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Game Strategy for Low-Carbon Investment by Electric Power Enterprises under the Dual Drivers of Carbon Quota Mechanism and Blockchain Technology

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ABSTRACT This study investigates low-carbon investment strategies in power supply chains under the combined influence of carbon quota mechanisms (CQM) and blockchain technology (BCT). A two-echelon system consisting of a power generator and an electricity retailer is modeled, and four decision scenarios are constructed by considering blockchain adoption under both the grandfathering method (GFM) and benchmarking method (BMM). A Stackelberg game framework is employed to analyze the interactions among low-carbon technology investment, low-carbon electricity promotion, market demand, and enterprise profitability. Results show that the BMM consistently induces higher low-carbon investment levels, stronger market demand, and greater retailer profitability than the GFM, regardless of blockchain adoption. Furthermore, blockchain-enabled information traceability exhibits a significant threshold effect: when implementation costs remain below a critical level, trusted information transmission enhances consumer green trust, stimulates demand for low-carbon electricity, and improves the economic performance of supply-chain participants. Sensitivity analysis further demonstrates that consumer green trust, low-carbon preference, and responsiveness to low-carbon promotion positively influence both emissionreduction efforts and enterprise profitability, whereas excessive blockchain deployment costs weaken these benefits. The proposed framework provides a quantitative methodology for analyzing information-enabled lowcarbon decision making and coordinated investment strategies in modern power systems.

INDEX TERMS carbon quota mechanism, blockchain technology, low-carbon investment, information traceability

I. INTRODUCTION

EXCESSIVE greenhouse gas emissions from energy-intensive production processes have intensified the global greenhouse effect and climate risks, severely threatening the sustainable development of environmental resources and hindering the industry's transition to low-carbon resource utilization [1]. In February 2021, China officially implemented a carbon quota mechanism, which is not only a key measure to address climate issues but also a core institutional design to advance environmental resource sustainable development. The main content of this carbon quota mechanism (CQM) is that the government allocates a certain amount of free carbon quotas to carbon-regulated enterprises based on their historical emission data. When carbon quotas are insufficient to meet production demands, enterprises must purchase additional quotas on the carbon trading market; conversely, if enterprises have surplus carbon quotas, they can benefit by selling them. Thus, this mechanism incentivizes enterprises to reduce carbon emissions through market-oriented means, laying a solid institutional foundation for the sustainable development of environmental resources within the spinning and weaving industries [2].

The allocation methods for carbon quotas primarily include grandfathering method (GFM) and benchmarking method (BMM). GFM sets the current carbon quota based on the total carbon emissions of regulated enterprises in the previous cycle with mandatory phased emission reduction requirements, using the enterprise's total carbon emissions as the basis [3]. For example, the first and second phases of the EU Emissions Trading System and the Tianjin region in China implemented GFM. BMM, on the other hand, uses the average emissions of advanced enterprises (the top 10% with the lowest carbon emission intensity) as the benchmark to allocate unit quotas, based on the unit carbon emissions of products. For instance, regions like Beijing and Shanghai in China have implemented BMM.The fundamental difference between GFM and BMM in promoting low-carbon technology (LCT) investment lies in the fact that under GFM, the quota allocated to an enterprise is always independent of its future output decisions and is directly related to its historical emissions. Higher historical carbon emissions correspond to stricter emission reduction obligations rather than more carbon quotas. Since carbon emissions entail high costs, reasonable quota allocation can alleviate the financial pressure on regulated enterprises, thereby incentivizing them to invest in LCT. Under BMM, quota allocation depends on the enterprise's historical output level. The quota an enterprise receives equals the product of its output and the benchmark quota per unit product. The lower the unit product carbon emissions, the more carbon quotas the enterprise can sell on the carbon trading market, and the greater the carbon trading revenue [4]. Thus, BMM incentivizes regulated enterprises to invest in LCT. Carbon emissions from China's power sector account for nearly 50% of the country's total carbon emissions [5]. Therefore, the power industry is the primary target for the implementation of the CQM, and the enforcement of this policy encourages power generators to invest in LCT.

Consumer demand for low-carbon electricity is increasingly growing. Taking Fortune Global 500 companies and their supply chains in China as an example, their demand for low-carbon electricity is projected to rise from 110 billion kW·h in 2020 to 1,440 billion kW·h in 2050 [6]. Mozumder et al. [7] also indicates that consumers exhibit a green preference for low-carbon electricity and are willing to pay a higher price for it. However, due to information asymmetry between consumers and electricity producers, it is difficult for consumers to verify whether the electricity they purchase is genuinely low-carbon. This undermines consumer trust in the green credentials of low-carbon electricity and hinders the role of consumer green preference in promoting its adoption. BCT can address the information asymmetry between entities in the low-carbon supply chain and consumers (see Figure 1), while ensuring the authenticity of information disclosure [8]. Sun et al. [9] considered the impact of BCT on consumer green trust in the low- carbon supply chain, demonstrating that the green trust coefficient reaches an optimum when BCT is adopted. A higher green trust coefficient leads to greater investment in LCT and higher profits (specific effects are shown in Table 1). Currently, BCT is already being used to disclose carbon emission reduction information in the power sector. For example, the State Grid BCT Company has established a BCT-based carbon monitoring platform to ensure the authenticity and reliability of carbon emission reduction data, thereby facilitating low-carbon electricity transactions [10].

TABLE 1. Impact of BCT on consumer behavior and corporate investment

Parameter	Without BCT	With BCT	Change Rate	Empirical Source
Consumer green trust coefficient	0.3–0.5	0.9–1.0	+100%	Sun et al. [9]
LCT investment	Baseline:100	Baseline:158	+58%	Bai et al. [8]
Willingness to pay a premium	10–15%	25–30%	+150%	Mozumder et al. [7]

Existing research on low-carbon investment by electric power enterprises under the dual drivers of CQM and BCT primarily focuses on three aspects: low-carbon investment in the power sector, low-carbon investment under CQM, and BCT-driven low-carbon investment. First, in the field of low-carbon investment by electric power enterprise, scholars have conducted progressively in-depth explorations from multiple perspectives. Initially, Yu et al. [11] employed a system dynamics approach to study the influence of the national carbon market on power enterprises' investment strategies through scenario simulations, noting that increasing investment in green power generation helps mitigate rising carbon costs. Li et al. [12] then developed an evaluation model for low-carbon investment projects in thermal power enterprises from a supply chain perspective, supporting scientific decision-making. Recent studies have placed greater emphasis on policy-technology synergy: Ji et al. [13] analyzed the impact of environmental policies on renewable energy investments in power supply chains, finding that both subsidies and green certificate policies contribute to emissions reduction. Sun et al. [9] proposed that hybrid systems based on complementary energy sources can promote the high-quality development of renewable energy. The latest research further focuses on market mechanisms and model optimization: Liu et al. [14] developed a high-resolution energy system optimization model to study low-carbon pathways for the power system in the Guangdong-Hong Kong-Macao region. Tan et al. [15] through empirical analysis, found that mixed price signals in carbon markets can encourage the adoption of low-carbon power generation technologies. Chen et al. [16] used game models to examine the effects of carbon tax policies on LCT investments in power supply chains under time-of-use electricity pricing. Overall, research in this field has gradually expanded from micro- level corporate behavior to macro-level system optimization, and from single-policy analysis to multi-mechanism synergistic perspectives, providing progressively deepening theoretical and practical insights for the low-carbon transition of electric power enterprises.

Regarding the driving effect of CQM on low-carbon investment in the power sector, scholars have conducted ongoing explorations from multiple dimensions such as quota allocation methods, market effects, and corporate behavior. In earlier stages, Chen et al. [17] investigated the impact of cap-and-trade mechanisms on renewable energy investment, indicating that BMM is more conducive to emission reduction than GFM. Zhou et al. [18] viewed the renewable portfolio standard as a mandatory institutional change and analyzed its supply-side incentive effects based on system dynamics. Similarly employing

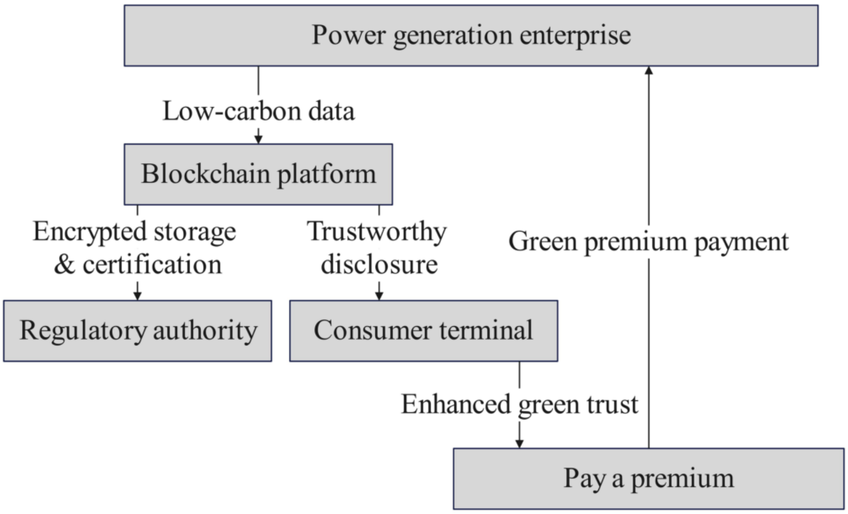


FIGURE 1. Application framework of BCT in power source tracing

system dynamics, Chi et al. [19] found that GFM allocation helps activate the carbon trading market and reduce unit carbon emissions. Subsequent research further refined mechanism design and its impacts: Li et al. [20] explored the role of carbon quotas in promoting carbon capture and storage retrofits for coal-fired units; Recent studies have placed greater emphasis on information bias and decision optimization: Chen et al. [21] constructed a model to analyze the impact of carbon quota policies on decision-making by financially constrained enterprises; Chen et al. [22] assessed the interference of quota misreporting on renewable energy investment. Overall, research in this field has gradually extended from mechanism comparison to corporate behavior and dynamic optimization, providing multi-layered evidence for understanding the role of carbon quotas in the low-carbon transition of the power sector. Unlike the studies mentioned above, this paper applies BCT to the low-carbon power supply chain, considering the low-carbon investment decisions of power enterprises from a BCT perspective.

In the realm of BCT driving LCT, existing research has focused on how it enhances data credibility, optimizes transaction mechanisms, and promotes the synergy between electricity and carbon markets. Ju et al. [23] early constructed a BCT-based credible carbon footprint tracking system, providing a technical foundation for the low-carbon economy. Subsequently, multiple studies explored BCT architecture and energy trading: Mu et al. [24] designed a hybrid energy BCT that effectively supports the development of distributed energy trading platforms; Chai et al. [25] proposed using smart contracts to construct a weakly centralized trading structure for generation rights to enhance market security; Wang et al. [26] introduced cross-chain technology to establish a real-time data sharing network between electricity and carbon markets, facilitating innovation in market coupling mechanisms; Research in 2024 has placed greater emphasis on practical applications and mechanism integration: Guo and Feng [27] simulated an intelligent trading mechanism for green certificates and electricity consumption vouchers based on BCT, verifying its operational feasibility; Zhang et al. [28] introduced BCT into the carbon trading supply chain with conventional and renewable energy manufacturer models, enhancing transaction transparency; Liu and Lu [29] further developed a pricing game and BCT integration method for electricity data trading in low-carbon smart energy systems.Studies indicate BCT is evolving from traceability and verification towards transaction coordination and system optimization, significantly strengthening the trust foundation and operational efficiency of low-carbon investments in power sector. For the differences between this study and previous research, see Table 2.

