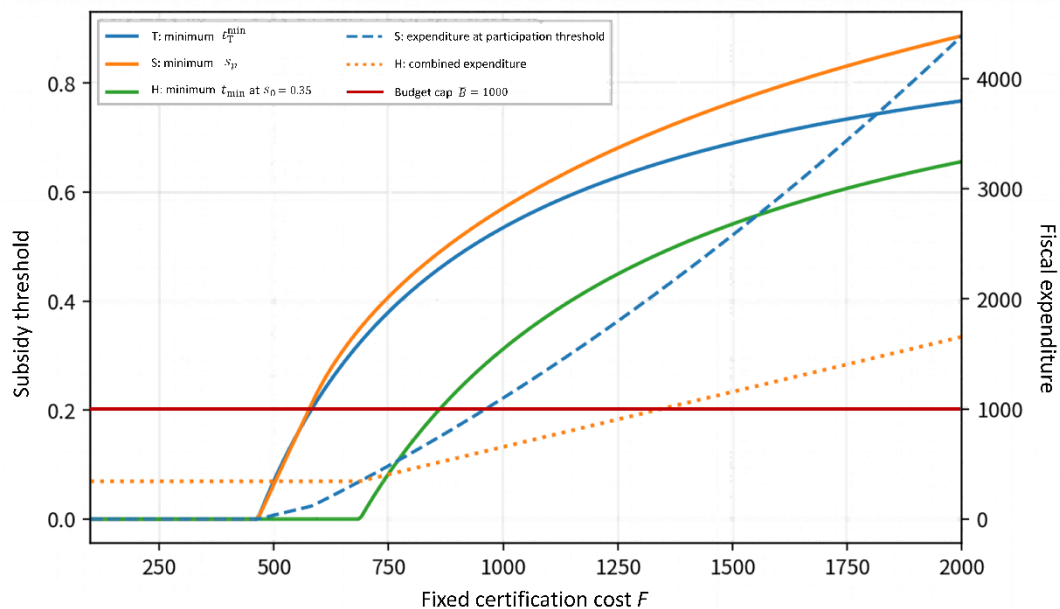


Figure 4: Effects of Fixed Certification Cost on Participation-Subsidy Thresholds and Fiscal Expenditure

Figure 4 further shows that the participation threshold and fiscal expenditure under a pure performance subsidy increase rapidly with F . Although the certification-cost subsidy ratio also rises continuously, its effect remains confined to the entry margin. In the medium-fixed-cost region, the combined subsidy can use t to fill the participation gap left by s_0 , thereby maintaining the emission-reduction intensity of state E. As F continues to rise, however, fiscal expenditure under the combined subsidy also reaches the budget constraint. The combined subsidy can therefore expand the region in which policy is executable, but it cannot eliminate the fiscal-budget constraint faced by firms with high certification costs.

Fixed certification cost subsidies only affect the participation constraint and do not enter the first-order conditions for output and emission reduction effort; therefore, they cannot directly raise the emission reduction intensity of certified firms. For a given performance intensity, a combined subsidy has implementation value only when filling the fixed-cost gap can induce participation and satisfy budget and welfare conditions; when a performance-based subsidy alone is sufficient to induce participation, the optimal fixed-cost support can be reduced to zero. This is consistent with the approach of Zhao et al. (2024) in distinguishing between cost-side and operational-side incentives; however,

whereas their investment subsidies can alter the cost of technological improvement, the subsidies in this paper cover predetermined certification costs, resulting in different post-certification effort responses. Therefore, the minimum necessary certification cost support should be allocated according to the actual entry gap, and the performance intensity should be selected according to the incremental emission reduction benefits; the larger feasible set of combined mechanisms should not be interpreted as meaning that any combination is superior to a single tool.

