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Collaborative Emission Reduction in Sustainable Coal-Power Supply Chains Under Carbon Trading: The Role of R&D Subsidies

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Abstract

To address the misaligned emission reduction incentives between upstream and downstream firms in coal-power supply chains under the dual carbon goals, and to promote their low-carbon transition and sustainable development, this study develops a coal supplier-led Stackelberg game model under carbon trading. With electricity output held constant, the model compares four scenarios—no subsidy, supplier-only subsidies, generator-only subsidies, and dual subsidies—and further examines subsidy allocation under a budget constraint. The results show that, under certain conditions, subsidizing one firm improves its technology but discourages technological improvement by the other firm. Consequently, subsidies may need to exceed a threshold to achieve net emission reductions. Contract acceptance conditions and the compatibility of the two technologies can alter these interactions. Appropriately allocated dual subsidies can promote technological improvement by both firms and achieve collaborative emission reductions. Under the baseline parameters and specified subsidy rates, dual subsidies yield the lowest emissions but also require the highest government expenditure. Under a budget constraint, the optimal subsidy allocation depends on the budget size and the emission reduction efficiency of the two firms and may involve supporting either one firm or both. Unspent funds may be retained when further expenditure cannot deliver additional emission reductions. This study reveals how R&D subsidies affect total supply-chain emissions through interactions between the two firms' technology choices, providing a basis for policies that coordinate firms' emission reduction incentives, allocate limited subsidy funds effectively, and promote sustainable development in coal-power supply chains.

Keywords: sustainable development; coal–power supply chain; collaborative emission reduction; R&D subsidies; budget constraint; carbon trading; Stackelberg game

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1. Introduction

In recent years, nations globally have recognized the urgent need to reduce carbon emissions to combat climate change. Historical policy initiatives in the European Union, China, and the United States illustrate efforts to reduce emissions [1–3]. One of the biggest challenges of these climate goals is reducing emissions from thermal power generation, with research addressing renewable integration, coal-power emission hotspots, and emission trends [4–7]. IEA assessments document the scale of electricity-sector emissions and the

need for low-emission generation [8]. To address this challenge, governmental policies for curbing emissions in the thermal power supply chain are increasingly important.

IEA's Coal in Net Zero Transitions reports that coal combustion emitted approximately 15 Gt CO_2 in 2021 [9]. Electricity 2026 reports approximately 13.9 Gt CO_2 annually from electricity generation across fuels and notes that global power-sector emissions stabilised in 2025 [10]. The former statistic covers coal combustion; the latter covers electricity generation across fuels. The electricity-sector context is also discussed in Electricity 2025 [8,11].

The research setting is an existing plant over a specified operating period. While renewable deployment, grid development, and plant retirement shape the transition [9,12], existing plants face fuel procurement and retrofit decisions while meeting their electricity obligations. The model examines these operating-period decisions at a fixed output.

The effectiveness of emission reduction policies is primarily determined by their impact on the development of abatement technologies, which are essential both for cutting emissions and for reducing long-term mitigation costs [13–15]. In the thermal power supply chain, the level of combustion emissions depends on the fuel emission factor per unit of energy and the energy conversion efficiency of power generation equipment [16–18]. Clean-coal reviews and coal-supply studies discuss a broader set of technologies and policy responses [19,20]. Gravity separation removes mineral impurities [21]; the modelled upstream improvement requires a measured reduction in CO_2 per unit of net fuel energy. On the other hand, energy conversion efficiency in thermal power companies reflects the efficiency of converting coal into electrical energy. Advanced power generation and efficient coal-combustion methodologies, including IGCC, can improve conversion efficiency [22,23]. Higher efficiency signifies more effective use of fuel and reduced energy wastage, which directly contributes to reductions in combustion emissions at the same electricity output [24–26]. However, the high costs and less-than-ideal returns associated with the research and development (R&D) of these technologies often deter companies from investing in them [27–29]. Studies of CCUS investment examine subsidy design and uncertainty [30–32]. Well-designed subsidy policies should carefully consider the R&D incentives of different entities within the electricity supply chain and their strategic interactions, thereby promoting collaborative emission reduction efforts.

A theoretical pre-drying study links moisture reduction with plant performance [33], whereas coal-sample analysis describes variation in carbon emission factors [34]. These sources respectively inform the generator efficiency mechanism and the interpretation of fuel carbon intensity.

A practical example is Jinneng Holding's online coal trading through the China Taiyuan Coal Transaction Center in Shanxi. Its reported services include listed sales and listed purchases [35]. The listed-sales channel motivates the supplier-offer setting used here: a seller announces a fuel offer, and the buyer decides whether to accept it. The model represents this procurement channel with a supplier commitment followed by the plant's retrofit choice.

In this study, we assess how various government R&D subsidy strategies influence investments in emission reduction technologies and overall carbon emissions within the supply chain. Specifically, we explore two main questions: (1) What R&D subsidy policies can governments implement to promote collaborative emission reductions among coal and electricity companies within a coal-fired electricity supply chain? (2) How do coal enterprises and thermal power companies determine their emission reduction strategies in response to various R&D subsidy policies?

To address these issues, we construct a power supply chain model consisting of a representative coal enterprise and a thermal power company in the context of a carbon emission trading scheme (ETS). Then, using the Stackelberg game approach, we evaluate

the impact of different government R&D subsidy policies on the collaborative emission reduction efforts of these enterprises. In this model, the coal enterprise decides on coal pricing and the investment in coal cleanliness, measured here by the achieved reduction in the energy-based emission factor, while the thermal power company decides on its investment in enhancing energy conversion efficiency. We analyze the optimal response strategies of each participant at equilibrium and compare the different R&D subsidy policies. Numerical analysis illustrates the mechanisms under stated parameter and feasibility assumptions.

Our study makes several contributions. First, this study examines governmental strategies affecting both entities in the power supply chain, distinguishing fuel carbon intensity from generator heat-rate improvement. Second, this study employs Stackelberg game theory to model the coal-dominated electricity supply chain under carbon ETS. This approach allows us to investigate how various government R&D subsidies influence the optimal strategies of both thermal power and coal enterprises. The analysis evaluates technical and participation constraints and compares emissions under subsidy schemes with an alternative carbon-price policy.

The remaining sections are structured as follows: Section 2 reviews the relevant literature. Section 3 presents the model, solves the four subsidy scenarios, and compares their equilibrium decisions and emissions. Section 4 presents the numerical analysis and discussion. Section 5 concludes the study.

2. Literature Review

This study is relevant to two streams of literature: the impact of government emission reduction policies on thermal power companies, and the interactive effects between the production decisions of coal enterprises and thermal power companies.

2.1. Technology Investment and Environmental Policy

In terms of the influence of government emission reduction policies on thermal power companies, Ai et al. [36] utilized a Difference-in-Differences (DID) model to explore the impact of desulfurization electricity price subsidies on emission reductions. They found that these subsidies significantly reduce SO_2 emissions, and their effectiveness is influenced by the level of marketization and economic development. Chen et al. [31] examined the synergistic effects of carbon markets and subsidy policies, analyzing subsidies for CCS retrofitting investment under uncertainty. Their findings indicate that the initial carbon trading price sets the effectiveness of subsidies, while the uncertainty in carbon trading prices affects the marginal impact of these subsidies. These desulfurization and capture studies address different technical outcomes from the fuel-factor and heat-rate improvements modelled here.

Lu et al. [37] employed the Multi-Leader Multi-Follower (MLMF) Stackelberg game to analyze how the carbon ETS influences bidding strategies of power generation companies and the outcomes of electricity market clearing. They suggest that the carbon ETS boosts the competitive advantage of low-emission power generation units. Fan et al. [27] investigated the retrofitting costs and emission reduction potential of thermal power companies, examining plant-level CCUS retrofit costs and the effects of incentive policies. Bai et al. [38] used the classical Slacks-based Measure and Tobit model to evaluate the green efficiency of thermal power companies and the impact of environmental subsidies on their efforts. Their study revealed that current environmental subsidies, particularly for companies meeting ultra-low emission standards to access on-grid electricity prices, notably enhance the green efficiency of enterprises.

Yao et al. [28] examine CCUS business models, while real option studies analyse investment timing and uncertainty [29,30,32]. These approaches differ from the fixed-period

technology choices studied here. Environmental externalities and knowledge spillovers provide distinct motivations for policy intervention [39,40], and carbon taxes and emissions trading differ in implementation and uncertainty [41]. Calel and Dechezleprêtre and Calel investigate innovation and adoption under carbon trading [14,15]. A 2026 study of 17 European countries examines energy patenting, carbon pricing, and R&D support over 2000–2020 [42]. These studies motivate policy comparisons; project-specific costs and benefits determine their application.

2.2. Coal and Electricity Supply-Chain Interactions

Another stream of literature explores the interactive effects between the production decisions of coal enterprises and thermal power companies. Fan et al. [43] developed a Stackelberg game model to analyze the profit dynamics of coal mining enterprises and thermal power companies under two Coal-Electricity Price Linkage (CEPL) mechanisms. The findings suggest that the CEPL mechanism helps mitigate profit losses for thermal power companies during periods of rising coal prices. Guo et al. [44] investigated operational strategies within coal-electricity supply chains, taking into account funding constraints at coal enterprises and production uncertainty. Employing a Stackelberg game model, they identified the optimal operational strategies where the thermal power company provides advance payments to the coal enterprise. The results show that, under this advance payment mechanism with equal order quantities, coal enterprises can produce more products compared to seeking financing from banks. Liu et al. [45] introduced a two-stage dynamic game model to illustrate the interactions between the coal and thermal power generation industries. Their findings suggest that the regulated electricity prices examined in their study are within a moderate range, suggesting that deregulating prices would likely lead to higher electricity prices but lower coal prices.

Wang et al. [46] study emission reduction under a revenue-sharing contract. Cao et al. examine emissions trading in a regulated electricity industry [47], while Ma et al. consider carbon trading and renewable-energy policy [48]. IEA's assessment of China's ETS provides institutional context [49]. At a fixed output, an output-linked allowance is represented by a fixed G.

Recent work by Da et al. (2025) explicitly models clean-coal investment in a coal-electricity supply chain under cap-and-trade [50]. It provides a close theoretical comparator with endogenous generation, whereas this study retains fixed electricity output and separately represents generator heat-rate investment. Zhang et al. (2025) examine generator preferences across policy instruments [51]. These studies provide comparators for the fuel-factor, heat-rate, and subsidy-allocation decisions examined here.

Alternative approaches include system dynamics for mitigation in a green electric-coal chain [52], comparisons of dominant modes [53], and research on supply-chain resilience [54]. Long-term coal contracts have also been analysed using evolutionary games [55]. A supplier-leading game represents a specified sequence of commitments. Demand-response research concerns a further margin intentionally held fixed here [56].

2.3. Functional Assumptions and Remaining Research Gap

Green supply-chain studies use cost-sharing and revenue-sharing structures to analyse investment [57,58]. Here, quadratic costs represent increasing marginal project expenditure over the feasible technical range. Section 4.4 examines the effects of changing both cost coefficients.

IPCC supplies the combustion-accounting identity [59]. Coal samples and engineering analysis inform the interpretation of technical variables [33,34,60]. Life-cycle and multi-regional accounting studies identify impacts beyond the combustion boundary [18,61].

