Technology Licensing Decision-Making Among Competitive Automakers Considering Government Subsidy: A Technological Innovation Diffusion Perspective

Miao-Miao Wang, Meng-Ying Li

Abstract—**The development of new energy vehicles (NEVs) has garnered significant attention against the backdrop of carbon neutrality and carbon trading policies. This study constructs distinct duopoly competition models within an NEV supply chain comprising a technology-holding manufacturer (Enterprise 1) and a non-technology manufacturer (Enterprise 2) that can obtain technology through licensing. Three licensing strategies are compared in this supply chain context: no technology licensing, per-unit royalty technology licensing, and fixed-fee technology licensing, with further analysis conducted under both subsidized and non-subsidized government policy scenarios. The impacts of government subsidy levels, green technology advantages, carbon reduction benefits, and competitive intensity on strategy selection are investigated. Numerical and case analyses are developed to examine how the technology cost coefficient, consumer preference for new energy technology, and different cost models affect equilibrium outcomes. The results indicate that as the technology cost coefficient increases, both the level of new energy technology in products and enterprise revenue decline. Enhanced consumers' preference for low-carbon technology leads to higher product prices, increased demand, greater enterprise profits, improved carbon reduction benefits, expanded consumer surplus, and higher social welfare. A comparison of licensing models reveals a fixed cost threshold below which Enterprise 1 prefers the per-unit royalty licensing model.**

Index Terms—**New energy vehicles; Technology licensing; Consumer preferences; Carbon emission reduction; Social welfare**

I. Introduction

Currently, global warming is intensifying. In response to the global climate crisis and to achieve sustainable development. China announced its dual carbon targets at the 75th United Nations General Assembly, underscoring the critical need for carbon emission reduction. This commitment was further emphasized at the 2024 Carbon Peaking and Carbon Neutrality Green Development Forum held in Beijing on April 29, 2024, with the theme "Implementing Dual Carbon Actions to build a World's Second-Largest Economy", China has proposed to achieve carbon peak by 2030 and carbon neutrality by 2060[1]. The European Union and other developed economies have set ambitious targets to achieve carbon neutrality by 2050 [2-4]. The transportation sector accounts for a substantial proportion of total carbon emissions and exhibits a high annual growth rate [5], rendering it one of the fastest-growing sources of greenhouse gas emissions in China. Within the transportation sector, road transport contributes over 80% of carbon emissions [6]. In actively responding to China's national strategy of carbon peaking and carbon neutrality, new energy vehicles (NEVs) have emerged as a strategic priority owing to their significant carbon reduction characteristics. The *New Energy Vehicle Industry Development Plan (2021-2035)* sets a target of 20% market penetration for new energy vehicles by 2025. Under the carbon trading policy, new energy enterprises can trade carbon emission allowances obtained through carbon reduction to generate substantial profits. For instance, in 2020, Tesla earned a staggering $1.58 billion in revenue solely from selling carbon emission credits, which exceeded twice its net profit. In 2020, BYD also obtained 750, 000 carbon credits through new energy vehicles. As an environmentally sustainable transportation solution, new energy vehicles are regarded the future direction of the automotive industry [7].

The continuous advancement of temperature control technology in new energy vehicle (NEV) thermal management systems, coupled with ongoing improvements in energy efficiency, will provide crucial support for achieving carbon neutrality. China has demonstrated a strong commitment to accelerating the development of the NEV industry, recognizing it as a critical pathway for facilitating energy structure transformation, promoting green development, ensuring energy security, and enhancing international competitiveness. Amid intensifying global climate change and environmental degradation, there is an urgent need to reassess the environmental impact and responsibilities of humanity. Through policy incentives, technological innovation, and market cultivation, China is poised to further advance its NEV industry, thereby contributing substantially to sustainable, green, and low-carbon development [8].

However, China still faces substantial gaps in core NEV technology. Prior to BYD's development of insulated-gate bipolar transistors (IGBT), nearly all electric vehicle motor

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control units (MCUs) in China were imported, with their prices and delivery times subject to foreign suppliers. The pace of domestic new energy technology development has accelerated in recent years. In 2015, Shanghai Advanced Semiconductor Manufacturing Corporation (Shanghai Advanced) and BYD Microelectronics Co., Ltd. in Shenzhen entered into a strategic industrial alliance cooperation agreement to jointly establish a domestic IGBT supply chain. The localization process of new energy vehicle chips is anticipated to accelerate. This strategic industrial alliance will enable both parties to fully leverage their respective strengths, integrating their proprietary IGBT core technologies and semiconductor chip manufacturing technologies to expedite the localization of IGBT chips for new energy vehicles. Nevertheless, the development of critical core technologies such as IGBT requires substantial upfront investment, and numerous enterprises are unable to conduct independent research and innovation owing to financial constraints.

Technology licensing serves as a critical mechanism for enterprises to access technological innovation, enabling them to secure production and R&D permissions through formal technology collaboration agreements with patent-holding enterprises. Within the organizational ecosystem framework, enterprise growth occurs in a dual-layered environment. This ecological perspective conceptualizes enterprises as interdependent entities whose evolutionary trajectories are determined by their natural operating environment and the complex network of competitive or cooperative relationships with peer organizations[9]. For non-technology enterprises, establishing strategic licensing partnerships with technology holders is a critical determinant of sustainable development within this industrial ecosystem. For instance, in 2012, BorgWarner provided BYD with advanced engine turbocharging technology, and BYD, in turn, licensed its Blade Battery technology to BorgWarner through a technology agreement, jointly producing lithium iron phosphate (LFP) battery packs to achieve technological output. BYD supplies power batteries to competitors such as Dongfeng Motor, Toyota, Changan Ford, Hyundai and Hongqi at wholesale prices through contract agreements [10]. In 1997, Ford Motor Company licensed its passenger-side airbag deactivation switch technology to competitors for a fee, reducing production costs through economies of scale and setting industry standards for the deactivation switch system [11]. These cases demonstrate how automotive manufacturers leverage patented technology licensing to establish symbiotic relationships with competitors and supply chain partners across vertical and horizontal dimensions, thereby fostering sustainable development and accelerating technological dissemination and industry-wide adoption. Technology licensing has become commonplace in both domestic and international transactions. According to the National Intellectual Property Administration, Chinese manufacturing enterprises conducted 217,000 technology license transactions in the first half of 2020.

Given the vast potential market for new energy vehicles and their significant environmental benefits, their coordinated development is crucial. While there has been extensive academic research on technology licensing between innovative and non-innovative enterprises, few studies have integrated NEVs and comprehensively examined their carbon reduction benefits and social welfare implications. This study aims to address the following research questions:

(1) Does consumers' preference for low-carbon technology contribute to the development of the new energy vehicle industry and increased social welfare? How should the government guide this?

(2) What impacts do different technology licensing models have on the profits of supply chain members, social welfare, and consumer surplus? Which technology licensing model is superior from the perspective of the technology-holding enterprise?

To address these research questions, we develop a duopoly competition model for the new energy vehicle supply chain, where non-technology enterprises may acquire innovations via licensing agreements. Accounting for government regulation, we systematically examine six scenarios by incorporating both subsidized and unsubsidized market conditions: under unsubsidized regimes, we consider no licensing (NN), per-unit royalty licensing (Nf), and fixed-fee licensing (NF); under subsidized regimes, we analyze their counterparts (GN, Gf, GF). This comprehensive framework enables comparative analysis of how different licensing strategies affect supply chain members' operational decisions and economic performance across policy environments.

The contributions of this study are threefold: (1) Unlike existing literature, this study integrates NEV enterprises and technology licensing models to comprehensively explore the impacts of different technology licensing models on environmental, economic, and social welfare outcomes, as well as consumer surplus, providing references for collaborative technological innovation. (2) Consumers' low-carbon preferences are incorporated to deeply explore the influence of consumer preference on NEV market dynamics and environmental benefits. (3) Through comparative analysis of licensing models, this study helps various members of the supply chain identify the most advantageous operational models and profit margins, providing additional references for the operational models of technology licensing in the supply chain.

The rest of this paper is organized as follows. Section II introduces related literature. Section III describes the research problem and develops the mathematical models. Section IV derives equilibrium solutions for the Stackelberg game models under various scenarios and establishes key theorems and corollaries. Section V conducts numerical analysis. Finally, Section VI concludes the study and discusses key insights.

II. Literature Review

This study primarily addresses three categories of literature: New energy vehicles and subsidy policies, consumers' low-carbon preferences, and enterprise technology licensing models.

A. *New energy vehicles and subsidy policies*

Su et al. [12] found that new energy vehicles (NEVs) have a positive impact on reducing air pollution. Regarding the future prospects of NEVs, Zahoor et al. [13] predicted that over the next 25 years, China will hold the highest global market share at 45.22%, and that achieving carbon neutrality in China will require the NEV industry to be supported by incentive policies, financial assistance, technological improvements, and research and development. Xian et al. [14] employed a logit model to examine the impact of different incentive policies (auctions, lotteries, and queues), vehicle attributes, and consumer attributes on the demand for NEVs in China's megacities. Zhu et al. [15] established distinct models for gasoline vehicles (GV) and electric vehicles (EV) under carbon regulation, analyzing the impact of such regulation on automakers. Their results indicate that when formulating carbon quota policies, the influence of carbon trading prices should be considered. Li et al. [16] investigated the importance of new energy vehicle subsidy policies for achieving sustainable development. Their findings suggest that new energy vehicle subsidy policies can effectively reduce carbon emissions in the transportation sector by promoting a green transformation in consumers' vehicle purchase structures. Guo et al. [17] explored the driving factors for achieving the 2035 market penetration target for new energy vehicles by designing carbon quota and battery recycling subsidy mechanisms. They found that carbon trading policies are superior to dual credit policies (DCP) and can better reduce carbon emissions in production and consumption.

B. *Consumers' low-carbon preferences*

Consumers' low-carbon preferences is crucial for promoting the development of the new energy vehicle market and fostering a low-carbon society to attain green and sustainable development. Xu and Lin [18] conducted a survey on the willingness to pay for carbon-labeled products in China's first-tier cities. The findings revealed that 85.97% of the respondents are willing to pay a premium for carbon-label products. Furthermore, male, younger, or wealthier respondents, as well as those with minor children at home, exhibited a stronger inclination to pay extra for such products, with a willingness to pay 7.85% more than the original price. Wang et al. [19] explored the dynamic control of corporate quality improvement and low-carbon investment under consumer quality and low-carbon preferences. Their research indicated that the higher the consumers' quality or low-carbon preferences, the more conducive it is to enterprises' profit maximization and social welfare enhancement. Liu et al. [20] constructed a three-tier supply chain consisting of manufacturers, retailers, and consumers, and investigated the impact of policy factors and consumer preferences on electric vehicle (EV) pricing. Chen et al. [21] proposed that the enhancement of consumers' environmental awareness exerts a positive influence on the supply chain. Qi et al. [22] contended that government subsidy and consumers' willingness to purchase green products contribute to encouraging enterprises to adopt greener production practices. Alyamani et al. [23] surveyed Saudi consumers' acceptance of electric vehicles and found that nearly 60% of the target population expressed interest in purchasing one within the next three years, with most indicating that the new vehicle would replace their existing one. Xue et al. [24] and Lu et al. [25] demonstrated that incentive policies and government subsidy policies can increase consumers' EV purchase rates.

C. *Technology licensing models*

How do competitive enterprises collaborate technologically to achieve mutual benefits, and what types of licensing methods do they choose? Hong et al. [26] revealed a threshold effect in manufacturers' optimal licensing strategies within closed-loop supply chains: royalty-based licensing is more advantageous when fixed fees fall below the critical threshold, whereas fixed-fee licensing becomes preferable above this threshold. Li et al. [27] discussed the scenario where a leading manufacturer in a developed country can license its innovative technology to a manufacturer in a developing country, suggesting that when parallel imports occur, the technology-holding manufacturer should reduce the fixed licensing fee when it holds market dominance. Zhao et al. [28] demonstrated that a fixed-fee remanufacturing model maximizes profits for all parties when consumer acceptance exceeds a critical threshold in closed-loop supply chains with third-party recovery. Sarmah et al. [29] examined the favorable conditions for pharmaceutical manufacturers' technology licensing in terms of economic and social benefits. Anand and Goyal [30] found that morally constrained companies often achieve greater profits. Han [31] studied the optimal technology licensing contracts in a duopoly supply chain in which technology is licensed to competitors, and found that the choice of licensing fee model is significantly influenced by the degree of product substitutability. Yan et al. [32] found that technology licensing universally benefits OEMs and social welfare, whereas fixed fee models generally optimize social benefits in tripartite supply chains. Liu et al. [33] revealed that higher pre-licensing remanufactured product quality reduces OEMs' patent fees and profits, whereas a two-part tariff strategy remains optimal. Jamali and Rasti-Barzoki [34] demonstrated government support strategies enhance innovation under market failure with cooperative suppliers, whereas information sharing negatively impacts procurement prices. Wang et al. [35] showed free licensing benefits supply chain innovators under moderate entrant quality, while fixed- fee licensing outperforms royalty models under strong network effects or weak entrants. Kong et al. [36] demonstrated royalty licensing enhances green technology levels, prices, and demand in online agency platforms with competing enterprises (including a green innovator), outperforming fixed-fee models in terms of environmental or economic benefits. Chen et al. [37] demonstrated that four licensing strategies can each maximize economic outcomes, with the optimal choice being context-dependent on tripartite manufacturers' cost disparities.