TABLE 2. The differences between our work and the previous related literature

Paper	BCT	GFM	BMM	LCT	SE
Bai et al. [8]	×	×	×	√	×
Tan et al. [15]	×	×	×	√	×
Chen et al. [17]	×	√	√	√	×
Zhou et al. [18]	×	√	√	√	×
Chen et al. [22]	×	√	√	√	×
Mu et al. [24]	√	×	×	√	×
Wang et al. [26]	√	×	×	√	×
Zhang et al. [28]	√	×	×	√	×
This work	√	√	√	√	√

Innovation. While most existing studies focus on CQM based on total emission caps, this paper compares the effects of total carbon quotas versus rate-based carbon quotas on low-carbon investments and pricing decisions, which is the key to advancing environmental resource sustainability. However, few scholars have conducted such comparative research. For example, Chen et al. [30] examined the impact of GFM and BMM on the power generator's investment in LCT, concluding that the BMM more effectively encourages such investments. Our findings align with Chen et al. [30]i n that the BMM provides greater incentives for LCT i nvestments, which is more conducive to environmental re-s ource sustainability. Nevertheless, key distinctions exist: (1) Although Chen et al. [30] investigated how CQM influence the power generator's investments in LCT, they did not incorporate BCT. This study, set against the backdrop of BCT, explores the impact of different CQM on LCT investments. It reveals that when BCT application costs are low,i ts adoption can promote LCT investments, increase low-c arbon electricity demand, and enhance profits for power e nterprises, providing stronger support for environmental r esource sustainability. (2) Chen et al. [30] primarily addr e ssed LCT investments by generators,whereas our resea r ch additionally considers the low-carbon electricity SE of t he electricity retailer. Results demonstrate that when applic ation costs fall below a critical threshold,BCT adoption si gnificantly boosts low- carbon investment levels for both p arties, jointly driving the power sector's role in environmenta l resource sustainability. (3) Chen et al. [30]found that whol esale and retail electricity prices under the GFM consistent ly exceed those under the BMM, and elec-tricity demand l evels are tied to the rate-based carbon quota.In contrast, ou r study indicates that low-carbon electricity demand under the BMM is always higher than under GFM,which better matching the goal of environmental resource sustainability.

Focus of the study. The implementation of CQM incentivizes power enterprises to undertake low-carbon initiatives and produce more low-carbon electricity, which is a key practice to advance environmental resource sustainability. Meanwhile, BCT enables consumers to trace the origins of low-carbon electricity, enhancing their green trust and thereby expanding demand for such electricity, which further boosts the power sector's contribution to environmental resource sustainability. Thus, this paper examines the combined impact of CQM and BCT on low-carbon investments by power enterprises, an exploration closely linked to environmental resource sustainability goals. Specifically, we addresses the following questions:(1) How do different CQMs affect the LCT efforts and profit of power enterprises? (2) How do different BCT adoption strategies influence the LCT efforts and profits of power enterprises, and in turn support environmental resource sustainability? (3) How do consumer green trust, green preference, and per-unit BCT application costs impact the profits and LCT efforts of power enterprises?

Research contributions. (1) Existing literature has explored the effects of CQM on LCT investment decisions by power enterprises but has not integrated BCT. This study focuses on the dual context of BCT and CQM, investigating low-carbon investment strategies in the power supply chain and identifying the boundaries of low-carbon investments under different CQMs within a BCT framework. This enriches theoretical research on low-carbon electricity supply chains and supplements studies related to environmental resource sustainability in this field. (2) In practice, various CQMs have been implemented in China, and BCT has been applied in the power supply chain. Based on real-world cases, this paper develops a theoretical model of BCT and CQM to study their impact on LCT investments, aiming to achieve emission reduction and efficiency gains for advancing environmental resource sustainability. This provides guidance for both government carbon quota allocation optimization and enterprise production operations, supporting the practice of environmental resource sustainability. (3) While existing research has largely focused on LCT investment decisions by power generators, less attention has been paid to the LCT efforts of electricity retailers. This paper innovatively incorporates the retailer's low- carbon SE into the analytical framework, revealing the interactive mechanism between the generator's investments and the retailer's marketing strategies. This offers new theoretical foundations and practical references for collaborative emission reduction strategies among power enterprises, further bolstering environmental resource sustainability.

II. PROBLEM DESCRIPTION AND RELATED ASSUMPTIONS

A. PROBLEM DESCRIPTION

Within the context of CQM and BCT, this study examines the low-carbon investment problem in an electric power supply chain consisting of a power generator and an electricity retailer. Influenced by factors such as the cost of BCT application, the power generator decides whether to adopt BCT. Meanwhile, both entities determine their low-carbon investment levels and electricity prices to maximize their respective profits. The supply chain structures, strategy combinations and corresponding game sequences are shown in Figure 2.

Assumptions

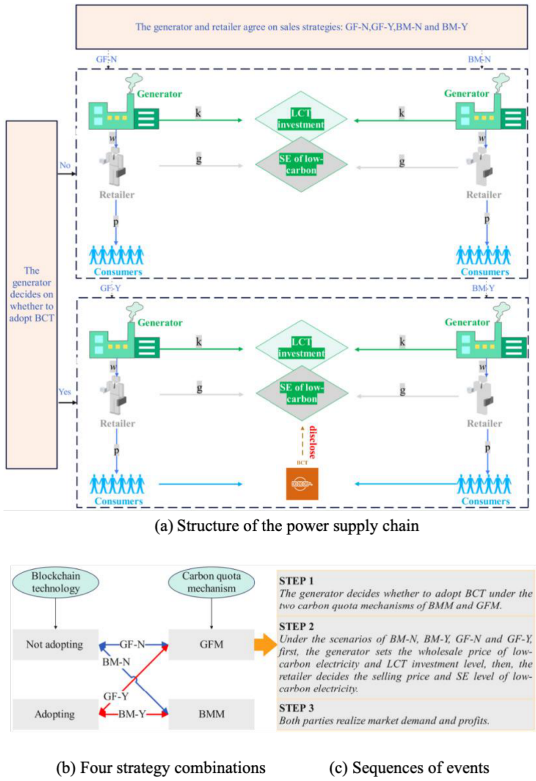
Assumption 1. Demand function. When BCT is not adopted, the green trust coefficient of consumers is λ $(0 < \lambda < 1)$; When adopting BCT, consumers can accurately distinguish low-carbon electricity. At this point, the green trust coefficient $\lambda = 1$. Therefore, the market demand functions are as follows

$$\text{Not adopted} \rightarrow q_1 = a - p + \lambda(\beta k + \gamma g) \tag{1}$$

$$\text{Adopted} \rightarrow q_2 = a - p + \beta k + \gamma g \tag{2}$$

a is the potential electricity demand, p is the retail electricity price, λ is the consumer green trust coefficient, β is the consumer green preference coefficient, γ is the consumer sensitivity to SE of retailer, k is the LCT investment level of generator, g is the SE level of electricity retailer.

Assumption 2. Low carbon investment cost. The low-carbon investment of generator and retailer is a one-time cost, specifically



(a) Structure of the power supply chain

(b) Four strategy combinations (c) Sequences of events

FIGURE 2. Main research contents

$$\text{Generator} \rightarrow c(k) = \frac{dk^2}{2} \tag{3}$$

$$\text{Retailer} \rightarrow c(g) = \frac{\omega g^2}{2} \tag{4}$$

d represents the cost coefficient of LCT investment, and ω denotes the cost coefficient of SE. Higher values of d and ω indicate lower effectiveness per unit of LCT investment or SE. To facilitate analysis, let $d = 1$ and $\omega = 1$.

Assumption 3. Production cost. Taking thermal power units as an example, the marginal coal consumption increases with the rise in the unit's power output (electricity generated per unit time), indicating increasing marginal costs. Thus, the production cost function of the generator is

$$c(q) = \frac{cq_i^2}{2} \tag{5}$$

$i = \{1, 2\}$, c is the production cost coefficient of the generator. To simplify the model, standardize c to 1.

Assump-tion 4. Restrictions. To ensure the negative de finiteness ofthe Haisai matrix and the non-negativity of th e equilibriumsolution, we have $\beta_2\lambda_2 + 2\gamma_2\lambda_2 + 2t\lambda\beta + t_2 - 5 < 0, \beta_2 + 2\gamma_2 + 2t\beta + t_2 - 5 < 0$ and $a > c_B + t$ established.

Assumption 5. The initial model adopts a uniform benchmark quota e0 to focus on the single-energy-structure scenario, aiming to isolate the core driving mechanisms of carbon quota policies and blockchain technology, free from the confounding effects of energy structure heterogeneity, with its applicability confined to single-energy-structure contexts.

The parameters and variable descriptions are shown in Table 3.

TABLE 3. Model symbols and explanations

Symbol	Explanation	Symbol	Explanation
BMM	Benchmarking method	CQM	Carbon quota mechanism
GFM	Grandfathering method	BCT	Blockchain technology
LCT	Low-carbon technology	SE	Sales effort
GF/BM	Subscript of GFM/BMM scenario	N/Y	Superscript of BCT non-adoption/adoption
a(GW)	Potential electricity demand	g	SE level of retailer
p(CNY/MWh)	Retail electricity price	k	LCT investment level of generator
w(CNY/MWh)	Wholesale electricity price	β	Consumer green preference coefficient
t(kCNY/tCO_2)	Carbon trading price	λ	Consumer green trust coefficient
c_B(CNY/MWh)	Unit cost of adopting BCT	γ	Consumer sensitivity to SE of retailer
e(tCO_2/MWh)	Unit electricity carbon emissions	q_1(GW)	Electricity demand without adopting BCT
e_0(tCO_2/MWh)	Unit carbon quota under the BMM	q_2(GW)	Electricity demand with adopting BCT
E_0(MtCO_2)	Total carbon quotas under the GFM	π(CNY)	Profit

III. MODEL ESTABLISHMENT AND SOLUTION

Four game-theoretic models of the electric power supply chain are constructed, and the optimal pricing, low-carbon investment levels, and profits of the supply chain members under each model are derived. The decision-making sequences in all models are as follows. First, the generator determines the wholesale electricity price w and the LCT investment level k; Then, the retailer determines the retail electricity price p and the SE level g.