Overall, although the existing literature has extensively explored the effectiveness of emission reduction policies and the interactive effects of production decisions between coal and thermal power companies, there are still notable limitations. Recent coal-electricity investment research [50] makes it necessary to specify the remaining gap more narrowly: this study jointly examines fuel carbon intensity, generator heat-rate improvement, and participation constraints. Technological policies should carefully consider the incentives and interactions of members within the electricity supply chain. The effects on subsidized and non-subsidized entities depend on technical and contractual conditions. This study aims to address these gaps by examining how governments can devise suitable R&D subsidy policies to foster collaborative emission reduction efforts among electricity and coal enterprises within the power supply chain.

3. Model Settings and Scenario Analysis

3.1. Problem Description

Our study focuses on the electricity supply chain, which consists of two entities: a representative coal company and a thermal power company. We have modeled this supply chain using the Stackelberg game framework. In our model, the coal company assumes a leadership role, setting the coal price and its investment in R&D for clean coal technologies, taking into account the reactions of the thermal power company, which acts as the follower. This power company purchases coal for electricity generation and decides its own R&D investment to enhance energy conversion efficiency. The government first announces the subsidy rates; the coal company then commits to a verified fuel specification and energy quotation, after which the power company accepts or rejects the offer and chooses its retrofit. Backward induction is used [62]. Additionally, the thermal power company is directly involved in a carbon emissions trading scheme to limit its emissions, mirroring practices in countries such as China [47,48]. For example, in China's national emissions trading scheme (ETS), when it was established, it covered the coal-fired and gas-fired power generation industries and allocated quotas based on the output of each power plant [49].

The model applies to coal-supplier-leading transactions in which the supplier commits to a fuel specification and energy quotation before the plant accepts the offer and chooses its retrofit. The listed-sales example in the Introduction provides a corresponding procurement setting. The plant's alternative procurement opportunity enters its participation condition, which constrains the supplier's acceptable quotation.

The operating period, electricity output q, and carbon price P are fixed. All costs and rewards refer to the same period. The generator's ETS account values surplus allowances and deficits at the same P. Surplus allowances therefore retain an opportunity value even when emissions are below G. The generator takes the carbon price as given.

The government can implement various strategies to subsidize R&D in emissions reduction technologies for coal companies and thermal power companies, with the aim of advancing these technologies and reducing carbon emissions. We have established four subsidy scenarios: no government subsidies, subsidies to the coal company, subsidies to the thermal power company, and subsidies to both entities. Within each policy scenario, we analyzed the optimal decisions of each participant in the coal-electricity supply chain and derived the equilibrium solutions of the Stackelberg game. This analysis enabled us to perform a comparative assessment of R&D investment levels and the effectiveness of emission reductions across these scenarios.

3.2. Model Hypotheses and Notations

Let h denote delivered fuel energy on a net-calorific basis, $H(e)$ the net calorific value per tonne of delivered coal, and m the delivered mass. E is the reference combustion factor

per unit of energy. The supplier's choice e is the achieved decrease in that factor relative to the reference fuel.

$$\begin{aligned} &h = q[R - t(e)r], t(e) = 1 + \tfrac{(\xi-1)e}{e_{\max}}, \\ &m = \tfrac{h}{H(e)}, F = (E - e)h \end{aligned} \tag{1}$$

Here, q is in GWh, h in TJ, H in TJ/t coal, m in t coal, and F in t CO_2. Both R and r are in TJ/GWh. R is the baseline heat requirement; r measures retrofit effort in heat-rate units, and $t(e)r$ is the realised heat-rate reduction. At $\xi = 1$, r equals that reduction. The dimensionless technology coefficient $\xi > 0$ adjusts the effectiveness of a given retrofit as fuel quality changes: $\xi = 1$ recovers $h = q(R - r)$, $\xi > 1$ strengthens the fuel-saving effect, and $0 < \xi < 1$ weakens it. The quality scale satisfies $e_{\max} > 0$. The analytical comparisons use $\xi = 1$; Section Sensitivity to the Technology Coefficient varies ξ within the same model. Prices and operating costs are specified per unit of delivered energy.

Fuel energy h is the total net-calorific energy needed to produce q during the operating period; multiplying output by the realised heat rate gives $h = q[R - t(e)r]$. Dividing this energy requirement by the delivered coal calorific value $H(e)$ gives the physical coal requirement $m = \frac{h}{H(e)}$. Multiplying h by the achieved combustion factor $E - e$ gives total combustion emissions F. Thus, h measures energy, m measures coal mass, and F measures CO_2 mass; they are distinct quantities connected by the fuel properties.

The factor $t(e) = 1 + \frac{(\xi-1)e}{e_{\max}}$ is a dimensionless multiplier converting retrofit effort r into the realised heat-rate reduction $t(e)r$; $e_{\max}$ is the upper bound on the fuel-factor reduction. The reference technology $\xi = 1$ gives $t(e) = 1$ and $h = q(R - r)$: a given retrofit effort then has the same direct fuel-saving effect at each fuel specification. The firms still influence each other through the energy quotation and fuel demand. Values of ξ above or below 1 describe stronger or weaker fuel-saving effectiveness as e increases.

For example, Stefanović et al. examined representative raw and dried lignite samples from Serbia's Kolubara basin and derived a coal-specific relationship between calorific value and carbon emission factor [34]. This supports using paired carbon-content and calorific-value measurements to define the feasible supplier improvement e. The feasible set is defined by the measured fuel portfolio and its attainable emission factors. If no qualifying option exists, the appropriate upstream feasible set is $e = 0$. The continuous formulation approximates an attainable portfolio or blending range.

The Taizhou power plant in Jiangsu provides an example of fuel savings from improved generation efficiency. A 2024 report by the National Energy Administration estimates that two phase II units using double-reheat technology and generating 13 billion kWh annually can save approximately 480,000 tonnes of standard coal and reduce CO_2 emissions by approximately 1.3 million tonnes per year [63]. This illustrates how reducing the heat required for electricity generation can lower fuel use and combustion emissions. Together with the Kolubara coal-sample evidence [34], it provides a practical basis for distinguishing fuel emission intensity from plant heat-rate improvement. These examples illustrate the technical mechanisms; they do not test the model's predicted subsidy effects.

The generator has a maximum feasible net efficiency $\varepsilon_{\max}$. Since 1 GWh = 3.6 TJ, the following bounds are imposed:

$$\begin{aligned} &0 \le e \le e_{\max} < E, \\ &0 \le r \le r_{\max}(e) = \tfrac{R - \frac{3.6}{\varepsilon_{\max}}}{t(e)}, \\ &R \ge \tfrac{3.6}{\varepsilon_{\max}} \end{aligned} \tag{2}$$

At $\xi = 1$, $r_{\max}(e)$ is the constant, with $r_{\max} = R - \frac{3.6}{\varepsilon_{\max}}$ used below. The supplier quotation satisfies $w \ge 0$. The bound keeps the heat-rate improvement within the maximum

net efficiency. $H(e)$ is used for mass conversion after optimisation. F covers the plant's combustion CO_2; the numerical technical limits are scenario assumptions.

In all scenarios, coal companies' revenues include coal sales, while costs encompass total production costs of coal and investments in emission reduction technologies aimed at enhancing coal cleanliness. For thermal power companies, revenues stem from electricity sales, and costs include the expenses related to purchasing coal for power generation and investments in technologies to improve energy conversion efficiency. Furthermore, in scenarios with government subsidies, the subsidized entities receive corresponding subsidy income.

Let $c + ke$ be the supplier's variable cost per TJ, with $k \geq 0$. The term keh is an incremental operating expense that scales with delivered energy; ηe^2 is period-equivalent project expenditure for developing or implementing fuel specification. θr^2 is the period-equivalent generator retrofit expenditure. Project expenditure can include annualised investment. The operating expenses represented by k are accounted for separately from the project expenditure represented by η. The linear operating premium is a local approximation; $k = 0$ is included in sensitivity analysis.

Quadratic project costs $C_c(e) = \eta e^2$ and $C_p(r) = \theta r^2$ imply marginal expenditures $2\eta e$ and $2\theta r$ and positive second derivatives 2η and 2θ. The assumption represents increasing marginal project expenditure over the feasible technical range: increasingly demanding fuel specifications can require additional treatment and blending, while deeper heat-rate reductions can require more extensive boiler and turbine modifications. Da et al. [53], in Strategies of Two-Level Green Technology Investments for Coal Supply Chain under Different Dominant Modes, provide a coal-supply-chain modelling precedent for quadratic green-technology investment costs. In this study, the two functions represent expenditure on verified fuel-factor reduction and generator retrofit, respectively. Table 1 specifies the period-equivalent cost coefficients and their distinct units.

The study considers procurement and retrofit decisions for the same existing power plant. Its previously incurred construction expenditure is treated as a common sunk cost across the alternatives. Deducting this expenditure lowers profit by the same amount under each option and leaves the profit differences between options unchanged. Since the expenditure does not vary with the current retrofit decision, it leaves both the optimal retrofit choice and the contract acceptance comparison unchanged. The resulting equilibrium emissions are therefore also unchanged.

Incremental retrofit investment is included in the generator's profit as θr^2 on a period-equivalent basis, with marginal expenditure $2\theta r$. Under the reference technology, for the given w, e, and y, the generator's interior best response is

$$r^* = \frac{q[w + P(E - e)] + y}{2\theta}$$

A higher retrofit cost coefficient θ therefore reduces the chosen retrofit level under these conditions. Fuel requirements and combustion emissions are

$$h = q(R - r^*), F = (E - e)q(R - r^*)$$

At an unchanged fuel emission factor, lower retrofit effort increases the fuel required for the same electricity output and consequently increases emissions. The full supply-chain equilibrium additionally incorporates the supplier's adjustments in its quotation and fuel technology.

The rewards are xe and yr, paid for verified achievement relative to the technical references $e = 0$ and $r = 0$. The government announces x and y before the firms choose their technologies; payment is then calculated by multiplying each announced rate by the corresponding verified achievement. This links each payment directly to the technical

outcome encouraged by the policy. Under the complete-information specification, $x = \eta s_c$ and $y = \theta s_p$ express the original cost-scaled rates in compact notation. Cost information is used to evaluate incentives and compare recipient choices, while payment at announced rates uses the verified e and r. Table 1 specifies the units, and the total subsidy expenditure is $xe + yr$.

$$\pi_c = (w - c - ke)h - \eta e^2 + xe \tag{3}$$

$$\pi_p = pq - wh + P(G - F) - \theta r^2 + yr \tag{4}$$

Complete information about costs and accurate verification and payment of e and r are baseline assumptions. Fuel assays and plant heat-rate records provide the verification inputs. The model assumes reliable indicators, full payment, and use of funds for the agreed purpose. The cost sensitivity analysis varies the true project-cost coefficients while retaining these information and implementation assumptions.

Table 1. Notation and units.