III. Problem Description

Assume there are two new energy vehicle (NEV) enterprises in the market, denoted as Enterprise 1 and Enterprise 2, both specializing in the production of homogeneous NEV products. Enterprise 1 is a technology-holding manufacturer, whereas Enterprise 2 is a non-technology-holding manufacturer. These two enterprises engage in price competition and actively pursue technological advancements in their NEV products to reduce carbon emissions, thereby gaining more carbon credits for trading and satisfying consumer demands. Initially, both enterprises produce incompatible products using existing technologies at the same cost. Additionally, there exists a large number of consumers in the market, with the demand functions for these two products being:

$$q_i = a - bp_i + cp_j(i, j = 1,2; i \neq j)$$

The market landscape and competitive environment motivate Enterprises 1 and 2 to continuously strive to enhance their technological capabilities meet consumer demand for new energy vehicles (NEVs) and reduce carbon emissions, thereby gaining a competitive edge in the market.

The relevant symbols used in this paper and their meanings are explained in TABLE I:

TABLE I
PARAMETER EXPLANATION

Parameter	Explanation
q_i	Product Demand
a	Basic Market Demand
c	Competition intensity (product substitutability) $(1 > c > 0)$
k	New energy technology R&D cost coefficient
α	Consumer technology quality preference coefficient $(0 < \alpha < 1)$
e_1	The carbon reduction benefits per unit of product sold by Company 1
e_2	The carbon reduction benefits per unit of product sold by Company 2
s	Government subsidy for corporate carbon emission reductions
F	The fixed fee F that Company 2 must pay to Company 1 as a one-time payment
f	The fee f that Company 2 must pay to Company 1 per unit of product sold
CS_i	Consumer Surplus$(i = 1,2)$
E_i	Environmental Benefits$(i = 1,2)$
SW	Social Welfare
Decision variables	
p_i	Unit product's retail price $(i = 1,2)$
θ	Product low-carbon technology quality level

Enterprise 1 has invested heavily in θ, developing more advanced new energy technologies and production techniques with a technological level of θ, and the R&D investment cost is $C(\theta) = \frac{1}{2}k\theta^2$, where k is the cost coefficient. As Enterprise 2 does not possess new energy production technology, it can achieve innovation by obtaining technical authorization. Enterprise 1 and Enterprise 2 can then engage in technology licensing transactions. In the scenario where Enterprise 2 obtains a technology license, the demand functions are as follows:

$$q_1 = a - bp_1 + cp_2 + \alpha\theta$$
$$q_2 = a - bp_2 + cp_1 + \alpha\theta$$

The process is as follows: first, Enterprise 1 (the holder of new energy technology) selects the licensing model and price of technology licensing, whether to adopt a royalty-based or fixed-fee licensing model; second, enterprise 2 (the follower enterprise) decides whether to accept the technology licensing under Enterprise 1's terms; finally, the two enterprises engage in non-cooperative quantity competition in the market. Enterprise 1's total revenue comprises profits and technology licensing fees.

The modeling and analysis are based on the following three assumptions:

Assumption 1. All consumers exhibit a preference for low-carbon new energy technologies, and based on real-world scenarios, all consumers are price-sensitive, such that high prices may lead them to switch to alternative products or abandon purchases. Therefore, the two competing manufacturers must comprehensively consider their product pricing strategies to maximize profits.

Assumption 2. For each unit of new energy vehicle sold, Enterprise 1 can achieve carbon emission reduction of e_1, and Enterprise 2 can achieve reduction of e_2. When Enterprise 2 obtains technology authorization from Enterprise 1, the carbon emission reduction benefit per unit of product is upgraded to e_1 $(e_1 > e_2)$. Additionally, it is assumed that the government does not provide subsidy to enterprises that have not innovated in new energy technologies. However, for enterprises that possess the technology, the government provides a subsidy of s per unit of product. When the authorized enterprise acquires the technology, each unit of the product generates the same social benefit, and the government provides a subsidy of s.

Assumption 3. E denotes the carbon emission reduction benefit and CS denotes consumer surplus, where $E = eq$, $CS = \frac{1}{2}q^2$. These variables represent the carbon emission reduction benefits and consumer surplus brought by new energy vehicles.

The sequence of the game is as follows: Enterprise 1 determines on the technological level of new energy vehicles by considering market demand dynamics, and decides whether to authorize Enterprise 2 with its technology and the method of authorization; subsequently, both enterprises simultaneously set the retail prices for retailing new energy vehicles.

IV. MODEL SETUP

A. Technology Licensing Model for Competitive Enterprise without Government Subsidy

In this scenario, neither the technology-holding manufacturer nor the non-technology-holding manufacturer receives any government subsidy.

1) No Government Subsidy and No Technology Licensing (NN)

$$\pi_{m1}^{NN} = p_1q_1 - \frac{1}{2}k\theta^2 + e_1p_eq_1$$
$$= -\frac{k\theta^2}{2} + p_1(a + \alpha\theta - p_1 + cp_2) + e_1(a + \alpha\theta - p_1 + cp_2)p_e \quad (1)$$

$$\pi_{m2}^{NN} = p_2q_2 + e_2p_eq_2$$
$$= (a + cp_1 - p_2)p_2 + e_2(a + cp_1 - p_2)p_e \quad (2)$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem 1(1) When $k_1 < k < k_2$, $p_1^{NN^*} > p_2^{NN^*}$; *or* $p_1^{NN^*} < p_2^{NN^*}$.

Here, $k_1 = \frac{8\alpha^2}{(-4+c^2)^2}$, $k_2 = \frac{4\alpha^2(a-((-2+c)e_1+e_2)p_e)}{(-2+c)^2(2+c)(e_1-e_2)p_e}$.

Theorem 1 (1) states that there exists a threshold for the technological cost coefficient k such that when k exceeds this threshold, the sales price of Enterprise 1 is greater than that of Enterprise 2 in the absence of government subsidy and technology licensing. Furthermore, as illustrated in Figure 1, the range of thresholds where Enterprise 1's product price exceeds that of Enterprise 2 expands as c consumer preference for technology increases.

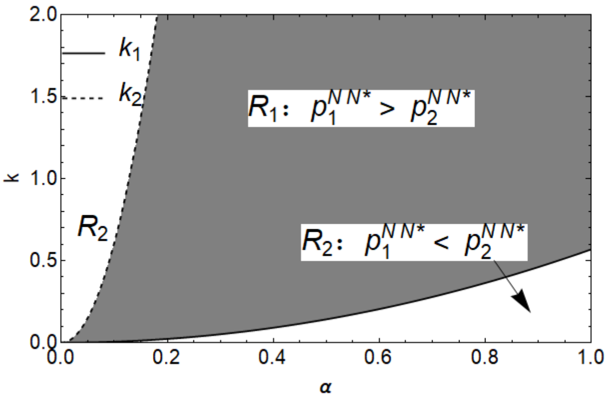

Figure 1. Comparison of Retail Prices Between Two Enterprises in NN Mode.

Theorem 1(2) $q_1^{NN^*} > q_2^{NN^*}$, $\pi_{m1}^{NN^*} > \pi_{m2}^{NN^*}$, $CS_1^{NN^*} > CS_2^{NN^*}$, $E_1^{NN^*} > E_1^{NN^*}$.

Theorem 1 (2) reveals that the demand for Enterprise 1's products is higher than that for Enterprise 2's products. This is attributed to Enterprise 1's superior technological level, which attracts a larger number of technology-oriented consumers, thereby increasing consumer surplus and carbon emission reduction benefits, while also enabling Enterprise 1 to generate higher profits.

Corollary 1(1) $\frac{\partial \theta^{NN^*}}{\partial p_e} > 0, \frac{\partial \pi_{m1}^{NN^*}}{\partial p_e} > 0$; when $\frac{8\alpha^2}{(-4+c^2)^2} < k < -\frac{4\alpha^2}{-4+c^2}$;or $k > -\frac{4\alpha^2}{-4+c^2}$ and $e_2 < \frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2}$, $\frac{\partial \pi_{m2}^{NN^*}}{\partial p_e} > 0$;

(2) $\frac{\partial \theta^{NN^*}}{\partial e_1} > 0, \frac{\partial \pi_{m1}^{NN^*}}{\partial e_1} > 0, \frac{\partial \pi_{m2}^{NN^*}}{\partial e_2} > 0.$

Corollary 1 indicates that the technological level and profit margin of Enterprise 1's new energy vehicle products are significantly positively correlated with the unit carbon trading price and the carbon emission reduction benefit per unit product. In contrast, the profit performance of Enterprise 2 does not necessarily follow the same pattern. Specifically, the profit enhancement of Enterprise 2 depends on the specific conditional constraints among the technological cost coefficient k, the carbon emission reduction benefit of its products, and the unit carbon trading price. Only when these factors meet certain thresholds can higher carbon emission reduction benefits and unit carbon trading prices exert a positive impact on the profit of Enterprise 2.

2) Model with Per-Unit Royalty Technology Licensing under No Government Subsidy (Nf)

$$\begin{aligned}\pi_{m1}^{Nf} &= p_1 q_1 - \frac{1}{2}k\theta^2 + e_1 p_e q_1 \\ &= -\frac{k\theta^2}{2} + p_1(a + \alpha\theta - p_1 + cp_2) \\ &\quad + e_1(a + \alpha\theta - p_1 + cp_2)p_e \end{aligned} \tag{3}$$

$$\begin{aligned}\pi_{m2}^{Nf} &= p_2 q_2 + e_2 p_e q_2 \\ &= (a + cp_1 - p_2)p_2 + e_2(a + cp_1 - p_2)p_e \end{aligned} \tag{4}$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem2(1) $p_1^{Nf^*} < p_2^{Nf^*}$, $q_1^{Nf} > q_2^{Nf^*}$, $CS_1^{Nf^*} > CS_2^{Nf^*}$, $E_1^{Nf^*} > E_1^{Nf^*}$.

(2) When $k > \frac{4(14+c(6+(-3+c)c))\alpha^2}{(1+c)(8-6c+c^2)^2}$ and $f_1 < f < f_2$, $\pi_{m1}^{Nf^*} > \pi_{m2}^{Nf^*}$; otherwise $\pi_{m1}^{Nf^*} < \pi_{m2}^{Nf^*}$.

Theorem 2 demonstrates that under the Nf mode, the sales price of Enterprise 1's new energy vehicles (NEVs) is lower than that of Enterprise 2. However, the product demand, consumer surplus, and carbon emission reduction benefits of Enterprise 1 still exceeded those of Enterprise 2.

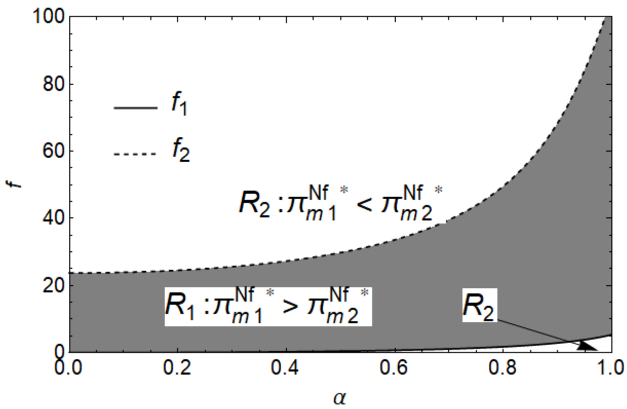

Figure 2. Comparison of Profits Between Two Enterprises in Nf Mode.

Corollary 2(1) when $\frac{2\alpha^2}{(-2+c)^2} < k \leq -\frac{(12+c(4+c+c^2))\alpha^2}{2(-1+c)(8+c^2)}$; $k > -\frac{(12+c(4+c+c^2))\alpha^2}{2(-1+c)(8+c^2)}$, $f < \frac{(8+c^3)k(-1+(-1+c)e_1 p_e)}{2(-1+c)(8+c^2)k+(12+c(4+c+c^2))\alpha^2}$, $\frac{\partial \pi_{m1}^{Nf^*}}{\partial f} > 0$; when $\frac{2\alpha^2}{(-2+c)^2} < k < \frac{4\alpha^2-c\alpha^2}{4-6c+2c^2}$, $\frac{\partial \pi_{m2}^{Nf^*}}{\partial f} > 0$;

(2) $\frac{\partial \theta^{Nf^*}}{\partial p_e} > 0, \frac{\partial \pi_{m1}^{Nf^*}}{\partial p_e} > 0, \frac{\partial \pi_{m2}^{Nf^*}}{\partial p_e} > 0$;

(3) $\frac{\partial \theta^{Nf^*}}{\partial e_1} > 0, \frac{\partial \pi_{m1}^{f^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m2}^{Nf^*}}{\partial e_1} > 0$.