A. NON-ADOPTION OF BCT VIA THE GFM (SCENARIO GF-N)

The profit functions of the power generator and the electricity retailer are respectively:

$$\pi^{N}_{g-GF} = wq_1 - t[(e-k)q_1 - E_0] - \frac{k^2}{2} - \frac{q_1^2}{2} \quad (6)$$

$$\pi^{N}_{s-GF} = (p-w)q_1 - \frac{g^2}{2} \quad (7)$$

Proposition 1. Under scenario GF-N, with the goal of profit maximization, the optimal wholesale electricity price, retail electricity price, LCT investment level, and SE level can be derived respectively using backward induction as follows:

$$k^{N*}_{GF} = \frac{(t+\beta\lambda)(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5} \qquad g^{N*}_{GF} = \frac{\gamma\lambda(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$w^{N*}_{GF} = \frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-2et-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$p^{N*}_{GF} = \frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-et-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$q^{N*}_{GF} = \frac{et-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5} \qquad \pi^{N*}_{g-GF} = E_0t - \frac{(et-a)^2}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$$

$$\pi^{N*}_{s-GF} = \frac{(et-a)^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$$

B. NON-ADOPTION OF BCT VIA THE BMM (SCENARIO BM-N)

The profit functions of the power generator and the electricity retailer are respectively:

$$\pi^{N}_{g-BM} = wq_1 - t[(e-k) - e_0]q_1 - \frac{k^2}{2} - \frac{q_1^2}{2} \quad (8)$$

$$\pi^{N}_{s-BM} = (p-w)q_1 - \frac{g^2}{2} \quad (9)$$

Proposition 2. Under scenario BM-N, with the goal of profit maximization, the optimal wholesale electricity price, retail electricity price, LCT investment level, and SE level can be derived respectively using backward induction as follows:

$$k^{N*}_{BM} = \frac{(t+\beta\lambda)[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5} \qquad g^{N*}_{BM} = \frac{\gamma\lambda[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$w^{N*}_{BM} = \frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-2(e-e_0)t-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$p^{N*}_{BM} = \frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-(e-e_0)t-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$$

$$q^{N*}_{BM} = \frac{(e-e_0)t-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5} \qquad \pi^{N*}_{g-BM} = \frac{[(e-e_0)t-a]^2}{2[5-(\beta^2+2\gamma^2)\lambda^2-2t\beta\lambda-t^2]}$$

$$\pi^{N*}_{s-BM} = \frac{[(e-e_0)t-a]^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$$

C. ADOPTION OF BCT VIA THE GFM (SCENARIO GF-Y)

The profit functions of the power generator and the electricity retailer are respectively:

$$\pi^{Y}_{g-GF} = (w-c_B)q_2 - t[(e-k)q_2 - E_0] - \frac{k^2}{2} - \frac{q_2^2}{2} \quad (10)$$

$$\pi^{Y}_{s-GF} = (p-w)q_2 - \frac{g^2}{2} \quad (11)$$

Proposition 3. Under scenario GF-Y, with the goal of profit maximization, the optimal wholesale electricity

price, retail electricity price, LCT investment level, and SE level can be derived respectively using backward induction as follows:

$$k^{Y*}_{GF} = \frac{(t+\beta)(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5} \qquad g^{Y*}_{GF} = \frac{\gamma(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5}$$

$$w^{Y*}_{GF} = \frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-2)]t+\beta^2c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5}$$

$$p^{Y*}_{GF} = \frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-1)]t+\beta^2c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5}$$

$$q^{Y*}_{GF} = \frac{et-a+c_B}{(\beta+t)^2+2\gamma^2-5} \qquad \pi^{Y*}_{g-GF} = E_0t - \frac{(et-a+c_B)^2}{2[(\beta+t)^2+2\gamma^2-5]}$$

$$\pi^{Y*}_{s-GF} = \frac{(et-a+c_B)^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}$$

D. ADOPTION OF BCT VIA THE BMM (SCENARIO BM-Y)

The profit functions of the power generator and the electricity retailer are respectively:

$$\pi^{Y}_{g-BM} = (w-c_B)q_2 - t[(e-k) - e_0]q_1 - \frac{k^2}{2} - \frac{q_2^2}{2} \quad (12)$$

$$\pi^{Y}_{s-BM} = (p-w)q_2 - \frac{g^2}{2} \quad (13)$$

retail electricity price, LCT investment level, and SE level can be derived respectively using backward induction as follows:

$$k^{Y*}_{BM} = \frac{(t+\beta)[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5} \qquad g^{Y*}_{BM} = \frac{\gamma[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5}$$

$$w^{Y*}_{BM} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-2)(e-e_0)]t+\beta^2c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5}$$

$$p^{Y*}_{BM} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-1)(e-e_0)]t+\beta^2c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5}$$

$$q^{Y*}_{BM} = \frac{(e-e_0)t-a+c_B}{(\beta+t)^2+2\gamma^2-5} \qquad \pi^{Y*}_{g-BM} = \frac{[(e-e_0)t-a+c_B]^2}{2[5-(\beta+t)^2-2\gamma^2]}$$

$$\pi^{Y*}_{s-BM} = \frac{[(e-e_0)t-a+c_B]^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}$$

IV. SENSITIVITY ANALYSIS

Proposition 5. When BCT is not adopted, the impacts of key parameters λ, β and γ on the low-carbon investments and profits of generator and retailer are as follows:

$$\begin{cases} \frac{\partial k_j^{N*}}{\partial \lambda} > 0, & \frac{\partial g_j^{N*}}{\partial \lambda} > 0, & \frac{\partial \pi_{g-j}^{N*}}{\partial \lambda} > 0, & \frac{\partial \pi_{s-j}^{N*}}{\partial \lambda} > 0; \\ \frac{\partial k_j^{N*}}{\partial \beta} > 0, & \frac{\partial g_j^{N*}}{\partial \beta} > 0, & \frac{\partial \pi_{g-j}^{N*}}{\partial \beta} > 0, & \frac{\partial \pi_{s-j}^{N*}}{\partial \beta} > 0; \\ \frac{\partial k_j^{N*}}{\partial \gamma} > 0, & \frac{\partial g_j^{N*}}{\partial \gamma} > 0, & \frac{\partial \pi_{g-j}^{N*}}{\partial \gamma} > 0, & \frac{\partial \pi_{s-j}^{N*}}{\partial \gamma} > 0. \end{cases}$$

where $j \in \{GF, BM\}$.

Proposition 5 indicates that an increase in consumers' green trust, green preference, and sensitivity to retailer's low-carbon electricity SE promotes both the LCT efforts and profits of generator and retailer. This reflects the pulling effect of green demand from the market side on the low-carbon transition of the supply side. In practice, clear corporate preferences for green electricity consumption have already created effective incentives. For example, Apple Inc. requires its supply chain to achieve full carbon neutrality by 2030, which has driven its suppliers to proactively procure green electricity. As reported, corporate demand for green electricity has surged from 110 billion kWh in 2020 to 1.44 trillion kWh in 2050 [31]. This demonstrates how green trust and preferences on the consumption side are transmitted through market mechanisms, stimulating LCT efforts by power enterprises and forming a virtuous cycle of "demand–investment–profit". It highlights the critical leveraging role of consumer behavior in the low- carbon transition of the energy sector.

Proposition 6. When BCT is adopted, the impacts of key parameters c_B, β and γ on the low-carbon investments and profits of generator and retailer are as follows:

$$\begin{cases} \frac{\partial k_j^{Y*}}{\partial c_B} < 0, & \frac{\partial g_j^{Y*}}{\partial c_B} < 0, & \frac{\partial \pi_{g-j}^{Y*}}{\partial c_B} < 0, & \frac{\partial \pi_{s-j}^{Y*}}{\partial c_B} < 0; \\ \frac{\partial k_j^{Y*}}{\partial \beta} > 0, & \frac{\partial g_j^{Y*}}{\partial \beta} > 0, & \frac{\partial \pi_{g-j}^{Y*}}{\partial \beta} > 0, & \frac{\partial \pi_{s-j}^{Y*}}{\partial \beta} > 0; \\ \frac{\partial k_j^{Y*}}{\partial \gamma} > 0, & \frac{\partial g_j^{Y*}}{\partial \gamma} > 0, & \frac{\partial \pi_{g-j}^{Y*}}{\partial \gamma} > 0, & \frac{\partial \pi_{s-j}^{Y*}}{\partial \gamma} > 0. \end{cases}$$

where $j \in \{GF, BM\}$.

Proposition 6 indicates that an increase in the unit cost of adopting BCT significantly diminishes the LCT efforts and profits of both generator and retailer. The results o f Propositions 5 and 6 are more intuitively re-flected i n Figure 3(a)–(d) (This study focuses on a hybrid energy power plant in Jiangsu Province, with an annual power generation duration of 350 days and an annual feed-in elec tricity volume of approximately 305,550MWh. For the su bsequent simulation, data integration is conducted by co mbining relevant parameter data from the research of L i et al. [20] with on-site survey data collected from this hybrid energy power plant. Additional information and dat a sources can be accessed via the following website :htt ps://news.bjx.com.cn/. The specific parameter settings are a s follows: $a = 4$(GW), $t = 0.5$(kCNY/tCO2), $\beta = 0.5$, $\lambda = 0.5$, $e = 0.5$(tCO2/MWh), $\tau = 0.6$, $E_0 = 0.5$(MtCO2), $e_0 = 0.5$(tCO2/MWh), $c_B = 0.3$(CNY/MWh).

Proposition 6 reveals a fundamental contradiction between the cost of BCT application and the low-carbon performance of power enterprises. Although the technology itself can enhance transparency and trust, its economic feasibility directly constrains its practical effectiveness. High costs not only compress corporate profit margins but also weaken the motivation for investing in emission reductions, creating a paradox of "technological empowerment versus economic burden". Although the State Grid BCT Company has established a carbon monitoring platform [32], if the unit verification cost exceeds a critical threshold—for example, exceeding 0.5 CNY/kWh as observed in cer-tai n regions-enterprises are inclined to maintain traditional op erations. The promotion of LCT requires not only tech-ni cal maturity but also cost controllability; otherwise, it m ay conversely inhibit the momentum for corporate green tr ansformation.

V. COMPARATIVE ANALYSIS

A. COMPARISON OF TWO CQMS WITHOUT ADOPTING BCT

Proposition 7. When BCT is not adopted, comparing the equilibrium strategies under the BMM and GFM yields: (1) $k_{BM}^{N*} > k_{GF}^{N*}$. (2) $g_{BM}^{N*} > g_{GF}^{N*}$. (3) $q_{BM}^{N*} > q_{GF}^{N*}$. (4) when $0 < e < V_1$, $w_{BM}^{N*} > w_{GF}^{N*}$; when $e > V_1$, $w_{BM}^{N*} < w_{GF}^{N*}$. (5) when $0 < e < V_2$, $p_{BM}^{N*} > p_{GF}^{N*}$; when $e > V_2$, $p_{BM}^{N*} < p_{GF}^{N*}$. (6) when $0 < E_0 < V_3$, $\pi_{g-BM}^{N*} > \pi_{g-GF}^{N*}$; when $E_0 > V_3$, $\pi_{g-BM}^{N*} < \pi_{g-GF}^{N*}$. (7) $\pi_{s-BM}^{N*} > \pi_{s-GF}^{N*}$.

Proposition 7(1), (2), (3) and (7) demonstrate that, in the absence of BCT, low-carbon investments (including those by both generator and retailer), market demand, and retailer's profit under the BMM are consistently higher than under the GFM. However, Proposition 7(6) indicates that the generator's profit under the BMM exceeds that under the GFM only when the total carbon quota in the GFM is sufficiently small ($< V_3$); otherwise, it is lower ($> V_3$). It is noteworthy that Proposition 7(4) and (5) show that, relative to the GFM, both the wholesale and retail electricity prices under the BMM decrease as the carbon emissions per unit of electricity increase. These findings are more intuitively illustrated in Figure 4(a)-(d). The BMM, which allocates quotas based on carbon emission intensity per unit of electricity, provides stronger incentives for enterprises to enhance emission reduction technologies and expand the green power market. In contrast, the GFM relies on historical total emissions and may safeguard profits for high-emission enterprises when quotas are generous, yet potentially dampens their motivation to reduce emissions. This highlights the critical policy trade-off between equity and efficiency: the BMM better aligns with the market principle of "who reduces emissions, benefits", thereby facilitating overall sectoral decarbonization, whereas the GFM may offer a transitional buffer for high-emission entities but could impede long-term transformation.