Symbol	Meaning	Unit
q; h; m	Electricity output; delivered fuel energy; coal mass	GWh; TJ; t coal
E; e; $e_{\max}$	Reference combustion factor; verified reduction; upper bound	t CO_2/TJ
R; r; $r_{\max}$	Reference heat rate; retrofit effort; effort bound	TJ/GWh
$H(e)$; $\varepsilon_{\max}$	Net calorific value; maximum net efficiency	TJ/t coal; dimensionless
w; c; w_{ref}	Energy quotation; base variable cost; alternative quote	CNY/TJ
k	Incremental variable cost coefficient	CNY/t CO_2
η; θ	Supplier and plant quadratic project-cost coefficients	CNY/(t CO_2/TJ)^2; CNY/(TJ/GWh)^2
x; y	Achievement reward rates	CNY/(t CO_2/TJ); CNY/(TJ/GWh)
p; P; G	Electricity price; carbon price; free allowances	CNY/GWh; CNY/t CO_2; t CO_2
F	Combustion emissions	t CO_2
π_c; π_p; $\overline{\pi}_c$; $\overline{\pi}_p$	Operating-period and outside-option payoffs	CNY
ξ; $t(e)$	Technical interaction coefficient; retrofit-effectiveness multiplier	dimensionless
Ω; L	Curvature determinant $8\eta\theta - q^2L^2$; net carbon-value coefficient $P - k$	Defined combinations of parameters
Superscripts I; B; b	Interior candidate; participation-binding candidate; plant best response	Notation labels
$\bar{z}$; $\bar{r}$; $\bar{h}$	Effective price, retrofit and fuel energy at participation ceiling	CNY/TJ; TJ/GWh; TJ

The corresponding observable inputs are project expenditure records paired with verified technical outcomes. Fuel carbon-content, oxidation, and calorific-value measurements determine e; plant output and fuel-energy records determine the realised heat rate and give $t(e)r$. Under the assumed cost functions, a positive outcome paired with its period-equivalent project expenditure implies $\eta = \frac{C_c}{e^2}$ or $\theta = \frac{C_p}{r^2}$. Within the assumed quadratic specification, these relationships connect the coefficients to period-matched project-cost and technical records. The complete-information analysis treats these coefficients as known when comparing policies. Project costs must be separated from the operating expense $(c + ke)h$ and from subsidy receipts and compared over the same period. Selecting a recipient therefore requires verified technical outcomes paired with the corresponding project costs.

$$\pi_p \geq \overline{\pi}_p(P, y), \pi_c \geq \overline{\pi}_c \tag{5}$$

The outside payoffs must be specified consistently with the policy. For the numerical example, $\overline{\pi}_c = 0$ and $\overline{\pi}_p$ are the larger of zero and the generator's optimised payoff from a reference supplier offering $e = 0$ at w_{ref} under the same P and y. The zero option represents not entering the modelled supply contract. The generator is assumed to accept an offer when indifferent. Offers violating participation are excluded before identifying an equilibrium.

To clarify our model, Table 1 defines the notations.

3.3. Game Analysis Under Four Subsidy Scenarios

The analytical solutions in Sections 3.3 and 3.4 are stated for the reference technology $\xi = 1$.

Lemma 1. *Generator best response at $\xi = 1$. For an accepted contract and $\theta > 0$, the generator has a unique best response on $[0, r_{max}]$:*

$$r^b(w, e) = \min\left\{r_{\max}, \max\left\{0, \frac{q(w + P(E - e)) + y}{2\theta}\right\}\right\} \tag{6}$$

Write $\hat{r} = \frac{q(w+P(E-e))+y}{2\theta}$. Equation (6) means $r^b = 0$ when $\hat{r} \le 0$, $r^b = \hat{r}$ when $0 < \hat{r} < r_{\max}$, and $r^b = r_{\max}$ when $\hat{r} \ge r_{\max}$. The inner max enforces the lower bound and the outer min enforces the upper bound. The superscript b denotes the generator's best response. Strict concavity follows from $\frac{\partial^2 \pi_p}{\partial r^2} = -2\theta$; the derivation is in Appendix A.1.

Define $L = P - k$, $\Omega = 8\eta\theta - q^2L^2$, and $A_0 = 2\theta R - q(c + PE)$. We use N, C, T, and D for no subsidy, coal-company subsidy, thermal-power-company subsidy, and dual subsidy, respectively. The superscript I denotes a candidate with interior technical choices and a slack participation constraint. The superscript B denotes a participation-binding candidate: the generator earns exactly its outside-option payoff. These superscripts describe equilibrium conditions; N, C, T, and D describe subsidy scenarios. Each scenario is solved by substituting the generator's best response into the supplier's objective and applying backward induction. The technical and participation conditions in Section 3 apply to all four scenarios; Section 3.3.5 selects the feasible equilibrium when a constraint binds.

3.3.1. Scenario 1 No Government Subsidy

In this benchmark, $x = y = 0$. The firms' payoffs are $\pi_c(N) = (w - c - ke)h - \eta e^2$ and $\pi_p(N) = pq - wh + P(G - F) - \theta r^2$. The generator responds with (6) at $y = 0$. For $\Omega > 0$, substitution into the supplier's objective gives:

$$e^I(N) = \frac{qLA_0}{\Omega} \tag{7}$$

$$w^I(N) = \frac{\theta R}{q} + \frac{c - PE + (P + k)e^I(N)}{2} \tag{8}$$

$$r^I(N) = \frac{R}{2} + \frac{q\left[c + PE - Le^I(N)\right]}{4\theta} \tag{9}$$

If the participation ceiling binds, Proposition 2 instead gives $e^B(N) = \frac{\overline{h}_0 L}{2\eta}$, subject to the quality bounds. The associated quotation is $w^B(N) = \overline{z}_0 - P\left[E - e^B(N)\right]$, and retrofit follows (6) with $y = 0$. Subscript 0 means that the ceiling and fuel demand are evaluated without plant support. The feasible no-subsidy equilibrium provides the reference for all comparisons.

3.3.2. Scenario 2 Subsidizing Only the Coal Enterprise

The government rewards the coal company at $x > 0$, with $y = 0$. The payoffs become $\pi_c(C) = (w - c - ke)h - \eta e^2 + xe$ and $\pi_p(C) = pq - wh + P(G - F) - \theta r^2$. The generator's response retains the form used in scenario N; the supplier's quality incentive includes x. The interior candidate is

$$e^I(C) = \frac{qLA_0 + 4\theta x}{\Omega} \tag{10}$$

$$w^I(C) = \frac{\theta R}{q} + \frac{c - PE + (P + k)e^I(C)}{2} \tag{11}$$

$$r^I(C) = \frac{R}{2} + \frac{q\left[c + PE - Le^I(C)\right]}{4\theta} \tag{12}$$

At a binding participation ceiling, $e^B(C) = \frac{\overline{h}_0 L + x}{2\eta}$, subject to the quality bounds, and $w^B(C) = \overline{z}_0 - P\left[E - e^B(C)\right]$. The generator has the same effective energy price $\overline{z}_0$ and retrofit $\overline{r}_0$ as in scenario N. Proposition 2 gives the conditions and derivation.

3.3.3. Scenario 3 Subsidizing Only the Thermal Power Company

Here, $x = 0$ and $y > 0$. The payoffs are $\pi_c(T) = (w - c - ke)h - \eta e^2$ and $\pi_p(T) = pq - wh + P(G - F) - \theta r^2 + yr$. The reward enters the generator's response in (6), which changes fuel purchases and the supplier's optimal decisions. The interior candidate is

$$e^I(T) = \frac{qL(A_0 - y)}{\Omega} \tag{13}$$

$$w^I(T) = \frac{\theta R}{q} + \frac{c - PE + (P + k)e^I(T)}{2} - \frac{y}{2q} \tag{14}$$

$$r^I(T) = \frac{R}{2} + \frac{q\left(c + PE - Le^I(T)\right) + y}{4\theta} \tag{15}$$

At a binding participation ceiling, $e^B(T) = \frac{\overline{h}_y L}{2\eta}$, subject to the quality bounds, and $w^B(T) = \overline{z}_y - P\left[E - e^B(T)\right]$. Here, $\overline{z}_y$ and $\overline{h}_y$ are evaluated with the plant reward y and its corresponding outside option; retrofit follows (6).

3.3.4. Scenario 4 Subsidizing Both Enterprises

Both x and y are positive. The payoffs are $\pi_c(D) = (w - c - ke)h - \eta e^2 + xe$ and $\pi_p(D) = pq - wh + P(G - F) - \theta r^2 + yr$. Applying backward induction with both rewards gives

$$e^I(D) = \frac{qL(A_0 - y) + 4\theta x}{\Omega} \tag{16}$$

$$w^I(D) = \frac{\theta R}{q} + \frac{c - PE + (P + k)e^I(D)}{2} - \frac{y}{2q} \tag{17}$$

$$r^I(D) = \frac{R}{2} + \frac{q\left(c + PE - Le^I(D)\right) + y}{4\theta} \tag{18}$$

At a binding participation ceiling, $e^B(D) = \frac{\overline{h}_y L + x}{2\eta}$, subject to the quality bounds, and $w^B(D) = \overline{z}_y - P\left[E - e^B(D)\right]$. Retrofit follows (6) at the same y. Setting either reward to zero recovers the corresponding single-recipient candidate; setting both to zero recovers scenario N.

3.3.5. Feasibility and Participation Conditions

Proposition 1. *Interior candidates and equilibrium selection. Equations (7)–(18) solve the first-order conditions for the four scenarios on the generator's interior-response region. The supplier's reduced Hessian is negative definite for* $\Omega > 0$. *These expressions describe an equilibrium only if they satisfy the technical and participation conditions and dominate all feasible boundary candidates. Appendix A.1 derives the first-order conditions and Hessian and gives the constrained candidate comparison.*

A significant feasibility restriction follows directly: $c + PE - Le = c + P(E - e) + ke > 0$ when $c \geq 0$, $P > 0$ and $e < E$. Thus, $r^I > \frac{R}{2}$ for non-negative y. Consequently, this interior candidate requires more than a doubling of baseline net efficiency and is feasible only if $\varepsilon_{\max} > 2\left(\frac{3.6}{R}\right)$. At the 36% baseline and 45% upper bound in Table 2, the applicable equilibrium is therefore selected from the constrained candidates. Theorems 1–7 distinguish interior comparisons from the participation-binding results used in Section 4.

Table 2. Baseline scenario inputs; monetary values are illustrative.

Parameter	Value	Basis/Interpretation
q; R	1000 GWh; 10 TJ/GWh	Annual operating block; reference efficiency 36%
E	95 t CO_2/TJ	Rounded IPCC-scale scenario; not a measured assay
$e_{\max}$; $\varepsilon_{\max}$	6 t CO_2/TJ; 0.45	Hypothetical fuel range and engineering bound
c; k	25,000 CNY/TJ; 20 CNY/t CO_2	Illustrative fuel supply costs
η; θ	0.30 million; 50 million	Illustrative project-cost coefficients; units in Table 1
p; w_{ref}	400,000 CNY/GWh; 40,000 CNY/TJ	Illustrative electricity price and alternative quote
P; G	100 CNY/t CO_2; 800,000 t CO_2	Carbon-price and allowance scenarios
x in C/D; y in T/D	1 million; 10 million	Reward rates with units in Table 1
ξ	1	Reference technology

Because output is fixed and $r_{\max} < R$, fuel demand remains positive even at the maximum retrofit. Without a participation condition or quotation limit, a supplier could raise w indefinitely after the generator reaches $r_{\max}$. A finite constrained procurement problem is therefore necessary.

Let $z = w + P(E - e)$ be the generator's effective energy price, and let $V(z,y)$ be its maximised payoff over the feasible r range. V is strictly decreasing in z wherever $h > 0$. The participation ceiling solves $V(\bar{z}, y) = \overline{\pi}_p(P, y)$. For a given P, y, and outside option, $\bar{z}$ does not depend on the incumbent supplier's*e* in the baseline technology. At a binding ceiling, $w = \bar{z} - P(E - e)$. Economically, this is the highest effective fuel price that leaves the plant as well off as its alternative procurement option. Define $\bar{r} = \min\left\{r_{\max}, \max\left\{0, \frac{q\bar{z}+y}{2\theta}\right\}\right\}$ and $\bar{h} = q(R - \bar{r})$. An overbar denotes evaluation at this ceiling.