Corollary 2 demonstrates that when the technological cost coefficient k and the unit royalty fee satisfy certain threshold conditions, the profit of Enterprise 1 is positively correlated with the unit technology licensing fee, whereas the profit of Enterprise 2 is negatively correlated with the unit technology licensing fee. Furthermore, under the unit royalty fee technology licensing model, the technological level of NEVs, as well as the profits of Enterprise 1 and Enterprise 2, are positively correlated with the carbon emission reduction benefit per unit product sold and the unit carbon trading price.

3) Model with Fixed-Fee Technology Licensing under No Government Subsidy (NF)

$$\begin{aligned}\pi_{m1}^{NF} &= p_1 q_1 - \frac{1}{2}k\theta^2 + e_1 p_e q_1 \\ &= -\frac{k\theta^2}{2} + p_1(a + \alpha\theta - p_1 + cp_2) + \\ &\qquad e_1(a + \alpha\theta - p_1 + cp_2)p_e \end{aligned} \tag{5}$$

$$\begin{aligned}\pi_{m2}^{NF} &= p_2 q_2 + e_2 p_e q_2 \\ &= (a + cp_1 - p_2)p_2 + e_2(a + cp_1 - p_2)p_e \end{aligned} \tag{6}$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem 3(1) $w_1^{NF^*} = w_2^{NF^*}$, $p_1^{NF^*} = p_2^{NF^*}$, $q_1^{NF^*} = q_2^{NF^*}$, $CS_{m1}^{NF^*} = CS_{m2}^{NF^*}$, $E_{m1}^{NF^*} = E_{m1}^{NF^*}$.

Theorem 3(1) indicates that under a technology licensing model with fixed fees as compensation, the wholesale prices, retail prices, demand quantities, consumer surplus, and carbon emission reduction benefits of both enterprises are equal. This is because Enterprise 2 has achieved technological innovation and reached the same level of technical quality as Enterprise 1 by obtaining technology licensing. Compared to the scenario without technology licensing, this is more advantageous for Enterprise 2, and the increase in product demand is also more conducive to the development of NEVs, thereby better reducing carbon emissions for both corporate and consumer entities.

3(2) When $F > F_1$, $\pi_{m1}^{NF^*} > \pi_{m2}^{NF^*}$; or $\pi_{m1}^{NF^*} < \pi_{m2}^{NF^*}$;

Here, $F_1 = \frac{k\alpha^2(a-(-1+c)e_1p_e)^2}{((-2+c)^2k-2\alpha^2)^2}$.

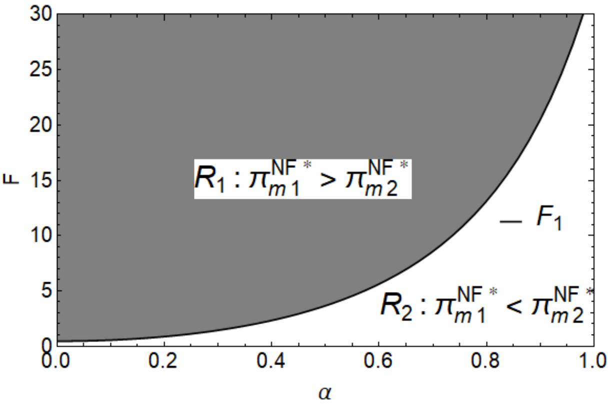

Figure 3. Comparison of Profits Between Two Enterprises in NF Mode.

In Theorem 3(2), it can be concluded that when the fixed fee that Enterprise 2 is required to pay to Enterprise 1 exceeds a certain threshold, Enterprise 1's profit will be higher than that of Enterprise 2. Otherwise, the fixed fee compensation Enterprise 1 receives from licensing technology to Enterprise 2 may not offset the profit compression caused by Enterprise 2's technological advancement, resulting in Enterprise 1's profit being lower than that of Enterprise 2. This suggests that Enterprise 1 should consider the fixed fee and its own earnings when deciding whether to license its technology.

Corollary 3 (1) $\frac{\partial \pi_{m1}^{NF^*}}{\partial F} = 1 > 0$, $\frac{\partial \pi_{m2}^{NF^*}}{\partial F} = -1 < 0$;

(2) $\frac{\partial \theta^{NF^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m1}^{NF^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m2}^{NF^*}}{\partial p_e} > 0$;

(3) $\frac{\partial \theta^{NF^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m1}^{NF^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m2}^{NF^*}}{\partial e_1} > 0$;

Corollary 3 intuitively indicates that under the fixed-fee technology licensing model, the profit of Enterprise 1 is positively correlated with the fixed fee, whereas the profit of Enterprise 2 is negatively correlated with it. Meanwhile, similar to the unit royalty fee model, under this model, the technological level of new energy vehicles, as well as the profits of Enterprise 1 and Enterprise 2, are positively correlated with the carbon emission reduction benefit per unit product sold and the unit carbon trading price.

B. Technology Licensing Model for Competitive Companies with Government Subsidy

In this scenario, the enterprise with advanced technology receives a government subsidy s per unit of vehicles sold.

1) Model under no Technology Licensing with Government Subsidy（GN）

$$\begin{aligned}\pi_{m1}^{GN} &= p_1q_1 - \tfrac{1}{2}k\theta^2 + e_1p_eq_1 + sq_1 \\ &= -\frac{k\theta^2}{2} + (s+p_1)(a+\alpha\theta-p_1+cp_2) \\ &\quad + e_1(a+\alpha\theta-p_1+cp_2)p_e \end{aligned} \tag{7}$$

$$\begin{aligned}\pi_{m2}^{GN} &= p_2q_2 + e_2p_eq_2 \\ &= (a+cp_1-p_2)p_2 + e_2(a+cp_1-p_2)p_e\end{aligned} \tag{8}$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem 4(1) when $k_3 < k < k_4$, $p_1^{GN^*} > p_2^{GN^*}$; or $p_1^{GN^*} > p_2^{GN^*}$;

Here, $k_3 = \frac{2\alpha^2}{(-2+c)^2}$, $k_4 = \frac{4\alpha^2(a+2s-cs-((-2+c)e_1+e_2)p_e)}{(-2+c)^2(2+c)(s+(e_1-e_2)p_e)}$.

(2) $q_1^{GN^*} > q_2^{GN^*}$, $CS_1^{GN^*} > CS_2^{GN^*}$, $E_1^{GN^*} > E_2^{GN^*}$, $\pi_{m1}^{GN^*} > \pi_{m2}^{GN^*}$.

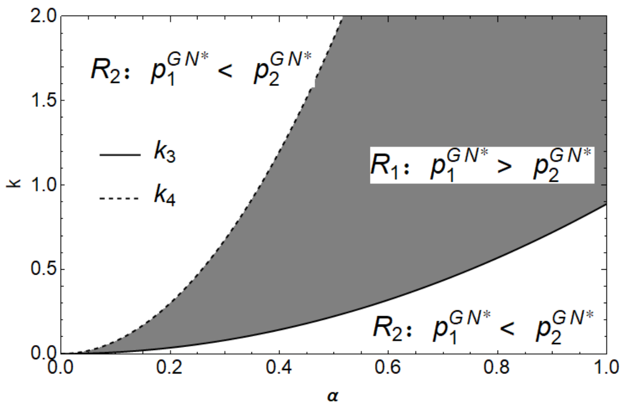

Figure 4. Comparison of Retail Prices Between Two Enterprises in GN Mode.

Compared to Theorem 1, in the no-technology-licensing model with government subsidy, the product prices of both enterprises still need to satisfy certain threshold conditions. Under these conditions, the product price of Enterprise 1 is higher than that of Enterprise 2. Furthermore, the market demand, consumer surplus, and carbon emission reduction benefits of Enterprise 1 are consistently higher than those of Enterprise 2.

Corollary 4(1) $\frac{\partial \theta^{GN^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m1}^{GN^*}}{\partial p_e} > 0$; when $0 < e_2 < -\frac{ce_1}{-2+c^2}$ and $k > \frac{4\alpha^2(-ce_1+e_2)}{(-4+c^2)(ce_1+(-2+c^2)e_2)}$, $\frac{\partial \pi_{m2}^{GN^*}}{\partial p_e} > 0$;

(2) $\frac{\partial \theta^{GN^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m1}^{NN^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m2}^{NN^*}}{\partial e_2} > 0$;

(3) $\frac{\partial \theta^{GN^*}}{\partial s} > 0$, $\frac{\partial \pi_{m1}^{GN^*}}{\partial s} > 0$.

Corollary 4 indicates that an increase in the unit carbon emission reduction benefit and the unit carbon trading price positively impacts the technological level of new energy vehicles (NEVs) and the profit of Enterprise 1. However, Enterprise 2 can only benefit from the increase in these two parameters when the unit carbon emission reduction benefit and the unit carbon trading price meet certain conditions.

Furthermore, calculations reveal that both the technological level and profit of Enterprise 1 are positively correlated with government subsidy.

2) Model with Per-Unit Royalty Technology Licensing with Government Subsidy (Gf)

$$\pi_{m1}^{Gf} = p_1 q_1 - \frac{1}{2} k\theta^2 + e_1 p_e q_1 + f q_2 + s q_1$$
$$= -\frac{k\theta^2}{2} + f(a + \alpha\theta + c p_1 - p_2) + (s + p_1 + e_1 p_e)(a + \alpha\theta - p_1 + c p_2) \quad (9)$$
$$\pi_{m2}^{Gf} = p_2 q_2 + e_1 p_e q_2 - f q_2 + s q_2$$
$$= (a + \alpha\theta + c p_1 - p_2)(s + p_2 + e_1 p_e - f) \quad (10)$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem 5(1) $p_1^{Gf^*} < p_2^{Gf^*}$, $q_1^{Gf^*} > q_2^{Gf^*}$, $CS_1^{Gf^*} > CS_2^{Gf^*}$, $E_1^{Gf^*} > E_1^{Gf^*}$;

(2) when $f_3 < f < f_4$, $\pi_{m1}^{Gf^*} > \pi_{m2}^{Gf^*}$; or $\pi_{m1}^{Gf^*} < \pi_{m2}^{Gf^*}$.

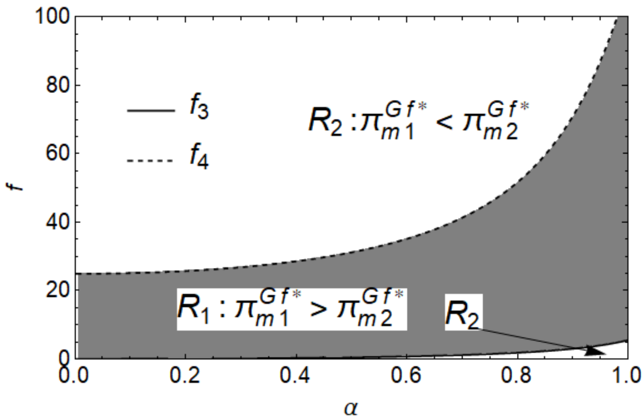

Figure 5. Comparison of Profits Between Two Enterprises in Gf Mode.

Corollary 5(1) when $k > -\frac{(12+c(4+c+c^2))\alpha^2}{2(-1+c)(8+c^2)}$ and $0 < f < -\frac{(8+c^3)k(a+s-cs-(-1+c)e_1p_e)}{2(-1+c)(8+c^2)k+(12+c(4+c+c^2))\alpha^2}$ or when $\frac{2\alpha^2}{(-2+c)^2} < k \leq -\frac{(12+c(4+c+c^2))\alpha^2}{2(-1+c)(8+c^2)}$, $\frac{\partial \pi_{m1}^{Nf^*}}{\partial f} > 0$; when $k > -\frac{(-4+c)\alpha^2}{2(-2+c)(-1+c)}$ and $0 < f < \frac{(-4+c^2)k(-a+(-1+c)s+(-1+c)e_1p_e)}{(1+c)(2(-2+c)(-1+c)k+(-4+c)\alpha^2)}$时$\frac{\partial \pi_{m2}^{Nf^*}}{\partial f} < 0$;

(2) $\frac{\partial \theta^{Gf^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m1}^{Nf^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m2}^{Nf^*}}{\partial p_e} > 0$;

(3) $\frac{\partial \theta^{Gf^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m1}^{f\ *}}{\partial e_1} > 0$, $\frac{\partial \pi_{m2}^{Nf^*}}{\partial e_1} > 0$;

(4) $\frac{\partial \theta^{Gf^*}}{\partial s} > 0$, $\frac{\partial \pi_{m1}^{Gf^*}}{\partial s} > 0$, $\frac{\partial \pi_{m2}^{Gf^*}}{\partial s} > 0$.

Under the unit royalty fee technology licensing model with government subsidy, when the technological cost coefficient k and the unit licensing fee fall within a specific range, an increase in the unit licensing fee enhances the profit of Enterprise 1 while reducing that of Enterprise 2. Additionally, the technological level of new energy vehicles (NEVs) and the profits of both enterprises are positively correlated with unit carbon trading price, unit carbon emission reduction benefit, and the unit subsidy.