B. COMPARISON OF TWO CQMS WITH ADOPTING BCT

Proposition 8. When BCT is adopted, comparing the equilibrium strategies under the BMM and GFM yields: (1) $k_{BM}^{Y*} > k_{GF}^{Y*}$. (2) $g_{BM}^{Y*} > g_{GF}^{Y*}$. (3) $q_{BM}^{Y*} > q_{GF}^{Y*}$. (4) when $0 < e < V_4$, $w_{BM}^{Y*} > w_{GF}^{Y*}$; when $e > V_4$, $w_{BM}^{Y*} < w_{GF}^{Y*}$. (5) when $0 < e < V_5$, $p_{BM}^{Y*} > p_{GF}^{Y*}$; when $e > V_5$, $p_{BM}^{Y*} < p_{GF}^{Y*}$. (6) when $0 < E_0 < V_6$, $\pi_{g-BM}^{Y*} > \pi_{g-GF}^{Y*}$; when $E_0 > V_6$, $\pi_{g-BM}^{Y*} < \pi_{g-GF}^{Y*}$. (7) $\pi_{s-BM}^{Y*} > \pi_{s-GF}^{Y*}$.

Proposition 8(1)-(7) yield results analogous to those of Proposition 7(1)-(7). In practice, Beijing and Shanghai have adopted the BMM. By 2022, the average coal consumption per unit of power supply of coal-fired units in these regions had decreased to approximately 290 grams per kWh, significantly lower than the national average of 302 grams per kWh [33]. Conversely, in a pilot region employing the traditional GFM, a large thermal power enterprise—due to ample historical quotas—recorded only a 5% growth in LCT investments from 2021 to 2023, lower than the 12% observed among enterprises in BMM-based regions

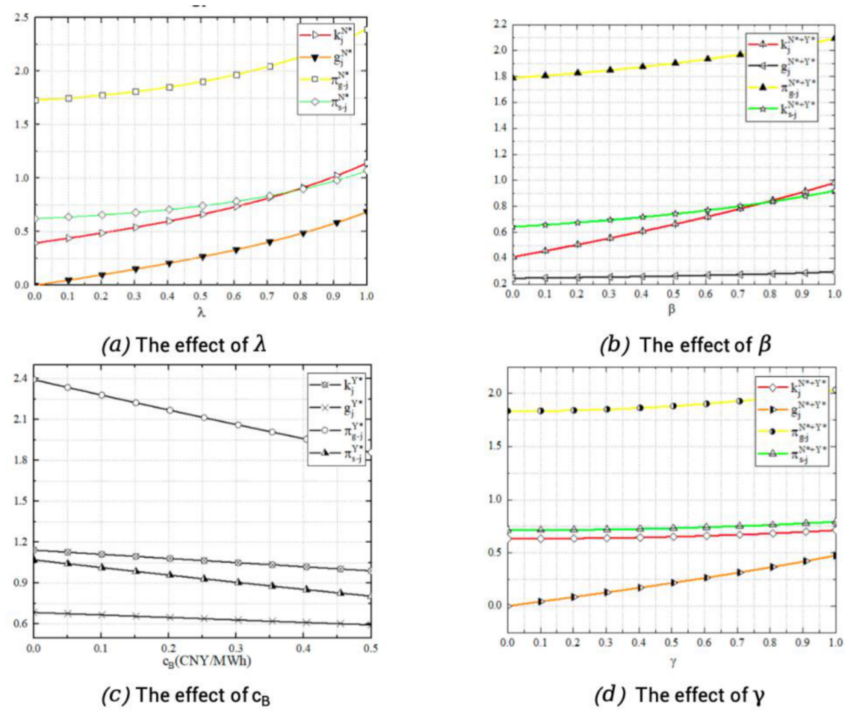


FIGURE 3. The impact of λ, β, c_B and γ on low-carbon investment and profit of power enterprises $j \in \{BM, GF\}$

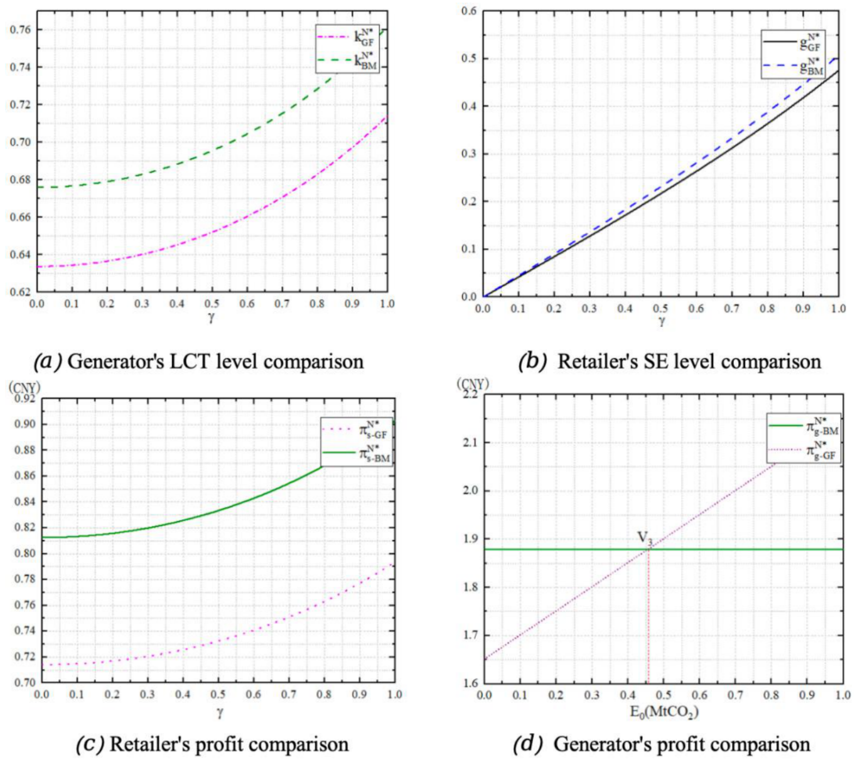


FIGURE 4. Low-Carbon investment and profit comparison under scenarios GFM and BMM without adopting BCT

[34]. This indicates that the BMM, by imposing stricter constraints on emissions per unit, more effectively drives technological upgrades and market responsiveness, particularly as quotas tighten, where its incentivizing effect becomes even more pronounced.

C. COMPARISON OF BCT ADOPTION STRATEGIES UNDER GFM

Proposition 9. Under the GFM, comparing the equilibrium strategies under the non adoption and adoption of BCT, it can be concluded that (1) when $0 < c_B < V_7$, $k_{GF}^{Y*} > k_{GF}^{N*}$;

when $c_B > V_7$, $k_{GF}^{Y*} < k_{GF}^{N*}$. (2) when $0 < c_B < V_8$, $g_{GF}^{Y*} > g_{GF}^{N*}$; when $c_B > V_8$, $g_{GF}^{Y*} < g_{GF}^{N*}$. (3) when $0 < c_B < V_9$, $q_{GF}^{Y*} > q_{GF}^{N*}$; when $c_B > V_9$, $q_{GF}^{Y*} < q_{GF}^{N*}$. (4) when $0 < c_B < V_{10}$, $\pi_{g-GF}^{Y*} > \pi_{g-GF}^{N*}$; when $c_B > V_{10}$, $\pi_{g-GF}^{Y*} < \pi_{g-GF}^{N*}$. (5) when $0 < c_B < V_{11}$, $\pi_{s-GF}^{Y*} > \pi_{s-GF}^{N*}$; when $c_B < V_{11}$, $\pi_{s-GF}^{Y*} < \pi_{s-GF}^{N*}$.

Proposition 9(1)-(5) shows that under the GFM, when BCT is introduced with a high application cost ($c_B > \max\{V_7, V_8, V_9, V_{10}\}$), the LCT efforts of generator and retailer, market demand, and profits will all be lower than in the scenario without BCT. Conversely, when the application cost is low ($c_B < \min\{V_7, V_8, V_9, V_{10}\}$), higher benefits are achieved through the adoption of BCT, making generators more inclined to implement it. The introduction of BCT is not unconditionally beneficial; its value highly depends on the balance between application cost and economic return. When the unit verification cost exceeds a critical threshold, high costs compress profit margins for enterprises and weaken motivation for emission reduction investments. This implies that power enterprises must carefully assess the actual cost-effectiveness of BCT rather than blindly pursuing technological advancement when promoting digital transformation.

D. COMPARISON OF BCT ADOPTION STRATEGIES UNDER BMM

Proposition 10. Under the BMM, comparing the equilibrium strategies under the non adoption and adoption of BCT, it can be concluded that:

: (1) when $0 < e_0 < V_{12}$, $k_{BM}^{Y*} > k_{BM}^{N*}$; when $c_B > V_{12}$, $k_{BM}^{Y*} < k_{BM}^{N*}$.

(2) when $0 < e_0 < V_{13}$, $g_{BM}^{Y*} > g_{BM}^{N*}$; when $c_B > V_{13}$, $g_{BM}^{Y*} < g_{BM}^{N*}$. (3) when $0 < c_B < V_{14}$, $q_{BM}^{Y*} > q_{BM}^{N*}$; when $c_B > V_{14}$, $q_{BM}^{Y*} < q_{BM}^{N*}$. (4) when $0 < c_B < V_{15}$, $\pi_{g-BM}^{Y*} > \pi_{g-BM}^{N*}$; when $c_B > V_{15}$, $\pi_{g-BM}^{Y*} < \pi_{g-BM}^{N*}$. (5) when $0 < c_B < V_{16}$, $\pi_{s-BM}^{Y*} > \pi_{s-BM}^{N*}$; when $c_B < V_{16}$, $\pi_{s-BM}^{Y*} < \pi_{s-BM}^{N*}$.

Proposition 10(1)-(5), similar to Proposition 9(1)-(5), indicates that whether under the BMM or the GFM, a generator's strategy for adopting BCT primarily depends on the unit cost. These results are more intuitively depicted in Figure 5(a)-(b). As previously mentioned in Proposition 6, although the State Grid BCT Company has established a carbon monitoring platform, enterprises are more inclined to maintain traditional

operational models if the unit verification cost exceeds 0.5 CNY/kWh. For example, a thermal power enterprise in a pilot region using the GFM recorded only a 5% annual growth rate in LCT investment from 2021 to 2023 due to high BCT application cost, significantly lower than the 12% observed among enterprises in regions applying the BMM [4]. This suggests that if BCT fails to achieve cost controllability, it may instead inhibit the momentum for corporate green transition, highlighting the critical constraint of economic feasibility on sustainable development in the promotion of technologies.

E. COMPARISON OF USING BCT STRATEGY UNDER THE BMM WITH ADOPTING BCT AND UNDER THE GFM WITHOUT ADOPTING BCT

Proposition 11. Comparing the equilibrium strategies under BM-Y and GF-N scenarios, it can be concluded that (1) when $0 < e_0 < V_{17}$, $k_{BM}^{Y*} < k_{GF}^{N*}$; when $e_0 > V_{17}$, $k_{BM}^{Y*} > k_{GF}^{N*}$. (2) when $0 < e_0 < V_{18}$, $g_{BM}^{Y*} < g_{GF}^{N*}$; when $e_0 > V_{18}$, $g_{BM}^{Y*} > g_{GF}^{N*}$. (3) when $0 < e_0 < V_{19}$, $q_{BM}^{Y*} < q_{GF}^{N*}$; when $e_0 > V_{19}$, $q_{BM}^{Y*} > q_{GF}^{N*}$. (4) when $0 < E_0 < V_{20}$, $\pi_{g-BM}^{Y*} > \pi_{g-GF}^{N*}$; when $E_0 > V_{20}$, $\pi_{g-BM}^{Y*} < \pi_{g-GF}^{N*}$. (5) when $0 < e_0 < V_{21}$, $\pi_{s-BM}^{Y*} < \pi_{s-GF}^{N*}$; when $e_0 > V_{21}$, $\pi_{s-BM}^{Y*} > \pi_{s-GF}^{N*}$.