Proposition 2. *Participation-binding equilibrium. On a region where the supplier's optimal offer attains the participation ceiling and its quality choice is interior, the unique quality choice on that ceiling and the corresponding quotation are*

$$e^B = \frac{\overline{h}(P-k)+x}{2\eta}, w^B = \overline{z} - P\left(E - e^B\right) \tag{19}$$

If the expression for e^B lies outside $[0, e_{\max}]$, its constrained value is the nearest endpoint. The ceiling candidate is an equilibrium when it maximises supplier profit over the feasible offers and satisfies supplier participation. Appendix A.1 proves (19). The four scenario substitutions are stated in Sections 3.3.1–3.3.4. The quotation follows (19), retrofit follows (6), and Appendix A.1 compares all feasible candidates.

3.4. Comparative Analysis of Different Subsidy Scenarios

The comparisons use the no-subsidy equilibrium under the same market and technical conditions as their reference. Let e_0 and r_0 denote that equilibrium and write $\Delta e = e - e_0$ and $\Delta r = r - r_0$. The exact reduction in combustion emissions is

$$\Delta F = F_0 - F = q[(R - r_0)\Delta e + (E - e_0)\Delta r - \Delta e \Delta r] \tag{20}$$

The first two terms represent the separate improvements evaluated at the baseline; the last corrects their overlap. Equation (20) applies to every feasible equilibrium at $\xi = 1$. For the interior comparisons below, define $a = \frac{4\theta}{\Omega}, b = \frac{qL}{\Omega}$, and $d = \frac{2\eta}{\Omega}$, with $L = P - k > 0$ and $\Omega > 0$. Both the no-subsidy and subsidised equilibria must remain on the same feasible interior branch. The participation-binding comparisons use Proposition 2 and the stated quality bounds.

3.4.1. No Government Subsidy vs. Subsidy to the Coal Enterprise

Theorem 1. *Compared with no government subsidy on the same feasible interior branch, subsidizing the coal company improves coal cleanliness, raises its energy quotation, and reduces the thermal power company's heat-rate improvement. The changes are*

$$\Delta e(C) = ax, \Delta r(C) = -bx, \Delta w(C) = \frac{2\theta(P+k)x}{\Omega} \tag{21}$$

The effects increase in magnitude with x, while the branch remains feasible. On a participation-binding branch with interior quality, supplier support instead gives $\Delta e(C) = \frac{x}{2\eta}, \Delta w(C) = \frac{Px}{2\eta}$, and $\Delta r(C) = 0$. The proof is in Appendix A.1.

The generator's retrofit incentive depends on the effective fuel price $w + P(E - e)$. Saving one unit of fuel energy avoids both the fuel purchase expenditure w and the carbon expenditure $P(E - e)$. For an interior generator response, a change in supplier support therefore gives

$$\frac{dr}{dx} = \frac{q}{2\theta}\left(\frac{dw}{dx} - P\frac{de}{dx}\right)$$

A higher quotation strengthens the incentive to save fuel, whereas a lower fuel emission factor reduces the carbon expenditure saved per unit of fuel. On the feasible interior branch in Theorem 1, the second effect dominates, and retrofit effort decreases. At a binding participation ceiling under the reference technology, the quotation increase exactly offsets the reduction in unit carbon expenditure. The effective fuel price and the generator's retrofit choice then remain unchanged. Surplus allowances retain their carbon-saving opportunity value in both comparisons.

L compares the carbon value of a one-unit reduction in the energy-based emission factor with its additional operating cost coefficient; the separate marginal project cost $2\eta e$ remains in the supplier's optimisation. At a binding participation ceiling, $\frac{dw^B}{dx} = \frac{Pde^B}{dx}$. The

effective price $w^B + P(E - e^B)$ therefore remains $\bar{z}$ and the plant's retrofit remains $\bar{r}$, as observed in the numerical baseline.

Theorem 2. *Let $K_C = (R - r_0)a - (E - e_0)b$. Under the same feasible interior conditions as Theorem 1, supplier-only support reduces combustion emissions precisely when*

$$\frac{\Delta F(C)}{q} = x(K_C + abx) > 0 \Leftrightarrow x > \max\left\{0, -\frac{K_C}{ab}\right\} \tag{22}$$

For $K_C < 0$, a positive subsidy below $-K_C/(ab)$ raises emissions, equality leaves emissions unchanged, and a larger feasible subsidy lowers emissions. For $K_C \geq 0$, every positive subsidy on the stated branch lowers emissions.

Economically, supplier support reduces the emission factor per unit of fuel energy but also lowers the generator's retrofit effort on this interior branch, increasing fuel requirements for the same electricity output. These effects operate in opposite directions. When $K_C < 0$, a small subsidy produces an increase in fuel use that outweighs the benefit of the lower emission factor. At

$$x_c = -\frac{K_C}{ab},$$

The two effects exactly offset each other. A subsidy above this threshold lowers total emissions, provided the equilibrium remains on the stated feasible interior branch. The threshold therefore identifies the subsidy rate required to achieve a net emission reduction after accounting for the generator's response.

At a binding participation ceiling under the reference technology, r is unchanged and

$$\Delta F_C = \bar{h}_0 \Delta e_C$$

Emissions fall whenever supplier support raises e. Appendix A.1 gives proof.

A threshold beyond the feasible interior branch is evaluated using the constrained equilibrium and (20).

3.4.2. No Government Subsidy vs. Subsidy to the Thermal Power Company

Theorem 3. *Compared with no government subsidy on the same feasible interior branch, subsidizing the thermal power company raises its heat-rate improvement, reduces coal cleanliness, and lowers the energy quotation. The changes are*

$$\begin{aligned} &\Delta e(T) = -by, \Delta r(T) = dy, \\ &\Delta w(T) = -\tfrac{(4\eta\theta + q^2 kL)y}{q\Omega} \end{aligned} \tag{23}$$

These signs hold for $P > k \geq 0$ and $\Omega > 0$. On a participation-binding branch with interior quality, $\Delta e(T) = -\frac{qL\Delta r(T)}{2\eta}$ and $\Delta w(T) = \Delta\bar{z} + P\Delta e(T)$; the quotation change therefore also depends on the outside option. The proof is in Appendix A.1.

The generator's retrofit reduces fuel purchases $h = q(R - r)$. Sales revenue is Rev $= wh$, and its local change is dRev $= hdw + wdh$. For a finite comparison with scenario N, the exact change is ΔRev $= h^N \Delta w + w^N \Delta h + \Delta w \Delta h$. The third term accounts for price and quantity changing together. The mass-based quotation is $wH(e)$, so comparing CNY per tonne also requires the corresponding calorific values.

The supplier's interior pricing condition is $2w = c - PE + (P + k)e + \frac{2\theta R}{q} - \frac{y}{q}$. Holding e fixed, plant support reduces the supplier's optimal quotation by $\frac{y}{2q}$; the induced quality change contributes $\frac{(P+k)\Delta e(T)}{2}$. Substituting $\Delta e(T) = -\frac{qLy}{\Omega}$ gives the negative quotation

difference in (23). The price result follows jointly from optimal pricing and the endogenous quality response. Sales revenue wh and profit in (3) are separate outcomes.

Economically, plant support raises retrofit effort and reduces fuel-energy purchases for a fixed electricity output. The supplier then reoptimises its quotation by balancing its sales margin against the induced fuel demand. On the feasible interior branch, the term $-\frac{y}{2q}$ is the direct downward shift in this optimal quotation, holding e fixed. The induced decrease in e adds the negative term $\frac{(P+k)\Delta e(T)}{2}$. Their sum establishes the price decrease in Theorem 3. The implication is that a policy directed at the generator also changes upstream pricing and technology incentives. Supplier sales revenue must therefore be evaluated from both price and quantity, and supplier profit additionally includes production costs, project expenditure, and any reward. When participation binds, the outside procurement opportunity constrains pricing through $\Delta\bar{z}$. The sign of $\Delta\bar{z}+P\Delta e(T)$ determines the quotation change on that branch.

Theorem 4. *Let $K_T = (E - e_0)d - (R - r_0)b$. Under the same feasible interior conditions as Theorem 3, plant-only support reduces combustion emissions precisely when*

$$\frac{\Delta F(T)}{q} = y(K_T + bdy) > 0 \Leftrightarrow y > \max\left\{0, -\frac{K_T}{bd}\right\} \tag{24}$$

For $K_T < 0$, a positive subsidy below $-K_T/(bd)$ raises emissions, equality leaves emissions unchanged, and a larger feasible subsidy lowers emissions. For $K_T \geq 0$, every positive subsidy on the stated branch lowers emissions.

Plant support increases retrofit effort and reduces fuel requirements, while the supplier's lower technology investment increases the emission factor per unit of fuel energy. When $K_T < 0$, the latter effect dominates at small subsidy rates. At

$$y_c = -\frac{K_T}{bd},$$

The two effects exactly offset each other. Above this threshold, fuel savings outweigh the adverse change in the emission factor, and total emissions decrease within the stated feasible interior branch.

When participation or technical bounds bind, substitute the constrained decisions into the exact emission-change expression in Equation (20). Theorem 3 explains why the supplier's technology response must be included alongside the plant's fuel savings. Appendix A.1 gives the proof.

3.4.3. Subsidy to the Coal Enterprise vs. Subsidy to the Thermal Power Company

Theorem 5. *For given positive reward rates x and y, with N, C, and T all on the same feasible interior branch, coal-company support achieves lower emissions than thermal-power-company support if and only if*

$$xK_C + abx^2 > yK_T + bdy^2 \tag{25}$$

Equality gives the same emissions, and the reversed inequality favours plant support. This compares the two policies at their specified reward rates. The reward rates x and y have different units, and actual payments are calculated from the corresponding rates and achieved technical outcomes. For constrained equilibria, compare $F(C)$ and $F(T)$ directly. The proof is in Appendix A.1.

3.4.4. No Government Subsidy vs. Subsidies to Both Enterprises

Theorem 6. *Compared with N on the same feasible interior branch, dual subsidies change the energy quotation by*

$$\Delta w(D) = \frac{2\theta(P+k)x}{\Omega} - \frac{(4\eta\theta + q^2kL)y}{q\Omega} \tag{26}$$

For $x, y > 0$, $P > k \geq 0$, and $\Omega > 0$, the quotation rises when $\frac{x}{y} > \frac{4\eta\theta+q^2kL}{2q\theta(P+k)}$, is unchanged at equality, and falls below this ratio. On a participation-binding branch with interior quality, $\Delta w(D) = \Delta\bar{z} + P\Delta e(D)$, with the ceiling evaluated at the corresponding plant reward. The proof is in Appendix A.1.

Theorem 7. *For positive dual rewards and N and D on the same feasible interior branch, both coal cleanliness and generator heat-rate improvement increase if and only if*

$$\frac{qL}{4\theta} < \frac{x}{y} < \frac{2\eta}{qL}, L > 0, \Omega > 0 \tag{27}$$

The ratio uses the reward-rate units in Table 1. Under these conditions, combustion emissions fall at fixed output. On a participation-binding branch with interior quality, $\Delta e(D) = \frac{x - qL\Delta r(D)}{2\eta}$, so joint improvement requires $\Delta r(D) > 0$ and $x > qL\Delta r(D)$. At a quality bound, use the clipped choice in Proposition 2. Appendix A.1 proves both statements.

3.5. Extension: Optimal Subsidy Allocation Under a Budget Constraint

The preceding comparisons take the subsidy rates as a given. They show how each policy changes the firms' decisions and emissions but do not determine how a limited government budget should be divided. This extension allows the government to choose x and y before the firms act while retaining the decision sequence, profits, carbon price, and technical and participation conditions of the main model. As in the analytical comparisons, $\xi = 1$.