3) Model with Fixed-Fee Technology Licensing under No Government Subsidy (GF)

$$\pi_{m1}^{GF} = p_1 q_1 - \frac{1}{2} k\theta^2 + e_1 p_e q_1 + F + s q_1$$
$$= (s + p_1 + e_1 p_e)(a + \alpha\theta - p_1 + c p_2 + F - \frac{k\theta^2}{2} \quad (11)$$
$$\pi_{m2}^{GF} = p_2 q_2 + e_1 p_e q_2 - F + s q_2$$
$$= -F + (s + p_2 + e_1 p_e)(a + \alpha\theta + c\, p_1 - p_2) \quad (12)$$

Based on the above model, we have derived the following theorems and corollaries through equilibrium analysis (all proofs are provided in the Appendix)

Theorem 6(1) $p_1^{GF^*} = p_2^{GF^*}$, $q_1^{GF^*} = q_2^{GF^*}$, $CS_1^{GF^*} = CS_2^{GF^*}$, $E_1^{GF^*} = E_1^{GF^*}$.

(2) When $F > F_2$, $\pi_{m1}^{GF^*} > \pi_{m2}^{GF^*}$; or $\pi_{m1}^{GF^*} < \pi_{m2}^{GF^*}$.

Here, $F_2 = \frac{k\alpha^2(a+s-cs-(-1+c)e_1p_e)^2}{((-2+c)^2k-2\alpha^2)^2}$.

Similar to the fixed-fee technology licensing model without government subsidy, under the government subsidy (GF) model, the product prices, market demand, consumer surplus, and carbon emission reduction benefits of both companies remain identical.

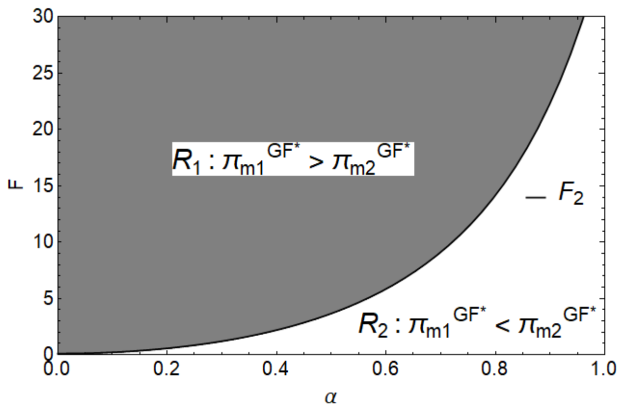

Figure 6. Comparison of Profits Between Two Enterprises in GF Mode.

Corollary 6(1) $\frac{\partial \pi_{m1}^{GF^*}}{\partial F} = 1 > 0$, $\frac{\partial \pi_{m2}^{GF^*}}{\partial F} = -1 < 0$;

(2) $\frac{\partial \theta^{GF^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m1}^{GF^*}}{\partial p_e} > 0$, $\frac{\partial \pi_{m2}^{GF^*}}{\partial p_e} > 0$;

(3) $\frac{\partial \theta^{GF^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m1}^{GF^*}}{\partial e_1} > 0$, $\frac{\partial \pi_{m2}^{GF^*}}{\partial e_1} > 0$;

(4) $\frac{\partial \theta^{GF^*}}{\partial s} > 0$, $\frac{\partial \pi_{m1}^{GF^*}}{\partial s} > 0$, $\frac{\partial \pi_{m2}^{GF^*}}{\partial s} > 0$.

Corollary 6 intuitively indicates that under the fixed-fee technology licensing model with government subsidy, the profit of Enterprise 1 is positively correlated with the fixed fee, whereas the profit of Enterprise 2 is negatively correlated with the fixed fee. Furthermore, the unit carbon emission reduction benefit, unit carbon trading price, and unit government subsidy all play a positive role in enhancing the technological level of NEVs, as well as promoting the market demand, profits, carbon emission reduction benefits, and consumer surplus of both companies.

C. Comparison of different models with and without government subsidy

Theorem 7. $\theta^{GN^*} > \theta^{NN^*}$, $\theta^{Gf^*} > \theta^{Nf^*}$, $\theta^{GF^*} > \theta^{NF^*}$

Based on this, it can be observed that under various technology licensing models with government subsidy, the technological level of new energy vehicles (NEVs) is higher than in scenarios without government subsidy. This phenomenon may be attributed to the fact that government subsidy provides additional financial support to enterprises, reducing the marginal costs of technology research and application, thereby incentivizing greater investment in advanced technologies. Furthermore, government subsidy may enhance the market competitiveness of companies, encouraging them to more actively adopt efficient and low-carbon technologies, which further elevates the overall technological level.

Theorem 8(1) When $\frac{2\alpha^2}{4-4c+c^2} < k < -\frac{4\alpha^2}{-4+c^2}$, $p_1^{GN^*} > p_1^{NN^*}, p_1^{Gf^*} > p_1^{Nf^*}, p_1^{GF^*} > p_1^{NF^*}$;

(2) $q_1^{GN^*} > q_1^{NN^*}, q_1^{GF^*} > q_1^{NF^*}$, *and when* $s > s_1$, $q_1^{Gf^*} > q_1^{Nf^*}$;

Here, $s_1 = \frac{(1+c)f(-(-2+c)^2k+2\alpha^2)}{(-4+c^2)k}$.

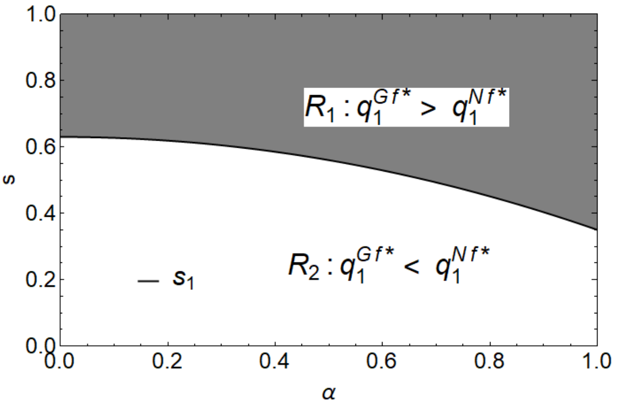

Figure 7. Comparison of Demand for Enterprise 1 under Gf Mode and Nf Mode.

For Enterprise 1, there exists a threshold range for the technological cost coefficient k When k falls within this range, the product price of NEVs with government subsidy is higher than that without subsidy. However, only when the government subsidy s exceeds a certain threshold will the product demand under the unit royalty fee model with subsidy be higher than that without subsidy. In contrast, under the no-technology-licensing model and the fixed-fee technology licensing model, there are no such threshold conditions, meaning that government subsidy always leads to superior outcomes such as higher demand or profits.

(3) $\pi_{m1}^{GN^*} > \pi_{m1}^{NN^*}, \pi_{m1}^{Gf^*} > \pi_{m1}^{Nf^*}, \pi_{m1}^{GF^*} > \pi_{m1}^{NF^*}$.

Through comparative analysis, we find that for Enterprise 1, regardless of the technology licensing mode adopted, its profit under government subsidy consistently outperforms the scenario without subsidy. This indicates that government subsidy invariably benefits Enterprise 1, thereby incentivizing innovation in the new energy vehicle sector.

Theorem 9(1) $CS_1^{GN^*} > CS_1^{NN^*}; CS_1^{GF^*} > CS_1^{NF^*}$;

When $\frac{2\alpha^2}{(-2+c)^2} < k \le \frac{(2+c)\alpha^2}{c(2-3c+c^2)}$, $CS_1^{Gf^*} > CS_1^{Nf^*}$;

when $k > \frac{(2+c)\alpha^2}{c(2-3c+c^2)}$, we have

$$\begin{cases} CS_1^{Gf^*} > CS_1^{Nf^*}, if\ 0 < f \le \frac{(-2+c)(-1+c)(2+c)ke_1p_e}{(1+c)((-2+c)(-1+c)ck-(2+c)\alpha^2)} \\ CS_1^{Gf^*} > CS_1^{Nf^*}, if\ s > s_2, and\ f > \frac{(-2+c)(-1+c)(2+c)ke_1p_e}{(1+c)((-2+c)(-1+c)ck-(2+c)\alpha^2)} \end{cases}.$$

(2) $E_1^{GN^*} > E_1^{NN^*}; E_1^{Gf^*} > E_1^{Nf^*}; E_1^{GF^*} > E_1^{NF^*}$.

Here, $s_2 = \frac{2(a+(1+c)f(\frac{(-1+c)c}{2+c}+\frac{\alpha^2}{2k-ck}))}{-1+c} - 2e_1p_e$.

Theorem 9(1) analytically demonstrates that in both no-licensing and fixed-fee licensing modes, Enterprise 1's operations under government subsidy generate higher consumer surplus than non-subsidized scenarios. For per-unit royalty licensing, the advantage of subsidies depends on meeting threshold requirements for both royalty fees and subsidy amounts: when technology cost coefficients are low, government subsidy unconditionally yield greater consumer surplus for Enterprise 1; whereas under high-cost conditions, specific quantitative relationships between per-unit subsidy and licensing fees must be satisfied to ensure the dominance of subsidized consumer surplus.

Theorem 9(2) further proves that for Enterprise 1, carbon emission reduction benefits under all technology licensing modes strictly dominate non-subsidized scenarios when government subsidy are implemented. These findings provide robust theoretical justification for policymakers to intensify R&D support for innovative new energy enterprises, as such subsidization mechanisms simultaneously promote industrial advancement and enhance societal environmental benefits through dual channels of consumer welfare optimization and environmental externality internalization.

Theorem 10 (1) When $\frac{2\alpha^2}{4-4c+c^2} < k < -\frac{4\alpha^2}{-4+c^2}$, $p_2^{GN^*} > p_2^{NN^*}, p_2^{Gf^*} > p_2^{Nf^*}, p_2^{GF^*} > p_2^{NF^*}$

(2) $q_2^{Gf^*} > q_2^{Nf^*}, q_2^{GF^*} > q_2^{NF^*}$; and when $\frac{2\alpha^2}{4-4c+c^2} < k < -\frac{4\alpha^2}{-4+c^2}$, $q_2^{GN^*} > q_2^{NN^*}$;

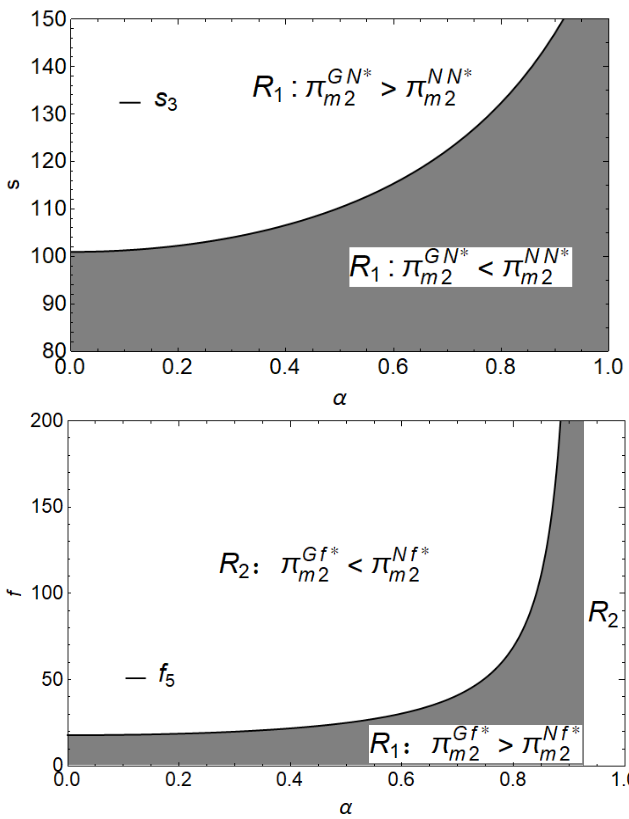

Figure 8. Comparison of Enterprise 2's Profits with and without Government Subsidy

Theorems 10(1) and 10(2) demonstrate that for Enterprise 2, there exists a threshold range for the technology cost coefficient k wherein, under government subsidy, Enterprise 2's product pricing under various technology licensing modes outperforms the non-subsidized scenario. Furthermore, under both per-unit royalty licensing and fixed-fee licensing modes, Enterprise 2's demand with government subsidy consistently exceeds that without subsidy. However, this does not universally hold for the no-licensing mode, which requires k to fall within a specific threshold range to achieve more favorable demand conditions under government subsidy.

(3) When $k > -\frac{4\alpha^2}{-4+c^2}$ or $k < -\frac{4\alpha^2}{(-2+c)(2+c)^2}$, we have

$$\begin{cases} \pi_{m2}^{GN^*} > \pi_{m2}^{NN^*}, if\ s > s_3\,, \frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2} + e_2 \geq 0 \\ \pi_{m2}^{GN^*} > \pi_{m2}^{NN^*}, if\ s > s_3\,, \frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2} + e_2 < 0 \\ \quad and\ p_e < \frac{a((-2+c)(2+c)^2k+4\alpha^2)}{c((-4+c^2)k+4\alpha^2)e_1+((8-6c^2+c^4)k-4\alpha^2)e_2} \end{cases}$$

When $k > -\frac{(-4+c)\alpha^2}{2(2-3c+c^2)}$ and $f < f_5$, $\pi_{m2}^{Gf^*} > \pi_{m2}^{Nf^*}$; $\pi_{m2}^{GF^*} > \pi_{m2}^{NF^*}$.