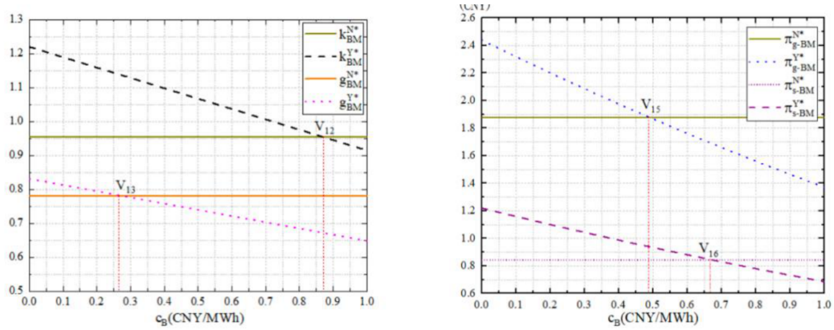
Proposition 11(1),(2),(3)and(5)indicate that under the BMM, when the unit carbon quota is relatively high ($e_0 > \max\{V_{17}, V_{18}, V_{19}, V_{21}\}$), the adoption of BCT is more likely to yield higher LCT efforts, market demand, and retailer profits compared to the GFM without BCT. Interestingly, Proposition 11(4) shows that the generator's profit is not affected by the unit carbon quota but depends primarily on the total carbon quota under the GFM. That is, when the total carbon quota is low ($E_0 < V_{20}$), the profit for the generator using BCT under the BMM will be significantly higher than under the GFM without BCT. This

implies that the generator's profit in policy selection is essentially determined by historical emission levels rather than current unit efficiency—even if BCT enhances transparency, enterprises with high historical emissions and ample quotas may still achieve higher profits under the GFM. Conversely, enterprises with low historical emissions are more likely to benefit from the combination of the BMM and BCT. The results of Proposition 11 are more intuitively illustrated in Figure 6(a)-(b).

F. COMPARISON OF USING BCT STRATEGY UNDER THE BMM WITHOUT ADOPTING BCT AND UNDER THE GFM WITH ADOPTING BCT

Proposition 12. Comparing the equilibrium strategies under BM-N and GF-Y scenarios, it can be concluded that (1) when $0 < e_0 < V_{22}$, $k_{BM}^{N*} < k_{GF}^{Y*}$; when $e_0 > V_{22}$, $k_{BM}^{N*} > k_{GF}^{Y*}$. (2) when $0 < e_0 < V_{23}$, $g_{BM}^{N*} < g_{GF}^{Y*}$; when $e_0 > V_{23}$, $g_{BM}^{N*} > g_{GF}^{Y*}$. (3) when $0 < e_0 < V_{24}$, $q_{BM}^{N*} < q_{GF}^{Y*}$; when $e_0 > V_{24}$, $q_{BM}^{N*} > q_{GF}^{Y*}$. (4) when $0 < E_0 < V_{25}$, $\pi_{g-BM}^{N*} > \pi_{g-GF}^{Y*}$; when $E_0 > V_{25}$, $\pi_{g-BM}^{N*} < \pi_{g-GF}^{Y*}$. (5) when $0 < e_0 < V_{26}$, $\pi_{s-BM}^{N*} < \pi_{s-GF}^{Y*}$; when $e_0 > V_{26}$, $\pi_{s-BM}^{N*} > \pi_{s-GF}^{Y*}$.

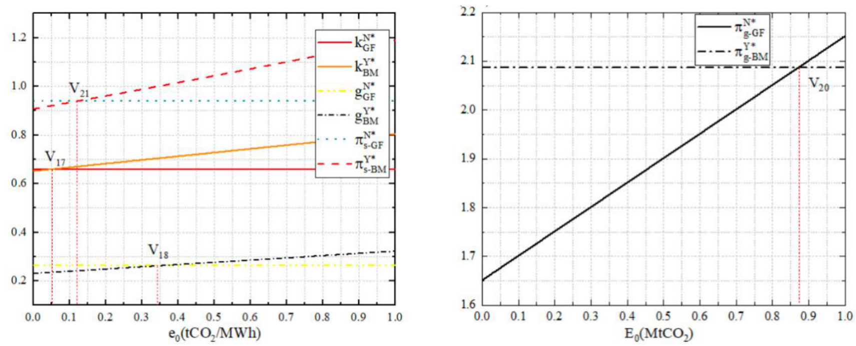
Similar to Propositions 11(1)-(5), Propositions 12(1)-(5) demonstrate that under the BMM without BCT and the GFM with BCT, the LCT efforts, market demand, and profits of retailer and generator primarily depend on the unit carbon quota e_0 and the total carbon quota E_0. For example, a large thermal power enterprise in a GFM pilot region (e.g., Tianjin) achieved an average annual profit growth rate of 8% from 2021 to 2023 due to sufficient historical quotas, yet its unit emission efficiency remained below the national average (with a coal consumption per power supply of approximately 305 g/kWh). In contrast, a high-efficiency



(a) Low — carbon investment comparison

(b) Profits comparison

FIGURE 5. Comparison of low-carbon investment and profit under scenarios BM-N and BM-Y



(a) Low — carbon investment and retailer's profit comparison

(b) Generator's profit comparison

FIGURE 6. Comparison of low-carbon investment and profit under scenarios GF-N and BM-Y

coal-fired power plant in Beijing (with coal consumption of 290 g/kWh), though required to purchase additional quotas under the BMM, enhanced consumer trust through BCT and leveraged premium sales of low- carbon electricity, resulting in a profit increase of up to 12% [21]. This indicates that policy design must balance historical equity and efficiency incentives: high-emission enterprises may use the GFM as a transitional mechanism, while high-efficiency enterprises can achieve green premiums through the " BMM+BCT " approach. The distinct strategic pathways underscore the deep coupling between carbon quota allocation mechanisms and the actual emission structure of enterprises.

VI. CONCLUSION

A. RESEARCH CONCLUSION

This study investigates the low-carbon investment strategies of manufacturing enterprises under CQM and BCT scenarios to promote environmental resource sustainability, constructing four game-theoretic models that evaluate GFM and BMM carbon quota allocations alongside the adoption of blockchain technology. Through a comparative analysis of these four models, the following conclusions are drawn: (1) An increase in consumers' green trust, green preference, and sensitivity to retailers' low-carbon electricity SE promotes the LCT efforts and profits of both the generator and the retailer, while an increase in the unit cost of adopting BCT significantly reduces the LCT efforts and profits of both parties, which is unfavorable to advancing environmental resource sustainability. (2) Regardless of the adoption of BCT, the LCT efforts of the generator and the retailer, market demand, and the retailer's profit under BMM are always higher than those under GFM, these outcomes are more aligned with the requirements of environmental resource sustainability, though the generator's profit under BMM is higher than that under GFM only when the total carbon quota is sufficiently small; otherwise, it is lower. (3) Whether under BMM or GFM, the generator's decision to adopt BCT depends primarily on the application cost, specifically, higher application costs discourage the generator from introducing BCT, while cost-effective BCT application can strengthen lowcarbon transformation effects and support environmental resource sustainability. (4) The benefits generated by BMM and GFM for power enterprises depend to some extent on the unit carbon quota and total carbon quota allowance; a higher unit carbon quota under BMM tends to yield higher returns compared to GFM, and a lower total carbon quota under GFM also makes BMM more advantageous, providing insights for optimizing mechanisms to drive the power industry's low-carbon transition and serve environmental resource sustainability.

B. MANAGEMENT INSIGHT

This study provides reference for power enterprise operations and carbon policy optimization. (1) In choosing carbon quota allocation methods, generators should align with "efficiency-equity" policy goals: the BMM, with advanced enterprises' average emissions as the benchmark, demonstrates superior economic efficiency by inducing LCT innovation, suitable for high efficiency, large output generators; the GFM, as a transitional equity measure, alleviates short-term pressure for high-historical-emission generators without dampening long term innovation motivation. (2) For BCT introduction, generator's cost benefit assessment should connect to environmental resource allocation efficiency. The government can offer targeted subsidies to lower BCT thresholds, this enhances carbon market transparency and further induces LCT innovation by strengthening market credibility. (3) Generator's participation in carbon quota policy formulation helps optimize "efficiency-equity" balance. Their feedback on unit/total quotas prevents weak emission reduction motivation (excessive quotas) or unfair pressure (over-tight quotas), enabling policies to better stimulate LCT innovation via carbon price signals. (4) Retailer's cultivation of consumers' green perception should link to policy led awareness promotion, forming a "policy guidance + market pull" mechanism, expanded low-carbon electricity demand induces generators to increase LCT investment, optimizing environmental resource allocation. (5) Retailer's SE under the BMM drives both profits and low-carbon demand, and reasonable carbon price signals can strengthen generator-retailer collaboration. This joint force promotes supply chain emission reduction and LCT innovation, improving the environmental and economic benefits of low-carbon transition.

C. FUTURE RESEARCH PROSPECT

Future research could be extended in the following directions: (1) We does not account for carbon emissions during electricity transmission or the constraints of grid stability; subsequent work could incorporate the physical characteristics of power grids for a more systematic analysis; (2) The model assumes complete information symmetry and rational decision-making; future studies could introduce behavioral factors and the impact of information asymmetry; (3) This paper focuses on a two-echelon supply chain with a single generator and a single retailer. Further investigation into markets with multiple competing enterprises and the superimposed effects of policies such as green certificate trading and carbon taxes would be valuable.

AUTHOR CONTRIBUTIONS

Conceptualization –Chunning He, Haidong Chen, Hongjie Tian, Jing Zhang and Lang Zhang; methodology – Chunning He, Haidong Chen, Hongjie Tian, Jing Zhang and Lang Zhang; investigation – Chunning He, Haidong Chen, Hongjie Tian, Jing Zhang and Lang Zhang; writing-original draft preparation – Chunning He, Haidong Chen, Hongjie Tian, Jing Zhang and Lang Zhang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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APPENDIX A.

Summary of equilibrium strategies.

Table A.1.

Equilibrium strategies of scenario GF-N

Scenario GF-N	
$k_{GF}^{N*}=\frac{(t+\beta\lambda)(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	$g_{GF}^{N*}=\frac{\gamma\lambda(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$
$w_{GF}^{N*}=\frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-2et-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	
$p_{GF}^{N*}=\frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-et-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	
$q_{GF}^{N*}=\frac{et-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	$\pi_{s-GF}^{N*}=\frac{(et-a)^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$
$\pi_{g-GF}^{N*}=E_0t-\frac{(et-a)^2}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$	

Table A.2.

Equilibrium strategies of scenario BM-N

Scenario BM-N	
$k_{BM}^{N*}=\frac{(t+\beta\lambda)[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	$g_{BM}^{N*}=\frac{\gamma\lambda[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$
$w_{BM}^{N*}=\frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-2(e-e_0)t-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	
$p_{BM}^{N*}=\frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-(e-e_0)t-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	
$q_{BM}^{N*}=\frac{(e-e_0)t-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$	$\pi_{g-BM}^{N*}=\frac{[(e-e_0)t-a]^2}{2[5-(\beta^2+2\gamma^2)\lambda^2-2t\beta\lambda-t^2]}$
$\pi_{s-BM}^{N*}=\frac{[(e-e_0)t-a]^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$	

Table A.3.

Equilibrium strategies of scenario GF-Y

Scenario GF-Y	
$k_{GF}^{Y*}=\frac{(t+\beta)(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5}$	$g_{GF}^{Y*}=\frac{\gamma(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5}$
$w_{GF}^{Y*}=\frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-2)]t+\beta^2c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5}$	
$p_{GF}^{Y*}=\frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-1)]t+\beta^2c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5}$	
$q_{GF}^{Y*}=\frac{et-a+c_B}{(\beta+t)^2+2\gamma^2-5}$	$\pi_{g-GF}^{Y*}=E_0t-\frac{(et-a+c_B)^2}{2[(\beta+t)^2+2\gamma^2-5]}$
$\pi_{s-GF}^{Y*}=\frac{(et-a+c_B)^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}$	

Table A.4.