3.5.1. Firm Decisions and the Government Budget

The actual payments to the coal supplier and generator are $xe^*(x,y)$ and $yr^*(x,y)$, respectively. Total subsidy expenditure is

$$S(x,y) = xe^*(x,y) + yr^*(x,y). \tag{28}$$

Here, $e^*(x,y)$ and $r^*(x,y)$ are the feasible equilibrium choices selected using Section 3.3.5. On the common feasible interior branch, let e^0,r^0 denote the no-subsidy equilibrium. Equations (7)–(18) give

$$e^* = e^0 + ax - by, \qquad r^* = r^0 - bx + dy, \tag{29}$$

where the coefficients retain the notation of Section 3.4:

$$a = 4\theta/\Omega, \quad b = qL/\Omega, \quad d = 2\eta/\Omega, \quad L = P - k > 0. \tag{30}$$

Thus, coal-company support increases the supplier's improvement but reduces the generator's retrofit on this branch; generator support has the opposite cross-firm effects. Government allocation must therefore compare the net effect on total emissions, rather than only the increase in investment by the subsidised firm. These response formulas apply only while both technical choices are interior and participation does not restrict the quotation. When a constraint binds, the constrained equilibrium from Section 3.3.5 replaces them.

For a budget ceiling $\overline{B}$, the government solves

$$\begin{aligned} \min_{x,y\geq 0} \quad & F(x,y) = q[E - e^*(x,y)][R - r^*(x,y)], \\ & \text{s.t.} \quad S(x,y) \leq \overline{B}, \\ & 0 \leq e^* \leq e_{\max}, \quad 0 \leq r^* \leq r_{\max}, \\ & w^* \geq 0, \quad \pi_c^* \geq \overline{\pi}_c, \quad \pi_p^* \geq \overline{\pi}_p(P,y). \end{aligned} \tag{31}$$

The government anticipates the firms' equilibrium choices; it does not choose their technologies directly. The budget limits actual payments, not the sum of the two rates. Substituting the interior responses into the budget gives

$$S(x,y) = e^0 x + r^0 y + ax^2 + dy^2 - 2bxy. \tag{32}$$

Since

$$a > 0, \qquad d > 0, \qquad ad - b^2 = 1/\Omega > 0, \tag{33}$$

The quadratic budget expression is strictly convex, and its sublevel set is bounded. Non-negativity and the technical and participation conditions further restrict which subsidy combinations can be used. On the same interior branch, emissions are

$$F(x,y) = q(E - e^0 - ax + by)(R - r^0 + bx - dy). \tag{34}$$

This gives a quadratic emissions objective over a quadratic budget set on the stated branch. The firm responses and the following single-recipient candidates have analytical expressions. The allocation to both firms can be reduced to a one-dimensional search. The constrained branches must also be checked before selecting a policy.

3.5.2. Single-Recipient and Dual-Subsidy Candidates

For coal-only support, set $y = 0$. If further support reduces emissions, the budget binds and the equilibrium remain on the stated interior branch, then $x(e^0 + ax) = \overline{B}$. The non-negative solution is

$$x_C(\overline{B}) = \frac{-e^0 + \sqrt{(e^0)^2 + 4a\overline{B}}}{2a}, \qquad y_C = 0. \tag{35}$$

The associated technologies and emissions are

$$e_C = e^0 + ax_C, \quad r_C = r^0 - bx_C, \quad F_C = q(E - e_C)(R - r_C). \tag{36}$$

For generator-only support, set $x = 0$. Under the same budget-binding and feasibility conditions, $y(r^0 + dy) = \overline{B}$, giving

$$y_T(\overline{B}) = \frac{-r^0 + \sqrt{(r^0)^2 + 4d\overline{B}}}{2d}, \qquad x_T = 0. \tag{37}$$

The corresponding outcomes are

$$e_T = e^0 - by_T, \quad r_T = r^0 + dy_T, \quad F_T = q(E - e_T)(R - r_T). \tag{38}$$

These expressions identify candidates that use the available budget on one firm. They do not establish that either candidate is globally optimal. Each must satisfy the original technical and participation conditions and be compared with support for both firms, no support, and feasible choices using less than the budget ceiling. If a constraint is reached earlier, its constrained solution is used instead of extending the interior formula beyond its range.

For dual support, write $u = E - e^*$ and $v = R - r^*$. On the interior branch, the marginal reductions in emissions from increasing each rate are

$$M_c = -\frac{\partial F}{\partial x} = q(av - bu), \qquad M_e = -\frac{\partial F}{\partial y} = q(du - bv). \tag{39}$$

The corresponding changes in total government expenditure are

$$C_c = \frac{\partial S}{\partial x} = e^0 + 2ax - 2by, \qquad C_e = \frac{\partial S}{\partial y} = r^0 + 2dy - 2bx. \tag{40}$$

For an allocation with $x > 0$, $y > 0$, a binding budget and no active technical or participation boundary, the first-order conditions are

$$M_c = \mu C_c, \qquad M_e = \mu C_e, \qquad S(x,y) = \overline{B}. \tag{41}$$

When both marginal expenditures are positive and the budget has a positive marginal abatement value, this becomes

$$\frac{M_c}{C_c} = \frac{M_e}{C_e} = \mu > 0. \tag{42}$$

The rule has a direct interpretation: the last unit of government expenditure must produce the same reduction in emissions through either subsidy. Otherwise, transferring a small amount of expenditure towards the more effective subsidy can reduce emissions further. Equal marginal effectiveness does not require equal rates or equal payments to the two firms.

Combining the marginal condition with the budget equation generally produces a fourth-degree equation after eliminating one variable. Its full root expression is lengthy and includes roots that may be negative, infeasible, or inferior to another policy. A simpler calculation uses the budget equation to express the generator rate as

$$y_{\pm}(x) = \frac{2bx - r^0 \pm \sqrt{(r^0 - 2bx)^2 - 4d\left(ax^2 + e^0 x - \overline{B}\right)}}{2d}. \tag{43}$$

Retain only real, non-negative roots that satisfy the branch conditions, then evaluate

$$F_{\overline{B}}(x) = F\left(x, y_{\pm}(x)\right). \tag{44}$$

Comparing all stationary points and feasible endpoints gives the dual-support candidates on that budget curve. These are compared with the two single-recipient candidates, the no-subsidy point, and candidates where a technical or participation condition binds. The analytical reduction therefore makes the calculation transparent without requiring a long formula for every possible root. Where the firm equilibrium changes branch, its actual response and subsidy expenditure must be recalculated.

3.5.3. Subsidy Priorities and Changes in Allocation

For a small budget and a feasible interior no-subsidy equilibrium with $e^0 > 0$ and $r^0 > 0$, marginal abatement per unit of expenditure is

$$\rho_c^0 = \frac{q\left[a\left(R - r^0\right) - b\left(E - e^0\right)\right]}{e^0}, \qquad \rho_e^0 = \frac{q\left[d\left(E - e^0\right) - b\left(R - r^0\right)\right]}{r^0}. \tag{45}$$

If $\rho_c^0 > \max\{0, \rho_e^0\}$, the first units of budget should favour the coal supplier. If $\rho_e^0 > \max\{0, \rho_c^0\}$, they should favour the generator. Equal positive values make dual support a possible initial allocation. If both are negative, sufficiently small subsidies increase emissions and are not worth using for the stated abatement objective. This local result does not exclude a better policy at a larger subsidy level; the full comparison below is still required. If an initial technology is zero, the corresponding ratio is undefined and the change in emissions and actual expenditure must be compared directly.

At a subsidy combination with positive marginal expenditures, define

$$\rho_c(x,y) = M_c/C_c, \qquad \rho_e(x,y) = M_e/C_e. \tag{46}$$

As the budget increases, the preferred allocation may change. Starting from coal-only support on a smooth feasible branch, reallocating some expenditure to the generator becomes locally beneficial when

$$\rho_e(x_C,0) > \rho_c(x_C,0). \tag{47}$$

Equality identifies a possible transition point. The reverse comparison applies when starting from generator-only support. The transition is confirmed by comparing the emissions of the feasible policies, since equality alone does not establish a global optimum. Thus, a larger budget does not automatically justify support for both firms from the outset. Carbon-price or project-cost changes also require recalculating the equilibrium responses and marginal effects before adjusting the rates.

3.5.4. Technical Limits and Unspent Budget

The budget ceiling is the maximum permitted expenditure, not a requirement to spend it all. On the interior coal-only response, the rate at which the supplier would reach its upper technical bound and the associated payment are

$$x_{\text{cap}} = (e_{\max} - e^0)/a, \qquad B_{c,\text{cap}} = e_{\max} x_{\text{cap}}. \tag{48}$$

On the interior generator-only response, the corresponding expressions are

$$y_{\text{cap}} = (r_{\max} - r^0)/d, \qquad B_{e,\text{cap}} = r_{\max} y_{\text{cap}}. \tag{49}$$

These expressions apply only if no other condition binds earlier. Reaching one firm's technical bound does not by itself imply that all further subsidies are ineffective: supporting the other firm may still reduce emissions. Unspent budget is retained when no feasible additional or reallocated payment improves the minimum emissions already achieved. With $e_{\max} < E$ and $r_{\max} < R$ in the present model, reaching the technical limits does not imply zero emissions. The formal zero-emission cases $e = E$ or $r = R$ lie outside these limits and are not used as attainable stopping points.

Let $F_C\left(\overline{B}\right)$ and $F_T\left(\overline{B}\right)$ now denote the lowest emissions among all feasible coal-only and generator-only choices within the budget, respectively. Let $F_D\left(\overline{B}\right)$ denote the lowest emissions among feasible positive dual-subsidy candidates away from binding firm constraints, and $F_\partial\left(\overline{B}\right)$ the lowest among candidates where a technical or participation constraint binds, including choices that leave budget unspent. Then,

$$F_{\min}\left(\overline{B}\right) = \min\left\{F_0, F_C\left(\overline{B}\right), F_T\left(\overline{B}\right), F_D\left(\overline{B}\right), F_\partial\left(\overline{B}\right)\right\}, \quad F_0 = F(0,0). \tag{50}$$

An unavailable candidate class is assigned $+\infty$. This comparison selects coal-only support when F_C is lowest, generator-only support when F_T is lowest, and dual support when a feasible allocation with both rates positive is lowest. No support is selected if F_0 is lowest. When several allocations attain the same lowest emissions, a lower-expenditure allocation can retain the remaining budget. The marginal ratios guide local allocation; the comparison of all feasible candidates determines the final choice.

For the numerical baseline, participation binds, so the interior expressions above cannot be applied directly to Table 3. The government instead uses the equilibrium from Equations (6) and (19), with the policy-consistent outside option, in the objective and expenditure in Equations (28) and (31). This preserves the same constraints used in the main analysis.

Table 3. Constrained equilibrium in the four reward regimes.

Regime	e	r	w (CNY/TJ)	F (t CO_2)	Payment (Million CNY)
N	1.2677	0.4921	39837.63	891,196.36	0.0000
C	2.9344	0.4921	40004.29	875,349.87	2.9344
T	1.2540	0.5950	40125.40	881,681.13	5.9500
D	2.9207	0.5950	40292.07	866,006.13	8.8707

3.5.5. Implications for the Original Conclusions

Introducing a budget does not change the firms' equilibrium for any given pair of subsidy rates. The conditional results in Sections 3.3 and 3.4 therefore remain valid: on the common feasible interior branch, a single-recipient subsidy raises that recipient's technology choice and crowds out the other firm's choice; dual subsidies raise both choices only within the ratio range in Theorem 7. The separate results for binding participation and technical limits also retain their original conditions.