Here, $s_3 = \frac{-2(c((-4+c^2)k+4\alpha^2)e_1+((8-6c^2+c^4)k-4\alpha^2)e_2)p_e}{c((-4+c^2)k+4\alpha^2)} + \frac{2a(-2+c)(2+c)^2k+8a\alpha^2}{c((-4+c^2)k+4\alpha^2)}$, $f_5 = \frac{(-4+c^2)k(-2a+(-1+c)s+2(-1+c)e_1p_e)}{2(1+c)(2(-2+c)(-1+c)k+(-4+c)\alpha^2)}$.

Theorem 10(3) compares Enterprise 2's profits with and without government subsidy. Under the no-licensing mode, Enterprise 2's post-subsidy profit exceeds the non-subsidized case only when: (1) the subsidy falls within a certain threshold range, and (2) Enterprise 2's unit carbon reduction and the market carbon trading price satisfy specific conditions. For the per-unit royalty licensing mode, Enterprise 2 achieves higher profits under subsidy only if the unit licensing fee remains below a certain threshold. This is because excessively high licensing fees may deter Enterprise 2 from seeking technology authorization even with subsidy, potentially reducing profits. Finally, under fixed-fee licensing, Enterprise 2's subsidized profits invariably dominate the no subsidized scenario.

Theorem 11(1) When $k < -\frac{4\alpha^2}{(-2+c)(2+c)^2}$, if $s > s_4$, $\frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2} + e_2 < 0\ and\ p_e \leq \frac{a((-2+c)(2+c)^2k+4\alpha^2)}{c((-4+c^2)k+4\alpha^2)e_1+((8-6c^2+c^4)k-4\alpha^2)e_2}$, $CS_2^{GN^*} > CS_2^{NN^*}$; $CS_2^{GF^*} > CS_2^{NF^*}$.

When $\frac{2\alpha^2}{(-2+c)^2} < k \leq \frac{(2+c)\alpha^2}{c(2-3c+c^2)}$, $CS_2^{Gf^*} > CS_2^{Nf^*}$; when $k > \frac{(2+c)\alpha^2}{c(2-3c+c^2)}$, we have

$$\begin{cases} CS_2^{Gf^*} > CS_2^{Nf^*}, \\ if\ 0 < p_e < \frac{(1+c)f(2(2-3c+c^2)k+(-4+c)\alpha^2)}{(4-4c-c^2+c^3)ke_1} \\ CS_2^{Gf^*} > CS_2^{Nf^*}, if\ s > s_5\,, and \\ p_e \geq \frac{(1+c)f(2(2-3c+c^2)k+(-4+c)\alpha^2)}{(4-4c-c^2+c^3)ke_1} \end{cases}$$

Here, $s_4 = \frac{2(a+(1+c)f(\frac{(-1+c)c}{2+c}+\frac{\alpha^2}{2k-ck}))}{-1+c} - 2e_1p_e$;

$s_5 = \frac{2a}{-1+c} + \frac{4(1+c)f}{2+c} + \frac{2(-4+c)(1+c)f\alpha^2}{(-2+c)(-1+c)(2+c)k} - 2e_1p_e$.

(2) $E_2^{Gf^*} > E_2^{Nf^*}$, $E_2^{GF^*} > E_2^{NF^*}$;

When $\frac{8\alpha^2}{(-4+c^2)^2} < k \leq \frac{4\alpha^2}{-4+c^2}$, we have $E_2^{GN^*} > E_2^{NN^*}$; When $k > -\frac{4\alpha^2}{-4+c^2}$ or $k < -\frac{4\alpha^2}{(-2+c)(2+c)^2}$, we have

$$\begin{cases} E_2^{GN^*} > E_2^{NN^*}, if\ s < s_6\,, \frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2} + e_2 \geq 0 \\ and\ p_e < \frac{a((-2+c)(2+c)^2k+4\alpha^2)}{c((-4+c^2)k+4\alpha^2)e_1+((8-6c^2+c^4)k-4\alpha^2)e_2} \\ E_2^{GN^*} > E_2^{NN^*}, if\ s < s_6\,, \frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2} + e_2 < 0 \end{cases}$$

Here, $s_6 = \frac{(e_1-e_2)(a(-2+c)(2+c)^2k+4a\alpha^2)}{c((-4+c^2)k+4\alpha^2)e_1} + \frac{-(e_1-e_2)(c((-4+c^2)k+4\alpha^2)e_1+((8-6c^2+c^4)k-4\alpha^2)e_2)p_e}{c((-4+c^2)k+4\alpha^2)e_1}$.

For Enterprise 1, under no-licensing mode and per-unit royalty licensing mode, Enterprise 2's subsidized consumer surplus exceeds the non-subsidized level only when the technology cost coefficient k, per-unit government subsidy s, per-unit carbon emission reduction, and per-unit carbon trading price simultaneously satisfy specific threshold conditions. In contrast, the fixed-fee licensing mode demonstrates unconditional superiority, where Enterprise 2's consumer surplus under government subsidy invariably exceeds that in the non-subsidized scenario.

Theorem 11(2) demonstrates that under both per-unit royalty licensing and fixed-fee licensing modes, Enterprise 2's operations with government subsidy generate superior carbon emission reduction benefits compared to non-subsidized scenarios. For the no-licensing mode, however, the advantage of government subsidy is conditional upon satisfying specific threshold requirements for the per-unit subsidy amount, Enterprise 2's unit carbon reduction capability, and the market carbon trading price. Only when these parameters meet the established threshold conditions does the subsidized scenario yield greater carbon reduction benefits than the non-subsidized case.

V. Numerical Analysis

This section employs numerical simulation to compare the effects of consumers' preferences for new energy low-carbon technology on product prices, demand, and profits under different scenarios and technology licensing models. Specifically, the parameters are assigned as follows: $a = 10, c = 0.5, k = 2, \alpha = 0.8, f = 0.7, F = 15, s = 1$, $p_e = 0.6, e_1 = 0.6, e_2 = 0.4$.

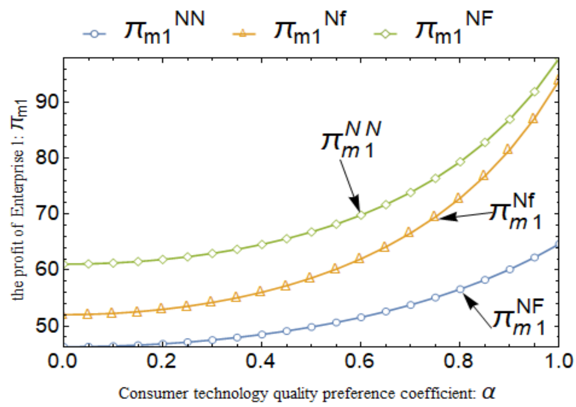

Figure 9. The impact of α on the profit of Enterprise 1 without government subsidy.

Figure 9 demonstrates that Enterprise 1's profitability maintains a positive correlation with consumers' preference for low-carbon technology in the absence of government subsidy. The growth trajectory remains consistent across all licensing models, though the absolute profit levels differ significantly between different approaches.

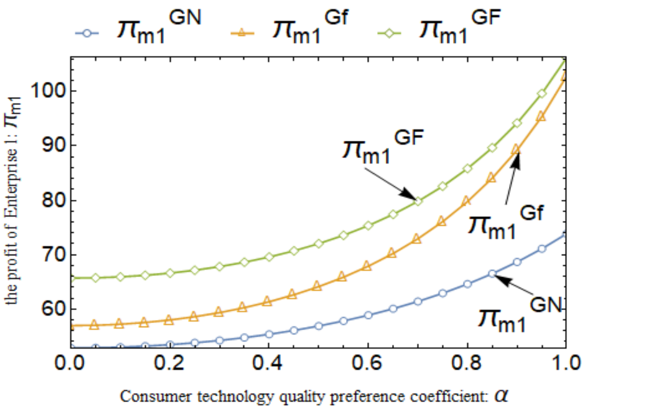

Figure 10. The impact of α on the profit of Enterprise 1 with government subsidy.

Figure 10 reveals that this positive relationship persists when government subsidies are introduced. Moreover, under the parameter assumptions of the case analysis in this section, fixed-fee technology licensing is always optimal, followed by per-unit royalty technology licensing, which is superior to the no-technology-licensing model.

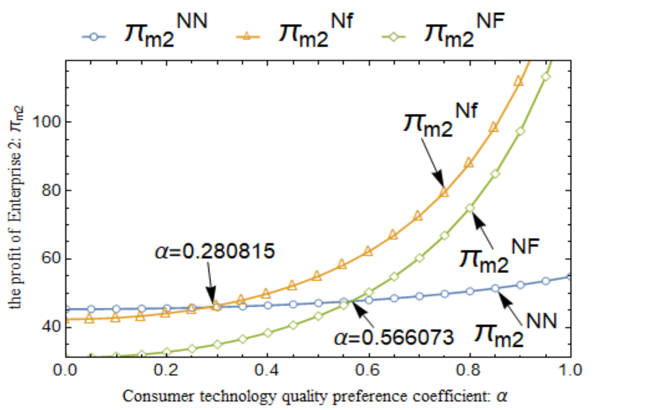

Figure11. The impact of α on the profit of Enterprise 2 without government subsidy.

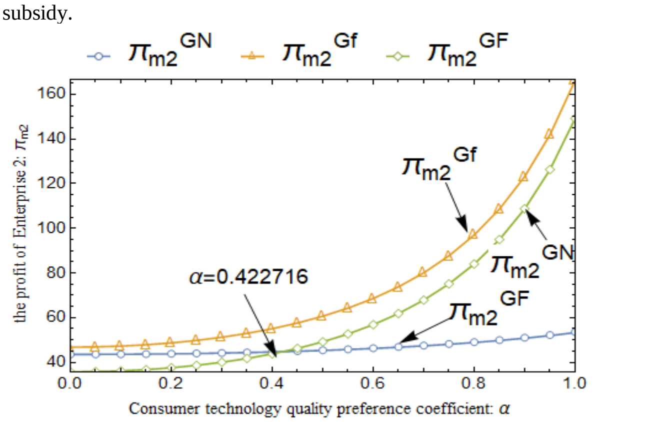

Figure12. The impact of α on the profit of Enterprise 2 with government subsidy.

For Enterprise 2 (Figures 11–12), fixed-fee licensing yields the highest profit when consumers' low-carbon preference is low. As α increases and $\alpha > 0.280815$, the per-unit royalty technology licensing consistently takes the optimal position. When $\alpha > 0.566073$, the fixed-fee technology licensing secures the second position in terms of profit. In Figure 12, the scenario is slightly different, the per-unit royalty licensing is always optimal for Enterprise 2. However, there exists a threshold where, when $\alpha > 0.422716$, the fixed-fee technology licensing model yields higher profits for Enterprise 2 than the no-technology- licensing model.

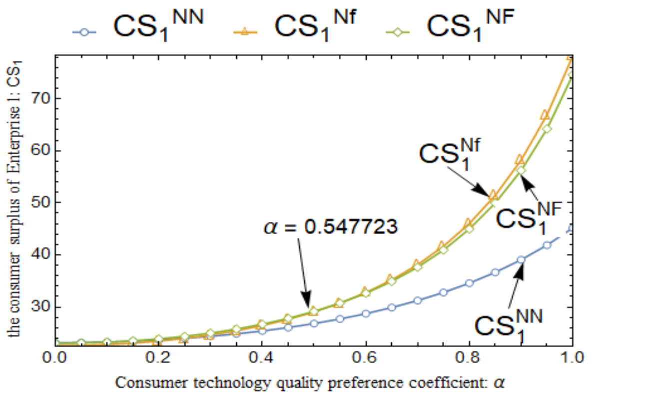

Figure 13. The impact of α on the consumer surplus of Enterprise 1 without government subsidy.

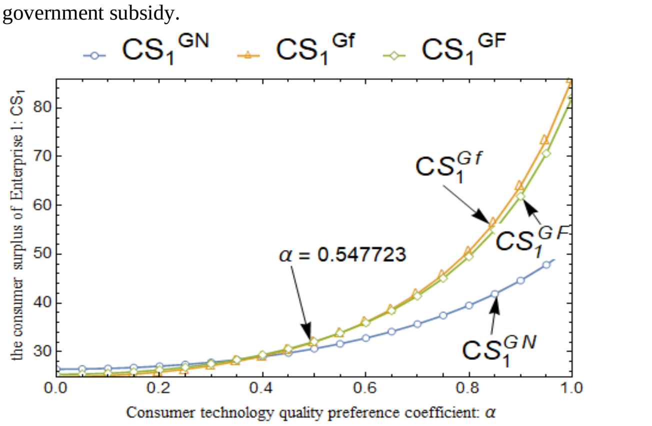

Figure 14. The impact of α on the consumer surplus of Enterprise 1 with government subsidy.