Equilibrium strategies of scenario BM-Y

Scenario BM-Y	
$k_{BM}^{Y*} = \frac{(t+\beta)[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5}$	$g_{BM}^{Y*} = \frac{\gamma[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5}$
$w_{BM}^{Y*} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-2)(e-e_0)]t+\beta^2c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5}$	
$p_{BM}^{Y*} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-1)(e-e_0)]t+\beta^2c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5}$	
$q_{BM}^{Y*} = \frac{(e-e_0)t-a+c_B}{(\beta+t)^2+2\gamma^2-5}$	$\pi_{g-BM}^{Y*} = \frac{[(e-e_0)t-a+c_B]^2}{2[5-(\beta+t)^2-2\gamma^2]}$
$\pi_{s-BM}^{Y*} = \frac{[(e-e_0)t-a+c_B]^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}$	

Appendix B.

Table B.1.

Threshold summary

Thresholds	
V_1	$\frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-3)}{t(2-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$
V_2	$\frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-4)}{t(1-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$
V_3	$\frac{e_0(2et-te_0-2a)}{2(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\beta\lambda+t^2-5)}$
V_4	$\frac{3a+2c_B-\beta^2c_B-t(a+c_B)\beta-at^2-a\gamma^2-c_B\gamma^2}{t(\beta^2+t\beta+\gamma^2-2)}$
V_5	$\frac{4a+c_B-\beta^2c_B-t(a+c_B)\beta-at^2-a\gamma^2-c_B\gamma^2}{t(\beta^2+t\beta+\gamma^2-1)}$
V_6	$\frac{e_0(2et-te_0-2a+2c_B)}{2(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_7	$\frac{(et-a)(1-\lambda)[\beta^3\lambda+t(\lambda+1)\beta^2+(2\lambda\gamma^2+t^2+5)\beta+2t\gamma^2(\lambda+1)]}{(t+\beta)(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_8	$\frac{(et-a)[(-\beta^2-2\gamma^2)\lambda+t^2-5](\lambda-1)}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$
V_9	$\frac{(et-a)(1-\lambda)[(\lambda+1)\beta^2+2t\beta+2\gamma^2(\lambda+1)]}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$
V_{10}	$a-et+\frac{(a-et)\sqrt{(\beta^2+2t\beta+2\gamma^2+t^2-5)(\beta^2\lambda^2+2t\beta\lambda+2\gamma^2\lambda^2+t^2-5)}}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$
V_{11}	$a-et+\frac{(a-et)\sqrt{(2-\gamma^2\lambda^2)(\beta^2+2t\beta+2\gamma^2+t^2-5)^2}}{\sqrt{2-\gamma^2}(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{12}	$\frac{(1-\lambda)[(e-e_0)t-a][\beta t^2+(\beta^2+2\gamma^2)(\lambda+1)t+\beta(\beta^2\lambda+2\gamma^2\lambda+5)]}{(t+\beta)(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{13}	$\frac{[(e-e_0)t-a][(-\beta^2-2\gamma^2)\lambda+t^2-5](\lambda-1)}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$
V_{14}	$\frac{(1-\lambda)[(e-e_0)t-a][2\beta t+(\beta^2+2\gamma^2)(\lambda+1)]}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$

V_{15}	$a-(e-e_0)t+\frac{[a-(e-e_0)t]\sqrt{(\beta^2+2t\beta+2\gamma^2+t^2-5)(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}}{\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5}$
V_{16}	$a-(e-e_0)t+\frac{[a-(e-e_0)t]\sqrt{(2-\gamma^2\lambda^2)(\beta^2+2\gamma^2+2t\beta+t^2-5)^2}}{\sqrt{2-\gamma^2}(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{17}	$\frac{\left\{[e(\lambda-1)t+(c_B-a)\lambda+a]\lambda\beta^3+t[(e\lambda^2-e)t+(c_B-a)\lambda^2+2c_B\lambda+a]\beta^2+\{e(\lambda-1)t^3+[(2c_B-a)\lambda+a+c_B]t^2+(\lambda-1)\mathrm{et}(2\lambda\gamma^2+5)-2\gamma^2(a-c_B)\lambda^2+a(2\gamma^2-5)\lambda+5a-5c_B\}\beta+t[t^2c_B+2et\gamma^2(\lambda^2-1)-2\gamma^2(a-c_B)\lambda^2+2a\gamma^2-5c_B]\right.}{t(t+\beta)(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{18}	$\frac{(\beta^2+2\gamma^2)(et-a+c_B)\lambda^2+[at^2-et^3+(5e+2\beta c_B-2e\gamma^2-e\beta^2)t+a(\beta^2+2\gamma^2-5)]\lambda+(t^2-5)(et-a+c_B)}{t(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{19}	$\frac{(2e\lambda\beta-2e\beta+c_B)t^2+[e(\beta^2+2\gamma^2)\lambda^2-2\beta(a-c_B)\lambda-e\beta^2-2e\gamma^2+2a\beta]t-(\beta^2+2\gamma^2)(a-c_B)\lambda^2+a\beta^2+2a\gamma^2-5c_B}{t(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)}$
V_{20}	$\frac{\left\{(2ee_0-e_0^2)t^4+[2e^2\beta-2\beta(e-e_0)^2\lambda-2ec_B-2e_0(a-c_B)]t^3+[-(\beta^2+2\gamma^2)(e-e_0)^2\lambda^2+4\beta(a-c_B)(e-e_0)\lambda+e^2\beta^2+2e^2\gamma^2-4ea\beta-10ee_0+2ac_B-c_B^2+5e_0^2]t^2+[2(\beta^2+2\gamma^2)(a-c_B)(e-e_0)\lambda^2-2\beta(a-c_B)^2\lambda-2ea\beta^2+2\beta a^2+(10c_B-4a\gamma^2)e+10e_0(a-c_B)]t-(\beta^2+2\gamma^2)(a-c_B)^2\lambda^2+a^2\beta^2+2a^2\gamma^2-10ac_B+5c_B^2\right.}{2t(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_{21}	$\frac{\left\{e(\gamma^2-2)t^3+(2e\lambda\beta-a+c_B)(\gamma^2-2)t^2+[e(\beta^2+2\gamma^2)\lambda^2-2\beta(a-c_B)\lambda-5e](\gamma^2-2)t-(\gamma^2-2)(\beta^2+2\gamma^2)(a-c_B)\lambda^2+(5a-5c_B)\gamma^2-10a+10c_B+\sqrt{(\gamma^2-2)(\gamma^2\lambda^2-2)(et-a)^2(\beta^2+2t\beta+2\gamma^2+t^2-5)^2}\right.}{t(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)(\gamma^2-2)}$
V_{22}	$\frac{\left\{-[e(\lambda-1)t+(c_B-a)\lambda+a]\lambda\beta^3-t[(e\lambda^2-e)t+(c_B-a)\lambda^2+2c_B\lambda+a]\beta^2+\{e(1-\lambda)t^3+[(a-2c_B)\lambda-a-c_B]t^2-(\lambda-1)\mathrm{et}(2\lambda\gamma^2+5)+2\gamma^2(a-c_B)\lambda^2+a(5-2\gamma^2)\lambda-5a+5c_B\}\beta-t[t^2c_B+2et\gamma^2(\lambda^2-1)-2\gamma^2(a-c_B)\lambda^2+2a\gamma^2-5c_B]\right.}{t(t+\beta\lambda)(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_{23}	$\frac{(\beta^2+2\gamma^2)(a-et-c_B)\lambda^2+[et^3-at^2+(e\beta^2+2e\gamma^2-2\beta c_B-5e)t-a(\beta^2+2\gamma^2-5)]\lambda+(t^2-5)(a-et-c_B)}{t\lambda(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_{24}	$\frac{[-2e(\lambda-1)\beta-c_B]t^2+\{(e-e\lambda^2)\beta^2+[(2a-2c_B)\lambda-2a]\beta-2e\gamma^2\lambda^2+2e\gamma^2\}t+[\lambda^2(a-c_B)-a]\beta^2+2\gamma^2\lambda^2(a-c_B)-2a\gamma^2+5c_B}{t(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_{25}	$\frac{\left\{(2ee_0-e_0^2)t^4+\{[(2\lambda-2)e^2+4ee_0-2e_0^2]\beta+2ec_B-2ae_0\}t^3+\{[e^2(\lambda^2-1)+2ee_0-e_0^2]\beta^2+\{[(4-4\lambda)a+4c_B\lambda]e-4ae_0\}\beta+(2\gamma^2\lambda^2-2\gamma^2)e^2+(4\gamma^2-10)ee_0-2ac_B+c_B^2+(5-2\gamma^2)e_0^2\}t^2+\{[(2a+2c_B\lambda^2-2a\lambda^2)e-2ae_0]\beta^2+[(2\lambda-2)a^2-4ac_B\lambda+2\lambda c_B^2]\beta+[(4\gamma^2-4\gamma^2\lambda^2)a+4c_B\gamma^2\lambda^2-10c_B]e-2(2\gamma^2-5)ae_0\}t+[(\lambda^2-1)a^2-2ac_B\lambda^2+c_B^2\lambda^2]\beta^2+(2\lambda^2\gamma^2-2\gamma^2)a^2+(10c_B-4c_B\lambda^2\gamma^2)a+2c_B^2\lambda^2\gamma^2-5c_B^2\right.}{2t(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\lambda\beta+t^2-5)(\beta^2+2\gamma^2+2t\beta+t^2-5)}$
V_{26}	$\frac{\left\{2\lambda^2\gamma^4(et-a)+(et-a)[-4+(\beta^2+2t\beta+t^2-5)\lambda^2]\gamma^2+(2a-2et)\beta^2+(4at-4et^2)\beta-2et^3+2at^2-10a+10et+\sqrt{(a-et-c_B)^2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2(\gamma^2\lambda^2-2)(\gamma^2-2)}\right.}{t(\beta^2+2\gamma^2+2t\beta+t^2-5)(\gamma^2\lambda^2-2)}$

Appendix C.

In Appendix C, we mainly verify the solutions of the four core models.

Proof of Proposition 1. According to the backward induction method, firstly, substitute $q_1=a-p+\lambda(\beta k+\gamma g)$ into $\pi_{s-GF}^{N}=(p-w)q_1-\frac{g^2}{2}$, we can obtain the profit of retailer. Let $\frac{\partial\pi_{s\text{-}GF}^{N}}{\partial p}=0$ and $\frac{\partial\pi_{s\text{-}GF}^{N}}{\partial g}=0$, we can obtain the Hessian matrix of π_{s-GF}^{N} with respect to p and g is

$$\begin{vmatrix} -2 & \lambda\gamma \\ \lambda\gamma & -1 \end{vmatrix}$$

Obviously, $-2<0$ and the second-order sequential principal polynomial $2-\gamma^2\lambda^2>0$. Thus the Hessian matrix is negative, and there exists optimal sales price and SE of low-carbon electricity $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$ .Substitute $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$ into $\pi_{g-GF}^{N}=wq_1-t[(e-k)q_1-E_0]-\frac{k^2}{2}-\frac{q_1^2}{2}$, the Hessian matrix of π_{g-GF}^{N} with respect to w and k can be obtained as

$$\begin{vmatrix} 2\gamma^2\lambda^2-5 & \gamma^2\lambda^2 t+3\beta\lambda-2t-\beta\gamma^2\lambda^3 \\ \gamma^2\lambda^2 t+3\beta\lambda-2t-\beta\gamma^2\lambda^3 & 4\gamma^2\lambda^2+4t\beta\lambda-4-\beta^2\lambda^2-\gamma^4\lambda^4-2t\beta\gamma^2\lambda^3 \end{vmatrix}$$

Obviously, $2\gamma^2\lambda^2-5<0$ .When the second-order sequential principal polynomial $5-(\beta^2+2\gamma^2)\lambda^2-2t\beta\lambda-t^2>0$, the Hessian matrix is negative definite, and there exists an optimal wholesale electricity price and low-carbon investment. Let $\frac{\partial\pi_{g-GF}^{N}}{\partial w}=0$ and $\frac{\partial\pi_{g-GF}^{N}}{\partial k}=0$, we have

$w_{GF}^{N*}=\frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-2et-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$ and $k_{GF}^{N*}=\frac{(t+\beta\lambda)(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$.