What changes is the policy choice. The fact that a specified dual-subsidy scheme reduces emissions does not prove that it gives the greatest reduction for a fixed budget. In Table 3, dual support produces the lowest emissions among the displayed policies but also requires the largest payment. An equal-budget decision must compare the feasible allocations in this extension. Depending on costs, the carbon price, technical limits, and the available budget, the preferred policy can support only the supplier, only the generator, or both at generally unequal rates and payments. The government may also leave funds unspent when additional expenditure cannot improve the best feasible emissions outcome.

Accordingly, the original conclusion that suitable dual subsidies can improve both firms' technologies remains conditional and unchanged. Its policy recommendation is made more precise: dual support is one possible optimal allocation, rather than a policy that should be adopted for every budget and market condition. The carbon-price comparisons in Section 4.3 still describe their specified rates and parameter settings; optimising those rates under a budget is a separate allocation decision.

4. Numerical Analysis and Discussion

4.1. Parameters and Computational Procedure

The numerical analysis uses an annual electricity block of 1000 GWh and illustrative operating-period costs. Table 2 distinguishes scenario inputs from the engineering scale reference. The baseline emission factor of 95 t CO_2/TJ is close to the IPCC default of 94.6 for other bituminous coal [59].

The quotation w_{ref} represents the alternative supplier's offer. The assumed 45% maximum net efficiency is compared with a 36% reference efficiency. The upstream limit $e_{\max} = 6$ represents a hypothetical 6.3% factor reduction. Cost coefficients and technical limits are scenario inputs; their effects are examined in Section 4.4.

For each e, the algorithm obtains the plant response and the highest acceptable quotation, then compares the supplier's interior quotation, response breakpoints, and participation ceiling. It searches the one-dimensional quality interval and compares its end points and local maxima. The main displayed solutions were checked using 41-point and 161-point quality meshes with local refinement. Constraint residuals were checked in monetary units and technical units.

4.2. Four Subsidy Regimes

All four displayed cases satisfy technical limits and supplier participation and follow Proposition 2. Table 3 illustrates the participation-binding parts of Theorems 1–3, 6, and 7: supplier support leaves r unchanged, while plant support changes the quotation through the participation ceiling. Emission reductions in these constrained cases are evaluated using (20); Theorems 4 and 5 apply to their stated interior branch.

The displayed equilibria are obtained by solving the participation equality for $\bar{z}$ and then applying (6) and (19). The generator's payoff equals its outside option up to numerical precision. The dual case has lower emissions and higher subsidy expenditure than either displayed single-recipient case. Figure 1 compares the fuel-intensity and heat-rate improvements under the four subsidy regimes.

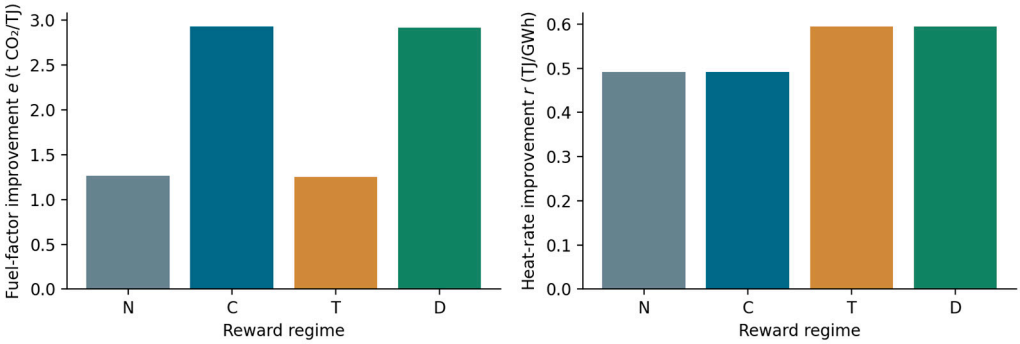

Figure 1. Verified fuel-intensity improvement and heat-rate improvement under four illustrative reward regimes. N (grey) denotes no subsidy, C (blue) denotes coal-supplier subsidies, T (orange) denotes thermal-power-plant subsidies, and D (green) denotes dual subsidies.

All policy cases use the same no-subsidy reference.

4.3. Carbon Price Compared with Subsidies

The environmental externality associated with carbon emissions provides a policy background for emission reduction [39]. Carbon trading introduces an economic value for emissions into the generator's decisions through the carbon price P. Building on this setting, the study examines how additional achievement-based subsidies affect technology choices at a given carbon price.

The supplier reduces the emission factor per unit of fuel energy, while the generator reduces the fuel energy required for a given electricity output. These two decisions jointly determine combustion emissions. Each firm chooses its technology to maximise its own profit, and support directed at one firm also affects the other through the fuel quotation, fuel demand, and technology responses. Comparing supplier support, generator support, and dual support therefore identifies how the recipient choice shapes the final emissions outcome.

The policy implications follow from the model's emission-reduction conditions and equilibrium comparisons. Theorems 2 and 4 establish the conditions for emission reductions under single-recipient subsidies, while Theorem 5 compares the emissions achieved by supplier and generator support. The cost and technology-coefficient sensitivity analyses show how these comparisons depend on project costs and technical compatibility. Fiscal expenditure is measured by the actual achievement payments

$$xe^* + yr^*,$$

Which are reported alongside equilibrium technology choices and emissions in Table 3.

The carbon-price comparison uses the same electricity output. In scenarios C, T, and D, the carbon price remains $P_0 = 100$ CNY/t CO_2, and the reward rates remain those in Table 2. The alternative is scenario N at $P_1 \geq P_0$, with $x = y = 0$. All other market, cost, and technical inputs remain fixed, and each policy's equilibrium is solved again.

Let

$$\Delta S = F^N(P_0) - F^S(P_0), S \in \{C, T, D\},$$

And

$$\Delta P = F^N(P_0) - F^N(P_1)$$

The subsidy policy has lower emissions when $\Delta S > \Delta P$, and the higher-carbon-price policy has lower emissions when $\Delta P > \Delta S$. Equality separates these rankings. Each comparison incorporates both firms' equilibrium responses.

As shown in Table 4, at $P_1 = 150$ CNY/t CO_2, N emits 879,830.79 t CO_2: C and D at P_0 have lower emissions, whereas T at P_0 has higher emissions. At $P_1 = 200$, only D has lower emissions than N; at $P_1 = 225$, N has lower emissions than all three subsidy scenarios. The comparison therefore gives an explicit policy ranking at each stated carbon price and reward rate.

Table 4. Direct emission comparison; emissions in t CO_2.

No-Subsidy P_1 (CNY/t CO_2)	N at P_1	C at $P_0 = 100$	T at $P_0 = 100$	D at $P_0 = 100$
100	891,196.36	875,349.87	881,681.13	866,006.13
125	885,499.13	875,349.87	881,681.13	866,006.13
150	879,830.79	875,349.87	881,681.13	866,006.13
175	874,191.31	875,349.87	881,681.13	866,006.13
200	868,580.64	875,349.87	881,681.13	866,006.13
225	862,998.77	875,349.87	881,681.13	866,006.13
250	857,445.66	875,349.87	881,681.13	866,006.13
300	846,425.60	875,349.87	881,681.13	866,006.13
400	824,729.21	875,349.87	881,681.13	866,006.13

Within the illustrated interval $P_1 = 100$–400 CNY/t CO_2, the crossover carbon prices are approximately 141.83 for T, 169.85 for C, and 211.51 for D. Each specified subsidy scenario has lower emissions below its corresponding crossover and higher emissions above it. Appendix A.2 gives the calculations and verifies the decreasing no-subsidy emission path over this interval.

The no-subsidy alternative has zero direct subsidy expenditure. When it also produces lower emissions, it performs better on both the emissions and direct subsidy expenditure measures used in this comparison. Policy selection therefore depends on the carbon price, project costs, technical conditions, and the actual subsidy payments associated with the equilibrium outcomes.

In the illustrated comparison, a subsidy is not necessary to attain the emissions achieved by the specified subsidy schemes when the carbon price can increase: the no-subsidy equilibrium at $P_1 = 225$ CNY/t CO_2 already has lower emissions than C, T, and D at $P_0 = 100$. Subsidies are nevertheless effective at the baseline price because each specified scheme lowers emissions relative to N at that same price. Necessity and effectiveness are therefore distinct. Which policy is better on the emission criterion is determined by the crossover comparisons above, at the stated carbon prices and reward rates.

4.4. Cost and Technical Sensitivity

The scenario ranges are $P = 20$–400 CNY/t CO_2, $\eta = 0.15$–0.60 million CNY/(t CO_2/TJ)^2, $\theta = 25$–100 million CNY/(TJ/GWh)^2, and $k = 0$–150 CNY/t CO_2. These are exploratory scenario ranges. Figure 2 uses the reward rates in Table 2 for all four regimes. D includes both rewards; its total payment is $xe^D + yr^D$ and generally differs from the payments in C and T. All policy comparisons are re-solved with the same value of the varied parameter. This includes $P \leq k$, where the sign condition behind the interior crowding-out result fails and upstream investment can reach its lower bound.

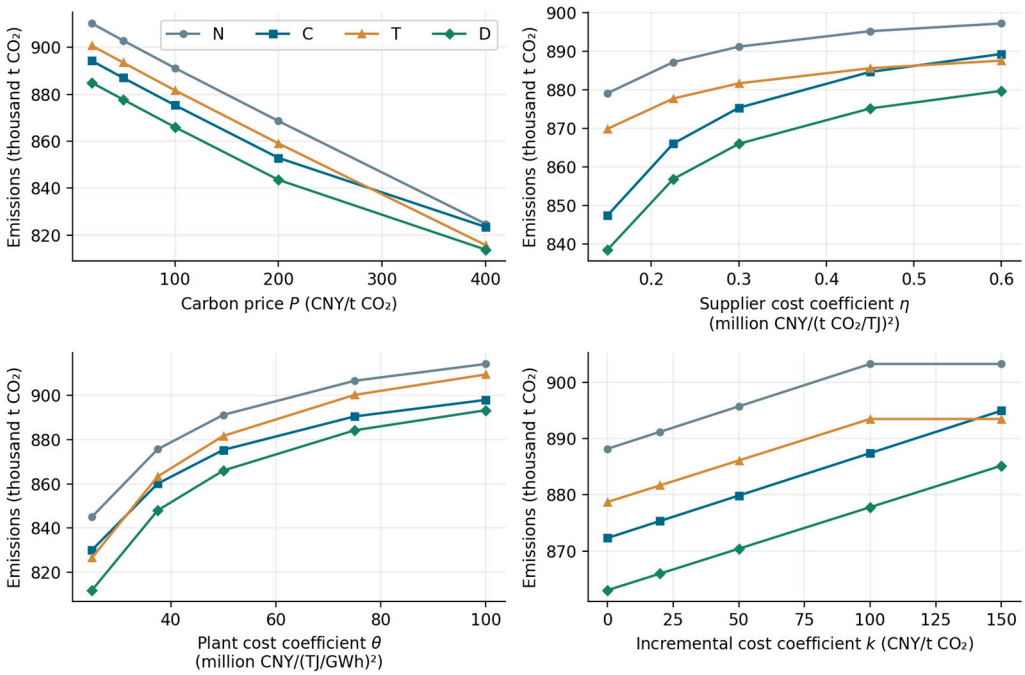

Figure 2. Sensitivity of combustion emissions to P, η, θ, and k under the four subsidy regimes N, C, T, and D.