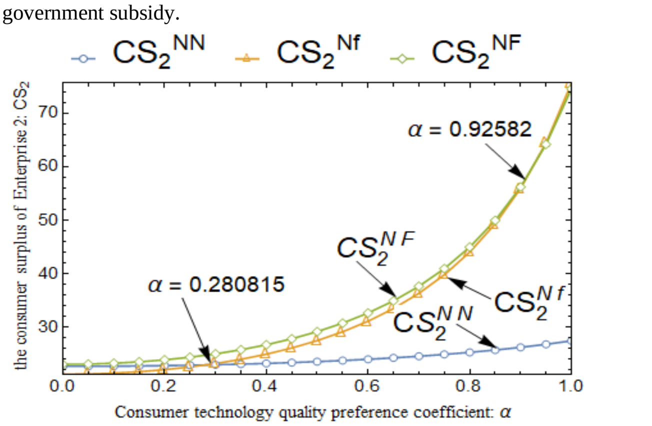

Figure 15. The impact of α on the consumer surplus of Enterprise 2 without government subsidy.

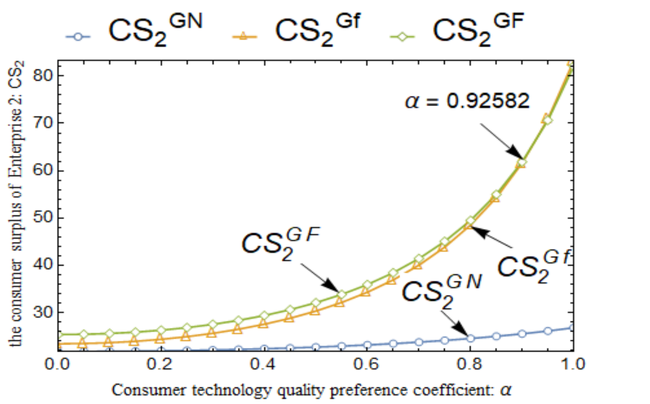

Figure 16. The impact of α on the consumer surplus of Enterprise 2 with government subsidy.

From the figure13-16, it can be observed that the consumer surplus of both Enterprise 1 and Enterprise 2 increases as consumers' preference for low-carbon technology rises. Under the numerical assumptions of this section, it is evident that the consumer surplus of both enterprises under government subsidy is greater than that without subsidy. Moreover, there exists a threshold for consumer technology preference (greater than 0.547723), beyond which the consumer surplus of Enterprise 1 under per-unit royalty licensing begins to exceed that of Enterprise 2. Similarly, Enterprise 2 also exhibits a threshold, beyond which the consumer surplus under per-unit royalty licensing becomes more favorable.

Notably, in the absence of subsidy, for different licensing modes, when consumer technology preference is relatively low, the consumer surplus of Enterprise 2 without technology licensing can even surpass that under per-unit royalty licensing.

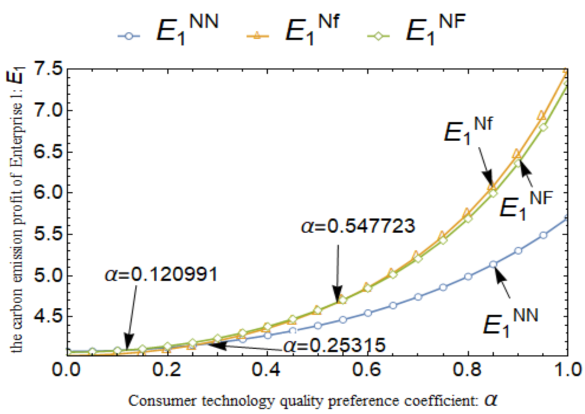

Figure 17. The impact of α on the carbon emission reduction of Enterprise 1 without government subsidy.

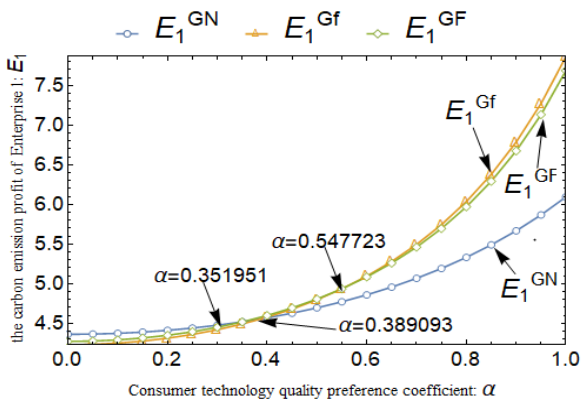

Figure 18. The impact of α on the carbon emission reduction of Enterprise 1 with government subsidy.

Regarding carbon emission reduction benefits and consumer surplus, their increasing trends are similar—both rise with the growth of consumers' technology preference.

For Enterprise 1, it can be observed that, compared to the scenario without government subsidy, the carbon emission reduction benefits under government subsidy are generally higher. Additionally, the threshold for adopting the no-licensing mode becomes less stringent (i.e., the threshold value increases), indicating that under government subsidy, the no-licensing mode may outperform the other two licensing modes within an appropriate range.

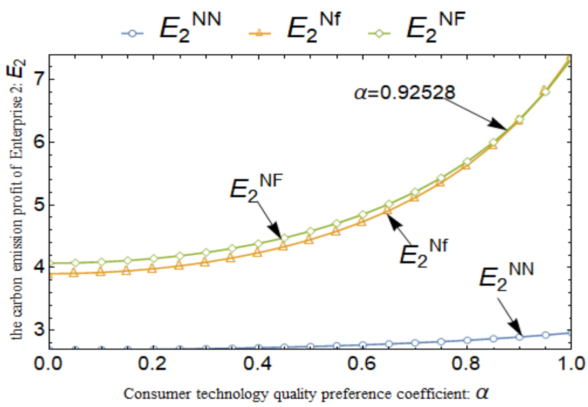

Figure 19. The impact of α on the carbon emission reduction of Enterprise 2 without government subsidy.

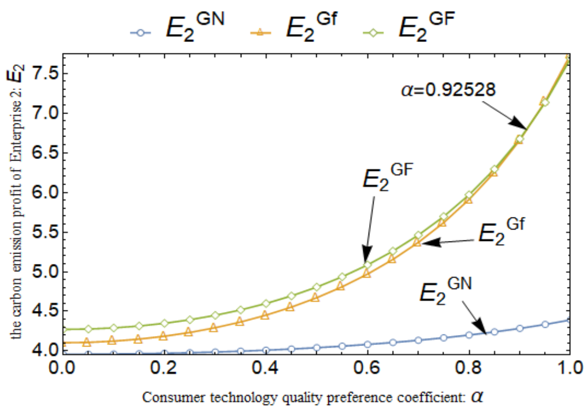

Figure 20. The impact of α on the carbon emission reduction of Enterprise 2 with government subsidy.

For Enterprise 2, it is evident that under the given numerical assumptions in this section, the carbon emission reduction benefits post-subsidy is significantly greater than those before the subsidy. This may be attributed to government subsidy incentivizing Enterprise 2 to actively pursue technology licensing, thereby increasing new energy sales and enhancing carbon emission reduction benefits. Furthermore, calculations reveal the existence of a threshold—beyond this threshold, Enterprise 2's carbon emission reduction benefits under per-unit royalty licensing surpass those under fixed-fee licensing.

VI. CONCLUSIONS

This study investigates the technology licensing strategies between two duopoly enterprises in the new energy vehicle (NEV) supply chain, while accounting for government subsidy. Game-theoretic modeling and comparative analysis are employed to assess how consumers' low-carbon preferences, government subsidy, and technology costs influence enterprise decision-making. The findings are as follows:

First, across all licensing strategies and subsidy scenarios, Enterprise 1 demonstrates sustained competitive advantages relative to Enterprise 2, particularly in market demand, emission reduction benefits, and consumer surplus. A price premium is achieved by Enterprise 1 when the technology cost coefficient k falls below a critical threshold. Under per-unit royalty licensing, Enterprise 1 is shown to maintain consistently lower selling prices compared to Enterprise 2, while simultaneously exhibiting greater NEV demand, superior emission reduction benefits, and higher consumer surplus. Fixed-fee licensing results in identical product pricing, demand levels, emission reduction benefits, and consumer surplus between the two enterprises.

Second, concerning parameter effects on enterprise performance: Our analysis reveals that consumers' preference for low-carbon technology exerts a consistently positive influence on both enterprises' profitability, regardless of subsidy conditions. The government subsidy demonstrates generally favorable impacts, enhancing selling prices, market demand, and profit margins for both firms across most scenarios. However, we identify a notable exception: in the no-licensing scenario with government subsidy, Enterprise 2's profits do not increase with subsidy levels, failing to benefit from increased government support.

Third, the research findings reveal significant differential effects of government subsidy on supply chain participants. As the technology holder, Enterprise 1 demonstrates unconditional benefits from subsidy across all licensing regimes, manifested as significant profit improvement, amplified returns on investment, and further strengthened market dominance. In contrast, Enterprise 2's subsidy benefits are strictly conditional, requiring simultaneous satisfaction of threshold conditions for key parameters including technology cost coefficient and per-unit subsidy level.

Additionally, our analysis further reveals that government subsidy significantly enhance NEV technological advancement. In most cases, the selling prices and demand From TABLE II, under the scenario NN, Analytical results for NEVs under the three technology licensing modes are more favorable when government subsidy are present. Specifically, the positive effects of government subsidy can still be achieved when the technology cost coefficient k and government subsidy s meet certain thresholds.

The conclusions of this study provide important theoretical foundations and practical guidance for decision-making in the NEV supply chain, government policy formulation, and consumer behavior. Enterprises should choose appropriate technology licensing strategies based on their technological advantages and market competition environment, and fully leverage consumers' low-carbon preferences and government subsidy policies to enhance competitiveness and market share. The government should promote the sustainable development of the NEV industry through differentiated subsidy policies and effective technology licensing mechanisms. Both enterprises and government should work together to achieve a balance between market competition and social benefits, driving the high-quality development of the NEV industry.

APPENDIX

Appendix A.

Appendix A presents the equilibrium solutions under different technology licensing models, as detailed in Table II-VII below.

TABLE II
OPTIMAL EQUILIBRIUM SOLUTION UNDER NN

	Optimal Equilibrium Solution
Demand	$q_1^{NN*} = \frac{(-4+c^2)k(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{(-4+c^2)^2k-8\alpha^2}$
	$q_2^{NN*} = \frac{-a(-2+c)(2+c)^2k-4a\alpha^2+A_1p_e}{(-4+c^2)^2k-8\alpha^2}$
Retail Price	$p_1^{NN*} = \frac{2\left((-4+c^2)k+4\alpha^2\right)e_1p_e}{(-4+c^2)^2k-8\alpha^2} - \frac{(-4+c^2)k(a(2+c)-ce_2p_e)}{(-4+c^2)^2k-8\alpha^2}$
	$p_2^{NN*} = \frac{-a(-2+c)(2+c)^2k-4a\alpha^2}{(-4+c^2)^2k-8\alpha^2} + \frac{A_1p_e}{(-4+c^2)^2k-8\alpha^2}$
Technology Level	$\theta^{NN*} = \frac{4\alpha(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{-(-4+c^2)^2k+8\alpha^2}$
Profit	$\pi_{m1}^{NN*} = \frac{k(a(2+c)-((-2+c^2)e_1+ce_2)p_e)^2}{(-4+c^2)^2k-8\alpha^2}$
	$\pi_{m2}^{NN*} = \frac{(a(-2+c)(2+c)^2k+4a\alpha^2-A_1p_e)^2}{((-4+c^2)^2k-8\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{NN*} = \frac{(-4+c^2)^2k^2(a(2+c)-((-2+c^2)e_1+ce_2)p_e)^2}{2((-4+c^2)^2k-8\alpha^2)^2}$
	$CS_{m2}^{NN*} = \frac{\left(a(-2+c)(2+c)^2k+4a\alpha^2-A_1p_e\right)^2}{2((-4+c^2)^2k-8\alpha^2)^2}$
Carbon Emission	$E_{m1}^{NN*} = \frac{(-4+c^2)ke_1(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{(-4+c^2)^2k-8\alpha^2}$
	$E_{m2}^{NN*} = \frac{e_2(-a(-2+c)(2+c)^2k-4a\alpha^2+A_1p_e}{(-4+c^2)^2k-8\alpha^2}$

Here, $A_1 = c((-4+c^2)k+4\alpha^2)e_1 + ((8-6c^2+c^4)k-4\alpha^2)e_2$,

TABLE III
OPTIMAL EQUILIBRIUM SOLUTION UNDER Nf

	Optimal Equilibrium Solution
Demand	$q_1^{Nf*} = \frac{-A_2+(1+c)(2+c)f\alpha^2+A_5}{(2+c)((-2+c)^2k-2\alpha^2)}$
	$q_2^{Nf*} = \frac{-A_2-(-4+c)(1+c)f\alpha^2+A_5}{(2+c)((-2+c)^2k-2\alpha^2)}$
Retail Price	$p_1^{Nf*} = \frac{(2+c)\left((-2+c)k+2\alpha^2\right)e_1p_e}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{-(-2+c)(a(2+c)+3cf)k-(-2+c+c^2)f\alpha^2}{(2+c)((-2+c)^2k-2\alpha^2)}$
	$p_2^{Nf*} = \frac{-A_2-(-1+c)cf\alpha^2}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{(2+c)((-2+c)k+2\alpha^2)e_1p_e}{(2+c)((-2+c)^2k-2\alpha^2)}$
Technology level	$\theta^{Nf*} = \frac{-2(-2+c+c^2)e_1p_e)}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{\alpha(2a(2+c)+(1+c)(4+(-2+c)c)f)}{(2+c)((-2+c)^2k-2\alpha^2)}$
Profit	$\pi_{m1}^{Nf*} = \frac{2a^2(2+c)^2k+2a(8+8c+c^3+c^4)fk}{2(2+c)^2((-2+c)^2k-2\alpha^2)} + \frac{(1+c)f^2A_3+2(-2+c+c^2)ke_1p_eA_4}{2(2+c)^2((-2+c)^2k-2\alpha^2)}$
	$\pi_{m2}^{Nf*} = \frac{(A_2+(-4+c)(1+c)f\alpha^2-A_5)^2}{(2+c)^2((-2+c)^2k-2\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{Nf*} = \frac{(-A_2+(1+c)(2+c)f\alpha^2+A_5)^2}{2(2+c)^2((-2+c)^2k-2\alpha^2)^2}$
	$CS_{m2}^{Nf*} = \frac{(A_2+(-4+c)(1+c)f\alpha^2-A_5)^2}{2(2+c)^2((-2+c)^2k-2\alpha^2)^2}$
Carbon Emission	$E_{m1}^{Nf*} = \frac{e_1\left(-A_2+(1+c)(2+c)f\alpha^2+A_5\right)}{(2+c)((-2+c)^2k-2\alpha^2)}$
	$E_{m2}^{Nf*} = \frac{e_1(-A_2-(-4+c)(1+c)f\alpha^2+A_5)}{(2+c)((-2+c)^2k-2\alpha^2)}$

.