6. Conclusion

6.1. Research Conclusions

This study addresses insufficient entry incentives and limited incentives for continued emission reduction after certification in PCF certification of energy-storage lithium batteries. Under a B2B residual procurement environment, the model incorporates a carbon-footprint certification threshold, the procurement value of certification, emission-reduction cost, fixed certification cost, and fiscal shadow cost, and compares four mechanisms: no subsidy, performance-based emission-reduction subsidy, certification-cost subsidy, and combined subsidy. The results show that manufacturer equilibrium is not simply a continuous change in emission reduction; instead, the firm switches among three states: uncertified, compliance-certified, and excess reduction. Without subsidies, voluntary certification depends on the certification procurement value, the minimum emission reduction required for certification, and the fixed certification cost. The performance subsidy has both a certification-participation threshold and an emission-reduction intensity threshold: crossing the participation threshold resolves whether the firm enters, whereas only crossing the intensity threshold addresses whether it reduces emissions beyond the minimum requirement. The certification-cost subsidy acts mainly on the entry margin, while the combined subsidy has a conditional advantage when the fixed certification cost is high and a standalone performance subsidy provides insufficient entry incentives. A higher fiscal shadow cost also reduces the government's optimal total subsidy expenditure.

6.2. Policy Implications

Based on these findings, five policy recommendations follow.

First, establish a “dual-threshold” subsidy mechanism. Provide moderate subsidies for the fixed certification costs of enterprises that have not yet met the certification participation threshold, thereby encouraging them to enter the certification system. After certification, gradually shift to performance subsidies and, by increasing incentive intensity, drive enterprises to move from minimum compliance emission reductions to beyond-compliance emission reductions.

Second, implement phased and differentiated support. Support can be allocated according to firms' certification participation and emission reduction status. When firms face difficulties in entering certification, the focus should be on easing fixed certification cost constraints; once compliance is achieved, the emphasis should shift to effective performance-based incentives; and for firms already able to obtain certification on their own, fixed subsidies with no incremental effect should be reduced. The specific timing and extent of subsidy phase-down need to be further determined based on firm-level data.

Third, strengthen B2B green procurement coordination. Incorporate PCF certification results into green procurement, tendering and bidding, and industry chain evaluation systems to enhance the procurement value of certification, expand the scope for voluntary enterprise certification, and reduce the need for fiscal subsidies.

Fourth, improve the foundational conditions for PCF accounting and emission reduction. Reduce certification costs by unifying accounting standards, improving the emission factor database, and strengthening the third-party verification system. In addition, reduce marginal abatement costs through technological progress and supply chain collaboration, thereby enhancing enterprises' capacity for sustained emission reduction.

Fifth, establish a dynamic phase-down mechanism under fiscal constraints. Support for fixed certification costs should follow the principle of the minimum level necessary to satisfy firms' participation constraints. Performance-based subsidies, by contrast, should weigh incremental emission reduction benefits against fiscal costs and be adjusted or phased out in a timely manner according to the procurement value of certification, firms' emission reduction status, and changes in social welfare, so as to control overall fiscal expenditure.

6.3. Future Research

Future research will further extend this study in the following three aspects. First, we will incorporate multi-firm competition, supply chain contracts, and green procurement decisions into a unified framework to examine how certification policies affect firms' emission reduction through market competition and supply chain transmission. Second, by introducing firm heterogeneity, technological progress, and policy uncertainty, we will construct a dynamic certification and subsidy model to further investigate the relationships among certification renewal, the phase-down of performance-based subsidies, and firms' long-term investment in emission reduction. Third, by integrating firm-level data on product carbon footprints, certification costs, procurement orders, and subsidies, we will empirically identify and calibrate the key thresholds and policy effects in the model, thereby enhancing the external validity of the conclusions across different firm types and policy scenarios.

Author Contribution

Conceptualization, (L,L); Methodology, (W,H); Software, (X,Z); Formal analysis, (Z,F); Writing - original draft, (W,L); Writing - review and editing, (L,L). All authors have read and agreed to the submitted version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations (if applicable)

BESS – battery energy storage system

EB – environmental benefit

EU – European Union

LCA – life-cycle assessment

R&D – research and development

SI – International System of Units

SW – social welfare.

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