Increasing P from 20 to 400 CNY/t CO_2 lowers emissions in all four displayed regimes. At $P = 100$, C emits 875,349.87 t CO_2 and T emits 881,681.13 t CO_2; at $P = 400$, T emits 815,667.17 t CO_2 and C emits 823,430.39 t CO_2. Hence, the preferred single-recipient policy changes in the tested range. A higher carbon price changes the incentive to save both fuel energy and combustion emissions, and each regime must be solved at that price. In the plant's payoff, each unit of avoided combustion emissions saves P units of carbon expenditure or increases the value of surplus allowances by P. A higher P therefore strengthens the return to reducing fuel use and fuel emission intensity. The reversal between C and T shows that the carbon-market condition should be considered when selecting the recipient of a given reward.

Increasing η from 0.15 to 0.60 million raises emissions in every displayed regime as upstream project expenditure becomes more demanding. C has lower emissions than T at $\eta = 0.15$ million (847,450.05 vs. 869,887.26 t CO_2), whereas T has lower emissions at $\eta = 0.60$ million (887,578.07 vs. 889,299.78 t CO_2). This shows why the relative attractiveness of supplier support depends on its project-cost conditions. At a given e, a higher η raises the supplier's marginal project cost $2\eta e$ while leaving its announced reward rate unchanged. This weakens the incentive to reduce the fuel emission factor and changes the plant's response through the resulting fuel specification and quotation. The observed ranking reversal indicates that supplier-directed support is more attractive on the emissions criterion when upstream technical improvement is relatively inexpensive.

Increasing θ from 25 to 100 million raises emissions in all four displayed regimes. At $\theta = 25$ million, T has lower emissions than C, at 826,601.19 vs. 830,109.32 t CO_2. At $\theta = 100$ million, C has lower emissions than T, at 897,964.55 vs. 909,478.50 t CO_2.

A higher θ increases marginal retrofit expenditure $2\theta r$. At given fuel conditions and reward rate, the generator chooses less retrofit and requires more fuel for the same electricity output. The supplier then reoptimises its quotation and fuel specification. The displayed results show that higher retrofit costs increase equilibrium emissions and weaken the relative emission advantage of generator-directed support. Retrofit investment costs therefore affect both the equilibrium emission outcome and the comparison between subsidy recipients.

Increasing k raises the operating cost associated with a positive fuel-factor reduction. N and T reach $e = 0$ when $k \geq P = 100$ in the displayed grid, and their emission paths then become flat; C and D retain positive e because of the supplier reward. At $k = 150$, T emits less than C (893,475.00 vs. 894,936.54 t CO_2), reversing their baseline ranking. D has the lowest emissions at all displayed points in these four panels under the reward rates in Table 2. Each regime's actual subsidy payment is determined by its reward rates and equilibrium technical outcomes. At a given fuel requirement h, the additional marginal operating expense of improving the fuel factor is kh, reducing the upstream incentive associated with $P - k$. A direct supplier reward adds x to its marginal return and can sustain positive e in the displayed cases where N and T choose $e = 0$. These results show why recurring fuel-supply expenses, alongside project investment costs, matter for choosing the subsidy recipient.

Sensitivity to the Technology Coefficient

The coefficient ξ in (1) is varied over 0.5, 0.75, 1, 1.1, 1.25, 1.5, and 2. For each value, the four original subsidy scenarios are solved using the same objectives (3) and (4), participation rules, and technical limits. The generator's response is

$$r^b = \min\left\{r_{\max}(e), \max\left\{0, \frac{qt(e)(w + P(E - e)) + y}{2\theta}\right\}\right\} \tag{51}$$

For $\xi > 1$, the mixed derivative $\frac{\partial^2 h}{\partial e \partial r} = -\frac{q(\xi - 1)}{e_{\max}}$ is negative: fuel improvement enhances a given retrofit's fuel saving. For $0 < \xi < 1$, the derivative is positive and fuel improvement attenuates that saving. The plant's marginal return to retrofit is $qt(e)[w + P(E - e)] + y$. Increasing e changes this return through both $t(e)$, and the effective fuel price $w + P(E - e)$, with w determined by the supplier's response. Thus, stronger technical interaction can offset the weakening of fuel-saving incentives caused by a lower combustion factor. The equilibrium comparison incorporates these channels together with participation and technical bounds.

As shown in Table 5, at $\xi = 0.75$, supplier support lowers r from 0.4784 in N to 0.4415 in C, and plant support lowers e from 0.6389 in N to 0.3897 in T. At $\xi = 1.1$, supplier support raises r from 0.5053 to 0.5198, and plant support raises e from 1.5262 to 1.6020. Thus, the cross-firm responses change from substitution to complementarity in these tested cases. At $\xi = 2$, all four scenarios reach the same technical frontier, $e = 6$ and $r = 1$; further rewards yield no additional emissions reduction at that frontier. The contrast between $\xi = 0.75$ and $\xi = 1.1$ shows that the direction of cross-firm responses depends on how fuel improvement changes retrofit effectiveness. For subsidy design, joint technical compatibility should therefore be considered alongside the two firms' separate project costs. When the common technical frontier is reached at $\xi = 2$, further rewards leave these technical choices and their associated combustion emissions unchanged.

Table 5. Re-solved technology choices under alternative interaction assumptions.

ξ	N: e/r	C: e/r	T: e/r	D: e/r
0.5	0.0000/0.4921	1.8436/0.4135	0.0000/0.5950	1.3103/0.5381
0.75	0.6389/0.4784	2.3632/0.4415	0.3897/0.5865	2.1136/0.5490
1	1.2677/0.4921	2.9344/0.4921	1.2540/0.5950	2.9207/0.5950
1.1	1.5262/0.5053	3.1907/0.5198	1.6020/0.6091	3.2652/0.6238
1.25	1.9367/0.5342	3.6146/0.5711	2.1451/0.6424	3.8168/0.6800
1.5	2.7139/0.6115	4.4279/0.6897	3.1344/0.7361	4.8110/0.8152
2	6.0000/1.0000	6.0000/1.0000	6.0000/1.0000	6.0000/1.0000

4.5. Discussion

The results show why a subsidy must be assessed through the decisions of both firms. A lower fuel emission factor reduces emissions per unit of fuel, while a plant retrofit reduces the fuel required for the same electricity output. However, reducing the emission factor also lowers the carbon expenditure avoided by saving fuel. Under the conditions in Section 3.4, this can weaken the plant's retrofit incentive; conversely, lower fuel purchases following a retrofit can reduce the supplier's incentive to improve its fuel. The total emission outcome therefore depends on whether the direct benefit of the subsidised improvement outweighs the other firm's response. This explains why a single-recipient subsidy can require a minimum effective rate and why the balance of support matters when both firms are subsidised.

The difference between the analytical comparison and the numerical baseline reflects the plant's ability to reject an unattractive offer. In the baseline, the supplier's quotation is limited by the profit the plant can obtain from its alternative procurement option. Supplier support then raises the quotation enough to offset the reduction in carbon expenditure per unit of fuel, leaving the plant's retrofit incentive unchanged. This explains why supplier support does not reduce retrofitting in Table 3, although it does so under the unrestricted pricing conditions of Theorem 1. The sensitivity analysis provides a further qualification: when fuel improvement makes the plant's retrofit more effective, the two firms can improve together. The direction of their interaction consequently depends on both contract conditions and the way their technologies work together.

The policy comparisons also distinguish lower emissions from more effective use of public funds. The dual-subsidy scheme in Table 3 achieves the lowest emissions among the displayed schemes but requires the largest payment. Section 3.5 therefore compares feasible allocations within a common budget ceiling; supporting both firms is justified only when that allocation performs best under the relevant conditions. Section 4.3 examines a different choice by comparing the specified subsidies with a higher carbon price without subsidies. Its results show that a policy that is effective at a given carbon price need not remain preferable when that price changes. These comparisons support adapting subsidy choices to costs, carbon prices, and available funds, while their illustrative nature limits claims about the effects of an actual subsidy programme.

5. Conclusions

This study examines how government subsidies affect technology choices, fuel pricing, and combustion emissions in a coal–power supply chain under carbon trading. A coal supplier leads the pricing and technology decisions, and a thermal power company chooses its retrofit level. The analysis compares four subsidy regimes and extends the model to allocate a limited government budget. The main findings are as follows.

First, subsidising one firm can weaken the other firm's incentive to improve its technology. Under the reference technology, when neither firm reaches a technical limit and the plant's acceptance condition does not restrict the quotation, supplier support increases the reduction in the fuel emission factor and raises the energy quotation but reduces the plant's retrofit effort. Plant support increases retrofit effort but reduces the supplier's improvement and energy quotation. This response is not universal: when the plant's acceptance condition limits pricing, supplier support can improve the fuel emission factor without changing retrofit effort, as in the numerical baseline. The technology sensitivity analysis also identifies cases where support for either firm encourages both firms to improve.

Second, improving the subsidised firm's technology does not necessarily reduce total emissions. The benefit can be offset by the other firm's reduced improvement. The analysis identifies when a positive subsidy threshold is needed for a net emission reduction and

when any positive subsidy within the stated range is sufficient. Appropriately balanced subsidies to both firms can increase both technology levels and reduce emissions. Once both firms reach their technical limits, further subsidies do not deliver additional technology improvements or emission reductions.

Third, the relative effectiveness of the subsidy options depends on carbon prices and technology costs. All three specified subsidy schemes reduce emissions at the numerical baseline. Subsidising both firms produces the lowest emissions among the four displayed regimes but also requires the largest government payment. However, varying the carbon price or either firm's project cost can change which single recipient achieves lower emissions. The comparison with a higher carbon price further shows that subsidies are not always needed to attain the same emission reduction: within the illustrated range, a sufficiently high carbon price without subsidies produces lower emissions than the specified subsidy schemes at the baseline carbon price, with no direct subsidy expenditure.

Fourth, a fixed budget does not make support for both firms automatically optimal. The budget extension leaves the firms' decisions unchanged for any given subsidy rates, but determines which rates the government should choose. Depending on the budget, costs, and technical conditions, the best feasible allocation can support the supplier alone, the generator alone, or both firms. Where both receive support and no technical or participation limit is reached, an efficient allocation equalises the additional emission reduction obtained from the last unit of expenditure on each firm; their subsidy rates and payments need not be equal. Funds can remain unspent when further feasible spending cannot reduce emissions.

These findings have three policy implications. First, subsidy assessments should measure emissions across the supply chain and account for the response of the firm that does not receive support. A larger technology investment by one recipient is insufficient evidence of an overall emission reduction. Subsidy rates should reflect the conditions for net emission reductions and, where joint improvement is intended, the balance between support for the two firms.

Second, recipient selection and subsidy rates should be reviewed as carbon prices, project costs, and the effectiveness of combined technologies change. The comparison should include the emission outcomes and actual government payments of feasible alternatives. The numerical results support conditional selection of subsidies; they do not justify a universal rule that both firms must always be subsidised or that higher carbon prices always make subsidies redundant.

Third, limited funds should be allocated according to the emission reductions they can achieve after both firms adjust their decisions. The government should compare single-recipient and joint support within the same budget ceiling, rather than infer efficiency from a scheme that spends more and emits less. When additional or reallocated funds cannot improve the achievable emission outcome, retaining the remaining budget avoids ineffective expenditure.

The study has several limitations. It considers one representative supplier and one generator, fixed electricity output, and complete information about costs and technology. The numerical inputs illustrate the mechanisms rather than estimate the effects of an implemented subsidy programme. Future research could use firm-level observations to test these predictions, incorporate electricity retailers and variable demand, and examine private cost information, measurement errors, and incomplete subsidy payments. The budget extension minimises combustion emissions; broader policy evaluation would also need to consider social welfare and the alternative uses of public funds.