Here, $A_2 = (-2+c)(a(2+c)+c(-1+c^2)f)k$,
$A_3 = 2(-1+c)(8+c^2)k + (12+c(4+c+c^2))\alpha^2$,
$A_4 = -2a(2+c) - (1+c)(4+(-2+c)c)f + (-2+c+c^2)e_1p_e$,
$A_5 = (-2+c)(-1+c)(2+c)ke_1p_e$

TABLE IV
OPTIMAL EQUILIBRIUM SOLUTION UNDER NF

	Optimal Equilibrium Solution
Demand	$q_1^{NF^*} = q_2^{NF^*} = \frac{(-2+c)k(-a+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$
Retail Price	$p_1^{NF^*} = p_2^{NF^*} = \frac{-a(-2+c)k+((-2+c)k+2\alpha^2)e_1p_e}{(-2+c)^2k-2\alpha^2}$
Technology level	$\theta^{NF^*} = \frac{2\alpha(a-(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$
Profit	$\pi_{m1}^{NF^*} = \frac{a^2k+(-2+c)^2Fk-2F\alpha^2}{(-2+c)^2k-2\alpha^2} + \frac{(-1+c)ke_1p_e(-2a+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$ $\pi_{m2}^{NF^*} = \frac{a^2(-2+c)^2k^2-F\left((-2+c)^2k-2\alpha^2\right)^2}{((-2+c)^2k-2\alpha^2)^2} + \frac{(-2+c)^2(-1+c)k^2e_1p_e(-2a+(-1+c)e_1p_e)}{((-2+c)^2k-2\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{NF^*} = CS_{m2}^{NF^*} = \frac{(-2+c)^2k^2(a-(-1+c)e_1p_e)^2}{2((-2+c)^2k-2\alpha^2)^2}$
Carbon Emission	$E_{m1}^{NF^*} = E_{m2}^{NF^*} = \frac{(-2+c)ke_1(-a+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$

TABLE V
OPTIMAL EQUILIBRIUM SOLUTION UNDER GN

	Optimal Equilibrium Solution
Demand	$q_1^{GN^*} = \frac{(-4+c^2)kB_1}{(-4+c^2)^2k-8\alpha^2}$ $q_2^{GN^*} = \frac{-B_2+A_1p_e}{(-4+c^2)^2k-8\alpha^2}$
Retail Price	$p_1^{GN^*} = \frac{-(-4+c^2)k(a(2+c)-2s)+8s\alpha^2}{(-4+c^2)^2k-8\alpha^2} + \frac{(2((-4+c^2)k+4\alpha^2)e_1+c(-4+c^2)ke_2)p_e}{(-4+c^2)^2k-8\alpha^2}$ $p_2^{GN^*} = \frac{-B_2+\left(c\left((-4+c^2)k+4\alpha^2\right)e_1\right)p_e}{(-4+c^2)^2k-8\alpha^2} \frac{2((-4+c^2)k+2\alpha^2)e_2)p_e}{(-4+c^2)^2k-8\alpha^2}$
Technology Level	$\theta^{GN^*} = \frac{4\alpha B_1}{-(-4+c^2)^2k+8\alpha^2}$
Profit	$\pi_{m1}^{GN^*} = \frac{k{B_1}^2}{(-4+c^2)^2k-8\alpha^2}$ $\pi_{m2}^{GN^*} = \frac{(B_2-A_1p_e)^2}{((-4+c^2)^2k-8\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{GN^*} = \frac{(-4+c^2)^2k^2{B_1}^2}{2((-4+c^2)^2k-8\alpha^2)^2}$ $CS_{m2}^{GN^*} = \frac{((-4+c^2)k(a(2+c)-cs)+4(a-cs)\alpha^2-A_1p_e)^2}{2((-4+c^2)^2k-8\alpha^2)^2}$
Carbon Emission	$E_{m1}^{GN^*} = \frac{(-4+c^2)ke_1B_1}{(-4+c^2)^2k-8\alpha^2}$ $E_{m2}^{N\ *} = \frac{e_2(-a(-2+c)(2+c)^2k-4a\alpha^2+A_1p_e}{(-4+c^2)^2k-8\alpha^2}$

Here, $A_1 = (c((-4+c^2)k+4\alpha^2)e_1 + ((8-6c^2+c^4)k - 4\alpha^2)e_2)$,
$B_1 = \left(-a(2+c) + (-2+c^2)s + \left((-2+c^2)e_1 + ce_2\right)p_e\right)$,
$B_2 = (-4+c^2)k(a(2+c)-cs) + 4(a-cs)\alpha^2$,
$B_3 = ((-4+c^2)^2k - 8\alpha^2)(-a(2+c) + (-2+c^2)s + ((-2+c^2)e_1 + ce_2)p_e)^2$.

TABLE VI
OPTIMAL EQUILIBRIUM SOLUTION UNDER Gf

	Optimal Equilibrium Solution
Demand	$q_1^{Gf^*} = \frac{(1+c)(2+c)f\alpha^2+A_5}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{-(-2+c)k(a(2+c)+c(1+c)((-1+c)f-s)+2s)}{(2+c)((-2+c)^2k-2\alpha^2)}$ $q_2^{Gf^*} = -\frac{(2+c)\left((-2+c)k+2\alpha^2\right)e_1p_e}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{-(-2+c)k\left(a(2+c)+2\left(-1+c^2\right)f-\left(-2+c+c^2\right)\right)}{(2+c)((-2+c)^2k-2\alpha^2)}$
Retail Price	$p_1^{Gf^*} = \frac{((-2+c)k+2\alpha^2)e_1p_eB_8}{(2+c)((-2+c)^2k-2\alpha^2)}$ $p_2^{Gf^*} = \frac{-(-2+c)k(a(2+c)+(2+c^2)f-(2+c)s)}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{(4s+c(f-cf+2s))\alpha^2+(2+c)((-2+c)k+2\alpha^2)e_1p_e}{(2+c)((-2+c)^2k-2\alpha^2)}$
Technology level	$\theta^{Gf^*} = \frac{\alpha(2a(2+c)+4s+(1+c)}{(2+c)((-2+c)^2k-2\alpha^2)} + \frac{((4+(-2+c)c)f-2cs)-2(-2+c+c^2)e_1p_e)}{(2+c)((-2+c)^2k-2\alpha^2)}$
Profit	$\pi_{m1}^{Nf^*} = \frac{2a^2(2+c)^2k+2a(8+8c+c^3+c^4)fk}{2(2+c)^2((-2+c)^2k-2\alpha^2)} + \frac{(1+c)f^2A_6+2(-2+c+c^2)ke_1p_eA_7}{2(2+c)^2((-2+c)^2k-2\alpha^2)}$ $\pi_{m2}^{Nf^*} = \frac{(A_5+(-4+c)(1+c)f\alpha^2-A_5)^2}{(2+c)^2((-2+c)^2k-2\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{Gf^*} = \frac{(-B_7+(1+c)(2+c)f\alpha^2+A_5)^2}{2(2+c)^2((-2+c)^2k-2\alpha^2)^2}$ $CS_{m2}^{Gf^*} = \frac{(B_7+(-4+c)(1+c)f\alpha^2-A_5)^2}{2(2+c)^2((-2+c)^2k-2\alpha^2)^2}$
Carbon Emission	$E_{m1}^{Gf^*} = \frac{e_1(-B_7+(1+c)(2+c)f\alpha^2+A_5)}{(2+c)((-2+c)^2k-2\ \alpha^2)}$ $E_{m2}^{Gf^*} = \frac{e_1(-B_7-(-4+c)(1+c)f\alpha^2+A_5)}{(2+c)((-2+c)^2k-2\alpha^2)}$

TABLE VII
OPTIMAL EQUILIBRIUM SOLUTION UNDER GF

	Optimal Equilibrium Solution
Demand	$q_1^{GF^*} = q_2^{GF^*} = \frac{(-2+c)k(-a+(-1+c)s+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$
Retail Price	$p_1^{GF^*} = p_2^{GF^*} = \frac{-(-2+c)k(a-s)+2s\alpha^2+((-2+c)k+2\alpha^2)e_1p_e}{(-2+c)^2k-2\alpha^2}$
Technology level	$\theta^{GF^*} = \frac{2\alpha(a-(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$
Profit	$\pi_{m1}^{GF^*} = \frac{k((-2+c)^2F+(a+s-cs)^2)-2F\alpha^2}{(-2+c)^2k-2\alpha^2} + \frac{(-1+c)ke_1p_e(-2(a+s-cs)+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$ $\pi_{m2}^{GF^*} = \frac{(-2+c)^2k^2\left(-(-2+c)^2F+(a+s-cs)^2\right)}{((-2+c)^2k-2\alpha^2)^2} + \frac{4(-2+c)^2Fk\alpha^2-4F\alpha^4+B_9}{((-2+c)^2k-2\alpha^2)^2}$
Consumer Surplus	$CS_{m1}^{GF^*} = CS_{m2}^{GF^*} = \frac{(-2+c)^2k^2(-a+(-1+c)s+(-1+c)e_1p_e)^2}{2((-2+c)^2k-2\alpha^2)^2}$
Carbon Emission	$E_{m1}^{GF^*} = E_{m2}^{GF^*} = \frac{(-2+c)ke_1(-a+(-1+c)s+(-1+c)e_1p_e)}{(-2+c)^2k-2\alpha^2}$
Social Welfare	$SW^{GF^*} = \frac{k(a+s-cs-(-1+c)e_1p_e)(B_{10}+e_1B_{11})}{((-2+c)^2k-2\alpha^2)^2}$

Here, $B_4 = ((8+8c+c^3+c^4)f - 2(-1+c)(2+c)^2s)$,
$B_5 = ((-8+7c^2+c^4)f^2 + (8+c^2(-8+c-c^3))fs + (-2+c+c^2)^2s^2)$,
$B_6 = (-2a(2+c) - (1+c)(4+(-2+c)c)f + 2(-1+c)(2+c)s + (-2+c+c^2)e_1p_e)$,

$B_7 = (-2+c)(a(2+c)+2(-1+c^2)f)k$,
$B_8 = -(-2+c)k(a(2+c)+3cf-(2+c)s)-(2+c)((-1+c)f$
$-2s)\alpha^2$
$B_9 = k^2e_1p_e(-2(-2+c)^2(-1+c)(a+s-cs)+(2-3c+c^2)^2e_1p_e)$,
$B_{10} = (a+s-cs)(3(-2+c)^2k-2\alpha^2)$,
$B_{11} = (-2(-2+c)^3k+4(-2+c)\alpha^2-(-1+c)(3(-2+c)^2k-$
$2\alpha^2)p_e)$.

The descriptions of TABLE III-VII are similar to TABLE I.