Substitute w_{GF}^{N*} and k_{GF}^{N*} into $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$,we have

$p_{GF}^{N*}=\frac{[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-et-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$ and $g_{GF}^{N*}=\frac{\gamma\lambda(et-a)}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$. Finally,we have

$q_{GF}^{N*}=\frac{et-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$, $\quad \pi_{g-GF}^{N*}=E_0t-\frac{(et-a)^2}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$ and

$\pi_{s-GF}^{N*}=\frac{(et-a)^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$.

Proof of Proposition 2. According to the backward induction method, firstly, substitute $q_1=a-p+\lambda(\beta k+\gamma g)$ into $\pi_{s-BM}^{N}=(p-w)q_1-\frac{g^2}{2}$,we can obtain the profit of retailer. Let $\frac{\partial\pi_{s-BM}^{N}}{\partial p}=0$ and $\frac{\partial\pi_{s-BM}^{N}}{\partial g}=0$, we can obtain the Hessian matrix of π_{s-BM}^{N} with respect to p and g is

$$\begin{vmatrix} -2 & \lambda\gamma \\ \lambda\gamma & -1 \end{vmatrix}$$

Obviously, $-2<0$ and the second-order sequential principal polynomial $2-\gamma^2\lambda^2>0$ .Thus the Hessian matrix is negative, and there exists optimal sales price and SE of low-carbon electricity $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$. Substitute $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$ into $\pi_{g-BM}^{N}=$

$wq_1 - t[(e-k)-e_0]q_1 - \frac{k^2}{2} - \frac{q_1^2}{2}$, the Hessian matrix of π_{g-BM}^N with respect to w and k can be obtained as

$$\begin{vmatrix} 2\gamma^2\lambda^2-5 & \gamma^2\lambda^2 t+3\beta\lambda-2t-\beta\gamma^2\lambda^3 \\ \gamma^2\lambda^2 t+3\beta\lambda-2t-\beta\gamma^2\lambda^3 & 4\gamma^2\lambda^2+4t\beta\lambda-4-\beta^2\lambda^2-\gamma^4\lambda^4-2t\beta\gamma^2\lambda^3 \end{vmatrix}$$

Obviously, $2\gamma^2\lambda^2-5<0$ .When the second-order sequential principal polynomial $5-(\beta^2+2\gamma^2)\lambda^2-2t\beta\lambda-t^2>0$, the Hessian matrix is negative definite, and there exists an optimal wholesale electricity price and low-carbon investment. Let $\frac{\partial\pi_{g-BM}^N}{\partial w}=0$ and $\frac{\partial\pi_{g-BM}^N}{\partial k}=0$, we have

$w_{BM}^{N*}=\frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-2(e-e_0)t-3a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$ and $k_{BM}^{N*}=\frac{(t+\beta\lambda)[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$.

Substitute w_{BM}^{N*} and k_{BM}^{N*} into $g=\frac{\lambda\gamma(\beta k\lambda+a-w)}{2-\gamma^2\lambda^2}$ and $p=\frac{a+w+\beta k\lambda-w\gamma^2\lambda^2}{2-\gamma^2\lambda^2}$,we have

$p_{BM}^{N*}=\frac{[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-(e-e_0)t-4a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$ and $g_{BM}^{N*}=\frac{\gamma\lambda[(e-e_0)t-a]}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$.

Finally, we have

$q_{BM}^{N*}=\frac{(e-e_0)t-a}{(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5}$, $\pi_{g-BM}^{N*}=\frac{[(e-e_0)t-a]^2}{2[5-(\beta^2+2\gamma^2)\lambda^2-2t\beta\lambda-t^2]}$ and

$\pi_{s-BM}^{N*}=\frac{[(e-e_0)t-a]^2(2-\gamma^2\lambda^2)}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2}$.

Proof of Proposition 3. According to the backward induction method, firstly, substitute $q_1=a-p+\beta k+\gamma g$ into π_{s-GF}^Y=(p-w)q_2-$\frac{g^2}{2}$,we can obtain the profit of retailer. Let $\frac{\partial\pi_{s-GF}^Y}{\partial p}=0$ and $\frac{\partial\pi_{s-GF}^Y}{\partial g}=0$, we can obtain the Hessian matrix of π_{s-GF}^Y with respect to p and g is

$$\begin{vmatrix} -2 & \gamma \\ \gamma & -1 \end{vmatrix}$$

Obviously, $-2<0$ and the second-order sequential principal polynomial $2-\gamma^2>0$. Thus the Hessian matrix is negative, and there exists optimal sales price and SE of low-carbon electricity $g=\frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p=\frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$ .Substitute $g=\frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p=\frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$ into $\pi_{g-GF}^Y=(w-c_B)q_2-t[(e-k)q_2-E_0]-\frac{k^2}{2}-\frac{q_2^2}{2}$, the Hessian matrix of π_{g-GF}^Y with respect to w and k can be obtained as

$$\begin{vmatrix} 2\gamma^2-5 & \gamma^2 t+3\beta-2t-\beta\gamma^2 \\ \gamma^2 t+3\beta-2t-\beta\gamma^2 & 4\gamma^2+4t\beta-4-\beta^2-\gamma^4-2t\beta\gamma^2 \end{vmatrix}$$

Obviously, $2\gamma^2-5<0$.When the second-order sequential principal polynomial $5-\beta^2-2\gamma^2-2t\beta-t^2>0$,the Hessian matrix is negative definite, and there exists an optimal wholesale electricity price and low-carbon investment. Let $\frac{\partial\pi^Y_{g-GF}}{\partial w}=0$ and $\frac{\partial\pi^Y_{g-GF}}{\partial k}=0$, we have

$w^{Y*}_{GF}=\frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-2)]t+\beta^2 c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5}$ and $k^{Y*}_{GF}=\frac{(t+\beta)(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5}$.

Substitute w^{Y*}_{GF} and k^{Y*}_{GF} into $g=\frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p=\frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$,we have

$p^{Y*}_{GF}=\frac{(e\beta+a)t^2+[e\beta^2+(a+c_B)\beta+e(\gamma^2-1)]t+\beta^2 c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5}$ and $g^{Y*}_{GF}=\frac{\gamma(et-a+c_B)}{(\beta+t)^2+2\gamma^2-5}$.

Finally, we have

$q^{Y*}_{GF}=\frac{et-a+c_B}{(\beta+t)^2+2\gamma^2-5}$, $\pi^{Y*}_{g-GF}=E_0 t-\frac{(et-a+c_B)^2}{2[(\beta+t)^2+2\gamma^2-5]}$ and $\pi^{Y*}_{s-GF}=\frac{(et-a+c_B)^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}$.

Proof of Proposition 4. According to the backward induction method, firstly,substitute $q_1=a-p+\beta k+\gamma g$ into π^Y_{s-BM}=(p-w)q_2-$\frac{g^2}{2}$,we can obtain the profit of retailer. Let $\frac{\partial\pi^Y_{s-BM}}{\partial p}=0$ and $\frac{\partial\pi^Y_{s-BM}}{\partial g}=0$, we can obtain the Hessian matrix of π^Y_{s-BM} with respect to p and g is

$$\begin{vmatrix} -2 & \gamma \\ \gamma & -1 \end{vmatrix}$$

Obviously, $-2<0$ and the second-order sequential principal polynomial $2-\gamma^2>0$.Thus the Hessian matrix is negative, and there exists optimal sales price and SE of low-carbon electricity $g=\frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p=\frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$ .Substitute $g=\frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p=\frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$ into $\pi^Y_{g-BM}=(w-c_B)q_2-t[(e-k)-e_0]q_1-\frac{k^2}{2}-\frac{q_2^2}{2}$, the Hessian matrix of π^Y_{g-BM} with respect to w and k can be obtained as

$$\begin{vmatrix} 2\gamma^2 - 5 & \gamma^2 t + 3\beta - 2t - \beta\gamma^2 \\ \gamma^2 t + 3\beta - 2t - \beta\gamma^2 & 4\gamma^2 + 4t\beta - 4 - \beta^2 - \gamma^4 - 2t\beta\gamma^2 \end{vmatrix}$$

Obviously, $2\gamma^2 - 5 < 0$ .When the second-order order main formula $5 - \beta^2 - 2\gamma^2 - 2t\beta - t^2 > 0$, the Hessian matrix is negative definite, and there exists an optimal wholesale electricity price and low-carbon investment.Let $\frac{\partial \pi^{Y}_{g-BM}}{\partial w} = 0$ and $\frac{\partial \pi^{Y}_{g-BM}}{\partial k} = 0$,the simultaneous equations can be obtained as follows

$$w^{Y*}_{BM} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-2)(e-e_0)]t+\beta^2 c_B+(a+c_B)\gamma^2-3a-2c_B}{(\beta+t)^2+2\gamma^2-5},\ k^{Y*}_{BM} = \frac{(t+\beta)[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5}.$$

Substitute w^{Y*}_{BM} and k^{Y*}_{BM} into $g = \frac{\gamma(\beta k+a-w)}{2-\gamma^2}$ and $p = \frac{a+w+\beta k-w\gamma^2}{2-\gamma^2}$,we have:

$$p^{Y*}_{BM} = \frac{[(e-e_0)\beta+a]t^2+[(e-e_0)\beta^2+(a+c_B)\beta+(\gamma^2-1)(e-e_0)]t+\beta^2 c_B+(a+c_B)\gamma^2-4a-c_B}{(\beta+t)^2+2\gamma^2-5},\ g^{Y*}_{BM} = \frac{\gamma[(e-e_0)t-a+c_B]}{(\beta+t)^2+2\gamma^2-5}.$$

Finally, we have

$$q^{Y*}_{BM} = \frac{(e-e_0)t-a+c_B}{(\beta+t)^2+2\gamma^2-5},\ \pi^{Y*}_{g-BM} = \frac{[(e-e_0)t-a+c_B]^2}{2[5-(\beta+t)^2-2\gamma^2]} \text{ and } \pi^{Y*}_{s-BM} = \frac{[(e-e_0)t-a+c_B]^2(2-\gamma^2)}{2[(\beta+t)^2+2\gamma^2-5]^2}.$$

Appendix D

In Appendix D, we mainly validate the sensitivity analysis and comparative analysis.