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Appendix A. Derivations and Proofs

Appendix A.1. Equilibrium Derivation and Feasible Candidate Selection

At $\xi = 1$, substituting h and F into the plant objective gives $\frac{\partial \pi_p}{\partial r} = q[w + P(E - e)] - 2\theta r + y$ and $\frac{\partial^2 \pi_p}{\partial r^2} = -2\theta < 0$. This yields (6). On its interior segment, $h = qR - \frac{q^2[w+P(E-e)]}{2\theta} - \frac{qy}{2\theta}$. For Lemma 1 and Proposition 1, substitution into (3) gives the supplier conditions $\frac{\partial \pi_c}{\partial w} = h - \frac{q^2(w-c-ke)}{2\theta} = 0$ and $\frac{\partial \pi_c}{\partial e} = -kh + \frac{q^2 P(w-c-ke)}{2\theta} - 2\eta e + x = 0$. Solving these equations jointly gives (16)–(18); setting x or y to zero yields (7)–(15). The supplier Hessian has first leading principal minor $-\frac{q^2}{\theta}$ and determinant $\frac{q^2\Omega}{4\theta^2}$; $\Omega > 0$ establishes strict concavity on that segment only.

For a fixed e, first find the maximum acceptable quotation $w_{\max}(e)$ from $\pi_p\left(r^b(w,e), w, e\right) = \overline{\pi}_p$. Monotonicity follows from the envelope derivative $-h < 0$. For (1), let $t = 1 + \frac{(\xi-1)e}{e_{\max}}$, $\kappa = \frac{q^2 t^2}{2\theta}$ and $h_0 = qR - \kappa P(E - e) - \frac{qty}{2\theta}$. On an interior response segment, $h = h_0 - \kappa w$, and the supplier's stationary quotation is

$$w_{\text{stat}} = \frac{h_0 + \kappa(c + ke)}{2\kappa} \tag{A1}$$

Compare all feasible candidates among $w = 0$,$w_{\max}(e)$,w_{stat}, and the quotation at which the plant reaches its technical bound. On a response-bound segment, the supplier payoff is linear in w, so endpoints suffice. The highest resulting payoff defines the supplier's one-dimensional value function in e. Compare all local maxima found by interval refinement with $e = 0$ and $e_{\max}$, then apply supplier participation. The grid checks assess the numerical stability of the candidate search.

On the interior response segment, $V(z, y) = pq + PG - qRz + \frac{(qz+y)^2}{4\theta}$. The participation ceiling therefore follows by equating this expression to $\overline{\pi}_p(P, y)$ and retaining the root satisfying $0 < \frac{qz+y}{2\theta} < r_{\max}$. If the root lies outside this segment, evaluate V at the clipped response in (6). This supplies the ceiling used in the equilibrium calculation in Section 4.2.

Proof of Proposition 2. At a binding participation ceiling in the baseline, $\bar{z}$ is independent of e because the outside option is specified independently of the incumbent quality. Thus, $\bar{r}$ and $\bar{h}$ are independent of x; substituting $w = \bar{z} - P(E - e)$ into the supplier payoff gives $\pi_c = [\bar{z} - PE - c + (P - k)e]\bar{h} - \eta e^2 + xe$. Its first derivative is $\bar{h}(P - k) - 2\eta e + x$, and its second derivative is $-2\eta < 0$, yielding (19) and the endpoint rule. The global candidate comparison remains the one stated above. This provides an independent check on the displayed $\xi = 1$ solutions. □

Proof of Theorem 1. Subtracting the no-subsidy interior solution from the supplier-subsidy interior solution gives

$$\Delta e_C = \frac{4\theta x}{\Omega}, \Delta r_C = -\frac{q(P-k)x}{\Omega},$$

And

$$\Delta w_C = \frac{(P+k)\Delta e_C}{2} = \frac{2\theta(P+k)x}{\Omega}.$$

For $x > 0$, $P > k \geq 0$, and $\Omega > 0$, these expressions imply

$$\Delta e_C > 0, \Delta w_C > 0, \Delta r_C < 0,$$

Provided both equilibria remain on the same feasible interior branch. In particular,

$$\Delta w_C - P\Delta e_C = \frac{2\theta(P+k)x}{\Omega} - \frac{4\theta Px}{\Omega} = -\frac{2\theta(P-k)x}{\Omega} < 0.$$

Substituting this difference into the generator's best response gives

$$\Delta r_C = \frac{q}{2\theta}(\Delta w_C - P\Delta e_C) = -\frac{q(P-k)x}{\Omega} < 0.$$

When the participation constraint binds at $y = 0$ under the reference technology, the effective-price ceiling $\bar{z}_0$ and fuel requirement $\bar{h}_0$ are identical in scenarios N and C. For interior supplier quality, Proposition 2 gives

$${e_N}^B = \frac{\bar{h}_0(P-k)}{2\eta}, {e_C}^B = \frac{\bar{h}_0(P-k)+x}{2\eta}.$$

Consequently,

$$\Delta {e_C}^B = {e_C}^B - {e_N}^B = \tfrac{x}{2\eta},$$
$$\Delta {w_C}^B = P\Delta {e_C}^B = \tfrac{Px}{2\eta}.$$

The effective-price change is therefore

$$\Delta {w_C}^B - P\Delta {e_C}^B = 0,$$

So, the generator's retrofit choice remains unchanged:

$$\Delta {r_C}^B = 0.$$

□

Proof of Theorem 2. Expanding $q[(E-e_0)(R-r_0) - (E-e_0-\Delta e)(R-r_0-\Delta r)]$ gives (20). Substituting $\Delta e = ax$ and $\Delta r = -bx$ yields $\frac{\Delta F(C)}{q} = x[(R-r_0)a - (E-e_0)b] + abx^2 = x(K_C + abx)$. Since x, a, $b > 0$, emissions decrease precisely for $x > \max\left\{0, -\frac{K_C}{ab}\right\}$. At a binding participation ceiling with $y = 0, \Delta r = 0$, so (20) reduces to $\Delta F(C) = q(R-r_0)\Delta e(C) = \bar{h}_0 \Delta e(C)$. The end-point rule in Proposition 2 applies when quality reaches a bound. □

Proof of Theorem 3. Subtracting (7)–(9) from (13)–(15) gives $\Delta e(T) = -\frac{qLy}{\Omega} = -by$. The retrofit difference is $\frac{\left[\frac{q^2L^2}{\Omega}+1\right]y}{4\theta} = \frac{2\eta y}{\Omega} = dy$. The quotation difference is $-\frac{q(P+k)Ly}{2\Omega} - \frac{y}{2q} = -\frac{(4\eta\theta+q^2kL)y}{q\Omega}$. On a binding participation branch with interior quality, $e^B(T) - e^B(N) = \frac{L(\bar{h}_y - \bar{h}_0)}{2\eta} = -\frac{qL\Delta r(T)}{2\eta}$. Subtracting the two ceiling quotations yields $\Delta w(T) = \Delta\bar{z} + P\Delta e(T)$. Finally, expanding $(w^N + \Delta w)(h^N + \Delta h) - w^N h^N$ proves the exact sales-revenue decomposition. □

Proof of Theorem 4. Substituting $\Delta e = -by$ and $\Delta r = dy$ from Theorem 3 into (20) gives $\frac{\Delta F(T)}{q} = y[(E-e_0)d - (R-r_0)b] + bdy^2 = y(K_T + bdy)$. Since y, b, $d > 0$, the condition $\Delta F(T) > 0$ is equivalent to $y > \max\left\{0, -\frac{K_T}{bd}\right\}$. The zero and negative cases follow from the sign of $K_T + bdy$. Equation (20) remains valid when constrained equilibrium choices replace the interior expressions. □

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Proof of Theorem 5. Both policy reductions use the same no-subsidy reference: $F(C) = F_0 - \Delta F(C)$ and $F(T) = F_0 - \Delta F(T)$. Therefore $F(C) < F(T)$ is equivalent to $\Delta F(C) > \Delta F(T)$. Substitution of (22) and (24), followed by division by $q > 0$, gives (25). Reversing or equating the expressions gives the other two cases. The result requires the common feasible interior branch used in deriving both reductions. □

Proof of Theorem 6. From (16) and (17), $\Delta e(D) = ax - by$. Subtraction of (8) from (17) then gives $\Delta w(D) = \frac{(P+k)(ax-by)}{2} - \frac{y}{2q}$, which simplifies to (26). Its coefficient on x is positive, and the magnitude of its negative coefficient on y is positive for $P > k \geq 0$ and $\Omega > 0$. Dividing by the positive coefficient on x and by y gives the stated ratio threshold. Subtracting the ceiling quotations in Proposition 2 gives the participation-binding comparison. □

Proof of Theorem 7. Equations (16)–(18) give $\Delta e(D) = ax - by$ and $\Delta r(D) = -bx + dy$ relative to N. Both are positive precisely when $\frac{b}{a} < \frac{x}{y} < \frac{d}{b}$, which gives (27). The interval is nonempty because $ad - b^2 = \frac{1}{\Omega} > 0$. Since $E - e$ and $R - r$ are positive over the feasible set, increasing both e and r lowers their product and hence F. At a binding participation ceiling with interior quality, subtract $e^B(N) = \frac{\overline{h}_0 L}{2\eta}$ from $e^B(D) = \frac{\overline{h}_y L + x}{2\eta}$. As $\overline{h}_y - \overline{h}_0 = -q\Delta r(D)$, joint improvement requires $\Delta r(D) > 0$ and $x > qL\Delta r(D)$. □

Appendix A.2. Numerical Verification and Emission Comparisons

On the baseline participation-binding branch, the closed-form candidate in Proposition 2 is applicable throughout the quality interval: the supplier's quotation derivative remains positive up to the participation ceiling. Every reported equilibrium was independently checked with the general quotation-candidate solver and a 161-point quality mesh with local refinement. The independent equilibrium checks differ by less than 0.02 t CO_2.

For the policy comparison in Section 4.3, define $D^S(P_1) = F^N(P_1) - F^S(P_0)$, with the reward rates of S fixed at Table 2. Positive D^S favours S, and negative D^S favours the higher-carbon-price alternative. A bracketed zero of D^S locates a change in the emissions ranking. Every evaluation solves the no-subsidy equilibrium and its outside payoff at the new P_1. The three residuals at the unrounded crossovers are below 0.001 t CO_2. The 41-point and 161-point quality searches with local refinement agree within 0.05 t CO_2 for the displayed technology-sensitivity cases.

The decreasing no-subsidy emission path on $P_1 = 100$–400 can also be checked analytically on the active branch. With a zero outside payoff, the participation equation is $pq + PG - qR\overline{z} + \frac{q^2\overline{z}^2}{4\theta} = 0$. Implicit differentiation gives $\overline{z}' = \frac{G}{\overline{h}} > 0, \overline{r}' = \frac{qG}{2\theta\overline{h}} > 0$, and $\overline{h}' = -\frac{q^2 G}{2\theta\overline{h}} < 0$. Until the quality bound is reached, $e' = \frac{\overline{h} + (P-k)\overline{h}'}{2\eta}$, which is positive when $\overline{h}^2 > \frac{(P-k)q^2 G}{2\theta}$. At the upper quality bound $e' = 0$. Hence, $F' = -\overline{h}e' + (E-e)\overline{h}' < 0$ on these segments. For the inputs of Table 2, the outside payoff stays at zero, the retrofit bound is slack, and the stated inequality holds throughout this interval. The supplier's quotation derivative is positive up to its participation ceiling, so Proposition 2 is the active solution. Thus, each displayed crossover separates the two emission rankings on the stated interval.

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