Proof of Proposition 5. By taking partial derivatives of coefficientsλ, β andγunder GF-N, we can obtain:

$$\frac{\partial k^{N*}_{GF}}{\partial \lambda} = \frac{(a-et)[(\beta^3+2\beta\gamma^2)\lambda^2+2t\lambda(\beta^2+2\gamma^2)+\beta(t^2+5)]}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,\ \frac{\partial k^{N*}_{GF}}{\partial \beta} = \frac{\lambda(a-et)[(\beta^2-2\gamma^2)\lambda^2+2t\beta\lambda+t^2+5]}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,$$

$$\frac{\partial k^{N*}_{GF}}{\partial \gamma} = \frac{2(a-et)(t+\beta\lambda)(\beta t+2\gamma\lambda^2)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,\ \frac{\partial g^{N*}_{GF}}{\partial \lambda} = \frac{\gamma(a-et)(\beta^2\lambda^2+2\gamma^2\lambda^2-t^2+5)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,$$

$$\frac{\partial g^{N*}_{GF}}{\partial \beta} = \frac{\gamma\lambda(a-et)(2\beta\lambda^2+2t\lambda)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,\ \frac{\partial g^{N*}_{GF}}{\partial \gamma} = \frac{\lambda(et-a)(\beta^2\lambda^2-2\gamma^2\lambda^2+2t\beta\lambda+t^2-5)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0,$$

$$\frac{\partial \pi^{N*}_{g-GF}}{\partial \lambda} = \frac{(a-et)^2(4\beta^2\lambda+8\lambda\gamma^2+4t\beta)}{\{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]\}^2} > 0,\ \frac{\partial \pi^{N*}_{g-GF}}{\partial \beta} = \frac{(a-et)^2(4\beta\lambda^2+4t\lambda)}{\{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]\}^2} > 0,$$

$$\frac{\partial \pi^{N*}_{g-GF}}{\partial \gamma} = \frac{8(a-et)^2\gamma\lambda^2}{\{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]\}^2} > 0,\ \frac{\partial \pi^{N*}_{s-GF}}{\partial \lambda} = \frac{(a-et)^2(\beta^2\gamma^2\lambda^3+2\gamma^4\lambda^3-\lambda\gamma^2t^2-4\lambda\beta^2-3\lambda\gamma^2-4t\beta)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^3} > 0,$$

$$\frac{\partial \pi^{N*}_{s-GF}}{\partial \beta} = \frac{(a-et)^2(\gamma^2\lambda^2-2)(2t\lambda+2\beta\lambda^2)}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^3} > 0,\ \frac{\partial \pi^{N*}_{s-GF}}{\partial \gamma} = \frac{4(a-et)^2(\gamma^2\lambda^2-2)\gamma\lambda^2}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^3} > 0.$$

The proofs of case BM-N and Proposition 6 are similar to above, and the result is intuitive, therefore, we omit it.

Proof of Proposition 7. When not using BCT, comparing the equilibrium solutions under the GFM and BMM yields:

$$k_{BM}^{N*} - k_{GF}^{N*} = \frac{(t+\beta\lambda)te_0}{-[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]} > 0,\ g_{BM}^{N*} - g_{GF}^{N*} = \frac{\gamma\lambda te_0}{-[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]} > 0,$$

$$q_{BM}^{N*} - q_{GF}^{N*} = \frac{te_0}{-[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]} > 0, \pi_{s-BM}^{N*} - \pi_{s-GF}^{N*} = \frac{te_0(\gamma^2\lambda^2-2)[(2e-e_0)t-2a]}{[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]^2} > 0.$$

Next, we compare wholesale prices, sales prices, and generator revenue functions, and the results are as follows:

(i) $w_{BM}^{N*} - w_{GF}^{N*} = \frac{[t\beta\lambda+(\beta^2+\gamma^2)\lambda^2-2]te_0}{-[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$.Considering w_{BM}^{N*} and w_{GF}^{N*} are positive, we have $[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-2(e-e_0)t-3a<0$ and $[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-2et-3a<0$ established.Thus when $0< e < \frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-3)}{t(2-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$, $w_{BM}^{N*} - w_{GF}^{N*} > 0$; When $e > \frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-3)}{t(2-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$, $w_{BM}^{N*} - w_{GF}^{N*} < 0$.

(ii) $p_{BM}^{N*} - p_{GF}^{N*} = \frac{[t\beta\lambda+(\beta^2+\gamma^2)\lambda^2-1]te_0}{-[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$ .Considering p_{BM}^{N*} and p_{GF}^{N*} are positive, we have $[(e-e_0)t(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta[(e-e_0)t+a]\lambda+at^2-(e-e_0)t-4a<0$ and $[et(\beta^2+\gamma^2)+a\gamma^2]\lambda^2+t\beta(et+a)\lambda+at^2-et-4a<0$ established. Therefore, when $0 < e < \frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-4)}{t(1-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$, $p_{BM}^{N*} - p_{GF}^{N*} > 0$; Whene $> \frac{a(\gamma^2\lambda^2+t\beta\lambda+t^2-4)}{t(1-\beta^2\lambda^2-\gamma^2\lambda^2-t\beta\lambda)}$, $p_{BM}^{N*} - p_{GF}^{N*} < 0$.

(iii) $\pi_{BM}^{N*} - \pi_{GF}^{N*} = \frac{(2ee_0t-2E_0\beta^2\lambda^2-4E_0\gamma^2\lambda^2-4E_0t\beta\lambda-2E_0t^2-e_0^2t-2ae_0+10E_0)t}{2[(\beta^2+2\gamma^2)\lambda^2+2t\beta\lambda+t^2-5]}$.By calculating the partial derivative of E_0, we can be obtained $\frac{\partial(\pi_{s-BM}^{N*}-\pi_{s-GF}^{N*})}{\partial E_0} =-t < 0$.Therefore, the result is about the monotonic decreasing function of E_0. Let$\pi_{s-BM}^{N*} - \pi_{s-GF}^{N*} = 0$,we can obtain that $E_0 = \frac{e_0(2et-te_0-2a)}{2(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\beta\lambda+t^2-5)}$.So when $0< E_0 < \frac{e_0(2et-te_0-2a)}{2(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\beta\lambda+t^2-5)}$, $\pi_{s-BM}^{N*} - \pi_{s-GF}^{N*} > 0$;When$E_0 > \frac{e_0(2et-te_0-2a)}{2(\beta^2\lambda^2+2\gamma^2\lambda^2+2t\beta\lambda+t^2-5)}$, $\pi_{s-BM}^{N*} - \pi_{s-GF}^{N*} < 0$.

The proof of Propositions 8-12 is similar to Proposition 7.

Appendix E.

Table E.1.

The optimal equilibrium in GF-N and BM-N

		γ = 0.2				γ = 0.3			
		β: = 0.1	0.2	0.3	0.4	β: = 0.1	0.2	0.3	0.4
SCENARIO GF-N	k_{GF}^{N*}	0.4409	0.4870	0.5348	0.5846	0.4433	0.4896	0.5377	0.5879
	g_{GF}^{N*}	0.0801	0.0811	0.0822	0.0835	0.1209	0.1224	0.1241	0.1259
	w_{GF}^{N*}	2.4266	2.4334	2.4428	2.4548	2.4282	2.4351	2.4445	2.4567
	p_{GF}^{N*}	3.2283	3.2451	3.2656	3.2900	3.2342	3.2512	3.2719	3.2966
	q_{GF}^{N*}	0.8017	0.8116	0.8228	0.8351	0.8060	0.8161	0.8273	0.8398
	π_{a-GF}^{N*}	1.7532	1.7719	1.7927	1.8159	1.7612	1.7801	1.8012	1.8247
	π_{s-GF}^{N*}	0.6395	0.6555	0.6736	0.6940	0.6423	0.6585	0.6768	0.6974
SCENARIO BM-N	k_{BM}^{N*}	0.4703	0.5194	0.5704	0.6236	0.4728	0.5223	0.5736	0.6270
	g_{BM}^{N*}	0.0855	0.0865	0.0877	0.0890	0.1289	0.1305	0.1323	0.1343
	w_{BM}^{N*}	2.3217	2.3290	2.3390	2.3518	2.3234	2.3307	2.3408	2.3538
	p_{BM}^{N*}	3.1769	3.1948	3.2166	3.2427	3.1832	3.2013	3.2233	3.2497
	q_{BM}^{N*}	0.8551	0.8658	0.8776	0.8908	0.8597	0.8705	0.8825	0.8958
	π_{a-BM}^{N*}	1.7103	1.7316	1.7553	1.7817	1.7195	1.7410	1.7650	1.7917
	π_{s-BM}^{N*}	0.7276	0.7458	0.7664	0.7896	0.7308	0.7492	0.7700	0.7935
		γ = 0.4				γ = 0.5			
		β: = 0.1	0.2	0.3	0.4	β: = 0.1	0.2	0.3	0.4
SCENARIO GF-N	k_{GF}^{N*}	0.4466	0.4934	0.5419	0.5925	0.4510	0.4983	0.5474	0.5986
	g_{GF}^{N*}	0.1624	0.1644	0.1667	0.1693	0.2050	0.2076	0.2105	0.2137
	w_{GF}^{N*}	2.4305	2.4375	2.4470	2.4593	2.4335	2.4406	2.4503	2.4627
	p_{GF}^{N*}	3.2426	3.2598	3.2808	3.3058	3.2536	3.2711	3.2925	3.3179
	q_{GF}^{N*}	0.8121	0.8223	0.8337	0.8465	0.8201	0.8305	0.8422	0.8551
	π_{a-GF}^{N*}	1.7727	1.7919	1.8133	1.8371	1.7877	1.8073	1.8291	1.8534
	π_{s-GF}^{N*}	0.6463	0.6627	0.6813	0.7022	0.6515	0.6682	0.6871	0.7084
SCENARIO BM-N	k_{BM}^{N*}	0.4764	0.5263	0.5780	0.6320	0.4811	0.5315	0.5839	0.6385
	g_{BM}^{N*}	0.1732	0.1754	0.1778	0.1805	0.2186	0.2214	0.2245	0.2280
	w_{BM}^{N*}	2.3259	2.3333	2.3435	2.3566	2.3291	2.3366	2.3469	2.3603
	p_{BM}^{N*}	3.1922	3.2105	3.2329	3.2595	3.2039	3.2225	3.2453	3.2725
	q_{BM}^{N*}	0.8662	0.8771	0.8893	0.9029	0.8747	0.8859	0.8983	0.9122
	π_{a-BM}^{N*}	1.7325	1.7543	1.7787	1.8058	1.7495	1.7718	1.7967	1.8244
	π_{s-BM}^{N*}	0.7354	0.7540	0.7751	0.7989	0.7413	0.7603	0.7818	0.8061

Table E.2.

The optimal equilibrium in GF-Y and BM-Y

		$c_B = 0.4$	$c_B = 0.5$	$c_B = 0.6$	$c_B = 0.7$
SCENARIO GF-Y	k_{GF}^{Y*}	0.8170	0.7926	0.7682	0.7439
	g_{GF}^{Y*}	0.4539	0.4403	0.4268	0.4132
	w_{GF}^{Y*}	2.7380	2.7757	2.8134	2.8510
	p_{GF}^{Y*}	3.6459	3.6565	3.6670	3.6776
	q_{GF}^{Y*}	0.9078	0.8807	0.8536	0.8265
	π_{a-GF}^{Y*}	1.7706	1.6812	1.5945	1.5105
	π_{s-GF}^{Y*}	0.7211	0.6787	0.6376	0.5977
SCENARIO BM-Y	k_{BM}^{Y*}	0.8780	0.8536	0.8292	0.8048
	g_{BM}^{Y*}	0.4878	0.4742	0.4607	0.4471
	w_{BM}^{Y*}	2.6439	2.6815	2.7192	2.7569
	p_{BM}^{Y*}	3.6195	3.6300	3.6406	3.6512
	q_{BM}^{Y*}	0.9756	0.9485	0.9214	0.8943
	π_{a-BM}^{Y*}	1.7560	1.6598	1.5663	1.4756
	π_{s-BM}^{Y*}	0.8328	0.7872	0.7428	0.6998