Appendix B:

Proof of Table II:

Proof. Using the backward induction method for solution, first, two manufacturers comprehensively determine the final product prices. Taking derivatives of the manufacturer profit functions in Equations (1)(2) with respect to p_i (i=1,2), we obtain: $\frac{\partial \pi_{m1}{}^{NN}}{\partial p_1{}^{NN}} = a+\alpha\theta-2p_1+cp_2-e_1p_e$, $\frac{\partial \pi_{m2}{}^{NN}}{\partial p_2{}^{NN}} = a+cp_1-2p_2-e_2p_e$,with $\frac{\partial^2 \pi_{mi}{}^{NN}}{\partial (p_i{}^{NN})^2} < 0$. By simultaneously solving $\frac{\partial \pi_{m1}{}^{NN}}{\partial p_1{}^{NN}} = 0$ and $\frac{\partial \pi_{m2}{}^{NN}}{\partial p_2{}^{NN}} = 0$, we derive: $p_1^{NN^*} = -\frac{2a+ac+2\alpha\theta-2e_1p_e-ce_2p_e}{-4+c^2}$, $p_2^{NN^*} = -\frac{2a+ac+c\alpha\theta-ce_1p_e-2e_2p_e}{-4+c^2}$, substituting $p_1^{NN^*}$and $p_2^{NN^*}$ into Equation (1) , when $k > \frac{8\alpha^2}{(-4+c^2)^2}$,we have: $\frac{\partial^2 \pi_{m1}{}^{NN}}{\partial (\theta^{NN})^2} = -k+\frac{8\alpha^2}{(-4+c^2)^2} < 0$,indicating a maximum exists. Setting $\frac{\partial \pi_{m1}{}^{NN}}{\partial \theta^{NN}} = 0$, we obtain:$\theta^{NN} = \frac{4\alpha(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{-(-4+c^2)^2k+8\alpha^2}$, backward substitution leads to Table I.

The proofs of Table III-VII:

The proofs of Table III-VII are similar to the proof of Table I.

Proof of Theorem 1:

Proof. $p_1^{NN^*} - p_2^{NN^*} = \frac{4a\alpha^2+\left(-(-2+c)\left((-4+c^2)k+4\alpha^2\right)e_1+((-2+c)^2(2+c)k-4\alpha^2)e_2\right)p_e}{(-4+c^2)^2k-8\alpha^2}$.
Since $(-4+c^2)^2k-8\alpha^2 > 0$, to ensure $p_1^{NN^*} - p_2^{NN^*} > 0$, it requires that $4a\alpha^2+\left(-(-2+c)\left((-4+c^2)k+4\alpha^2\right)e_1+((-2+c)^2(2+c)k-4\alpha^2)e_2\right)p_e > 0$. By solving $p_1^{NN^*} - p_2^{NN^*} = 0$, we find that there exist thresholds: $k_1 = \frac{8\alpha^2}{(-4+c^2)^2}, k_2 = \frac{4\alpha^2(a-((-2+c)e_1+e_2)p_e)}{(-2+c)^2(2+c)(e_1-e_2)p_e}$, such that when $k_1 < k < k_2$,we have $p_1^{NN^*} > p_2^{NN^*}$; otherwise, $p_1^{NN^*} < p_2^{NN^*}$.

$q_1^{NN^*} - q_2^{NN^*} = \frac{4a\alpha^2+((-2+c)^2(1+c)(2+c)k-4c\alpha^2)e_1p_e}{(-4+c^2)^2k-8\alpha^2} + \frac{(-(-2+c)^2(1+c)(2+c)k+4\alpha^2)e_2)p_e}{(-4+c^2)^2k-8\alpha^2}$. Given $e_1 > e_2$, we can obtain $e_1 - e_2 > 0$, then we have $\left(((-2+c)^2(1+c)(2+c)k-4c\alpha^2)e_1+(-(-2+c)^2(1+c)(2+c)k+4\alpha^2)e_2\right) > 0$. Moreover, given that $(-4+c^2)^2k-8\alpha^2 > 0$, we can get $q_1^{NN^*} - q_2^{NN^*} > 0$.

Similarly, we can obtain $\pi_{m1}^{NN^*} > \pi_{m2}^{NN^*}$, $CS_{m1}^{NN^*} > CS_{m2}^{NN^*}$, $E_{m1}^{NN^*} > E_{m1}^{NN^*}$.

Proof of Theorem 2:

Proof. $p_1^{Nf^*} - p_2^{Nf^*} = \frac{(-1+c)f}{2+c}$, $q_1^{Nf} - q_2^{Nf^*} = \frac{f-c^2f}{2+c}$, $E_{m1}^{Nf^*} - E_{m1}^{Nf^*} = -\frac{(-1+c^2)fe_1}{2+c}$. Since $1 > c > 0$, we can easily get $(-1+c) < 0$, $1-c^2 > 0$, $(-1+c^2) < 0$, $2+c > 0$, so we can obtain $p_1^{Nf^*} < p_2^{Nf^*}$, $q_1^{Nf} > q_2^{Nf^*}$, $E_{m1}^{Nf^*} > E_{m1}^{Nf^*}$.

Similarly, we can get $CS_{m1}^{Nf^*} > CS_{m2}^{Nf^*}$, $\pi_{m1}^{Nf^*} > \pi_{m2}^{Nf^*}$.

Proof of Theorem 3-6:

The proofs of Theorem 3-6 are similar to Theorem 1 and Theorem 2.

Proof of Theorem 7:

Proof. $\theta^{GN^*} = \frac{4\alpha(-a(2+c)+(-2+c^2)s+((-2+c^2)e_1+ce_2)p_e)}{-(-4+c^2)^2k+8\alpha^2}$, $\theta^{NN^*} = \frac{4\alpha(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{-(-4+c^2)^2k+8\alpha^2}$, $\theta^{GN^*} - \theta^{NN^*} = \frac{4(-2+c^2)s\alpha}{-(-4+c^2)^2k+8\alpha^2}$, since $-(-4+c^2)^2k+8\alpha^2 < 0$ and $(-2+c^2) < 0$, given that $\alpha > 0$, $s > 0$, we have $\theta^{GN^*} > \theta^{NN^*}$.

$\theta^{Gf^*} = \frac{\alpha(2a(2+c)+4s+(1+c)((4+(-2+c)c)f-2cs)-2(-2+c+c^2)e_1p_e)}{(2+c)((-2+c)^2k-2\alpha^2)}$,

$\theta^{Nf^*} = \frac{\alpha\left(2a(2+c)+(1+c)(4+(-2+c)c)f-2\left(-2+c+c^2\right)e_1p_e\right)}{(2+c)((-2+c)^2k-2\alpha^2)}$, $\theta^{Gf^*} - \theta^{Nf^*} = \frac{2(-1+c)s\alpha}{-(-2+c)^2k+2\alpha^2}$, since $-(-2+c)^2k+2\alpha^2$ and $(-1+c) < 0$, given that $\alpha > 0$, $s > 0$, we have $\theta^{Gf^*} > \theta^{Nf^*}$.

Similarly, we can obtain $\theta^{GF^*} > \theta^{NF^*}$.

Proof of Theorem 8:

Proof. $p_1^{GN^*} - p_1^{NN^*} = \frac{2s((-4+c^2)k+4\alpha^2)}{(-4+c^2)^2k-8\alpha^2}$, $p_1^{Gf^*} - p_1^{Nf^*} = \frac{s((-2+c)k+2\alpha^2)}{(-2+c)^2k-2\alpha^2}$, $p_1^{GF^*} - p_1^{NF^*} = \frac{s((-2+c)k+2\alpha^2)}{(-2+c)^2k-2\alpha^2}$. Since $(-4+c^2)^2k-8\alpha^2 > 0$ and $(-2+c)^2k-2\alpha^2$, to ensure $p_1^{GN^*} - p_1^{NN^*} > 0$, it requires that $2s((-4+c^2)k+4\alpha^2) > 0$ and $s((-2+c)k+2\alpha^2)$. By solving $2s\left((-4+c^2)k+4\alpha^2\right) = 0$ and $s\left((-2+c)k+2\alpha^2\right) = 0$, we can get that there exist thresholds: when $\frac{2\alpha^2}{4-4c+c^2} < k < -\frac{4\alpha^2}{-4+c^2}$, $p_1^{GN^*} > p_1^{NN^*}$, $p_1^{Gf^*} > p_1^{Nf^*}$, $p_1^{GF^*} > p_1^{NF^*}$; otherwise, $p_1^{GN^*} < p_1^{NN^*}$, $p_1^{Gf^*} < p_1^{Nf^*}$, $p_1^{GF^*} < p_1^{NF^*}$.

$q_1^{GN^*} - q_1^{NN^*} = \frac{(8-6c^2+c^4)ks}{(-4+c^2)^2k-8\alpha^2}$. From $1 > c > 0$, we can easily get $(8-6c^2+c^4) > 0$, given that $(-4+c^2)^2k-8\alpha^2 > 0$, $k > 0$, $s > 0$, we can obtain $q_1^{GN^*} > q_1^{NN^*}$.

$q_1^{GF^*} - q_1^{NF^*} = \frac{(-2+c)(-1+c)ks}{(-2+c)^2k-2\alpha^2}$. From $1 > c > 0$, we can get that $(-2+c) < 0$, $(-1+c) < 0$. Given that $(-2+c)^2k-2\alpha^2$, $k > 0$, $s > 0$, we can obtain $q_1^{GF^*} > q_1^{NF^*}$.

$q_1^{Gf^*} - q_1^{Nf^*} = (1-c)(-\frac{(1+c)f}{2+c} - \frac{(-2+c)ks}{(-2+c)^2k-2\alpha^2})$. Since $(1-c) > 0$, to ensure $q_1^{Gf^*} - q_1^{Nf^*} > 0$, it requires that $(-\frac{(1+c)f}{2+c} - \frac{(-2+c)ks}{(-2+c)^2k-2\alpha^2}) > 0$. By solving $\left(-\frac{(1+c)f}{2+c} - \frac{(-2+c)ks}{(-2+c)^2k-2\alpha^2}\right) = 0$, we can get that there exist thresholds: $s_1 = \frac{(1+c)f(-(-2+c)^2k+2\alpha^2)}{(-4+c^2)k}$, such that when $s > s_1$, $q_1^{Gf^*} > q_1^{Nf^*}$; otherwise, $q_1^{Gf^*} < q_1^{Nf^*}$.

Similarly, we can obtain $\pi_{m1}^{GN^*} > \pi_{m1}^{NN^*}$, $\pi_{m1}^{Gf^*} > \pi_{m1}^{Nf^*}$, $\pi_{m1}^{GF^*} > \pi_{m1}^{NF^*}$.

Proof of Theorem 9-11:

The proofs of Theorem 9-11 are similar to Theorem 7 and Theorem 8.

Proof of Corollary 1:

Proof. $\frac{\partial\theta^{NN^*}}{\partial p_e}=\frac{4\alpha((-2+c^2)e_1+ce_2)}{-(-4+c^2)^2k+8\alpha^2}$, $\frac{\partial\theta^{NN^*}}{\partial e_1}=\frac{4(-2+c^2)\alpha p_e}{-(-4+c^2)^2k+8\alpha^2}$, $\frac{\partial\pi_{m1}^{NN^*}}{\partial p_e}=\frac{2k((-2+c^2)e_1+ce_2)(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{(-4+c^2)^2k-8\alpha^2}$,

$\frac{\partial\pi_{m1}^{NN^*}}{\partial e_1}=\frac{2(-2+c^2)kp_e(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)}{(-4+c^2)^2k-8\alpha^2}$.

Since $1>c>0$, we can get $(-2+c^2)e_1<-e_1$, so $(-2+c^2)e_1+ce_2<0$, given that $-(-4+c^2)^2k+8\alpha^2<0$, we can get $\frac{\partial\theta^{NN^*}}{\partial p_e}>0$.

Since $1>c>0$, we can get $-2+c^2<0$, given that $-(-4+c^2)^2k+8\alpha^2<0$, we can get $\frac{\partial\theta^{NN^*}}{\partial e_1}>0$.

Since $1>c>0$, we can get $(-2+c^2)e_1<-e_1$, so $(-2+c^2)e_1+ce_2<0$, such that $2k((-2+c^2)e_1+ce_2)(-a(2+c)+((-2+c^2)e_1+ce_2)p_e)>0$. Given that$(-4+c^2)^2k-8\alpha^2$, we can get $\frac{\partial\pi_{m1}^{NN^*}}{\partial p_e}>0$.

Similarly, we can obtain $\frac{\partial\pi_{m1}^{NN^*}}{\partial e_1}>0$, $\frac{\partial\pi_{m2}^{NN^*}}{\partial e_2}>0$.

$\frac{\partial\pi_{m2}^{NN^*}}{\partial p_e}=\frac{2\left(c\left((-4+c^2)k+4\alpha^2\right)e_1+\left((8-6c^2+c^4)k-4\alpha^2\right)e_2\right)}{((-4+c^2)^2k-8\alpha^2)^2}+\frac{A_1}{((-4+c^2)^2k-8\alpha^2)^2}$. To ensure $\frac{\partial\pi_{m2}^{NN^*}}{\partial p_e}>0$, it requires that $\frac{2\left(c\left((-4+c^2)k+4\alpha^2\right)e_1+\left((8-6c^2+c^4)k-4\alpha^2\right)e_2\right)}{((-4+c^2)^2k-8\alpha^2)^2}+\frac{A_1}{((-4+c^2)^2k-8\alpha^2)^2}>0$. By solving $\frac{\partial\pi_{m2}^{NN^*}}{\partial p_e}=0$, we can easily have that there exist thresholds: when$\frac{8\alpha^2}{(-4+c^2)^2}<k<-\frac{4\alpha^2}{-4+c^2}$; $or\ k>-\frac{4\alpha^2}{-4+c^2}\ and\ e_2<\frac{c((-4+c^2)k+4\alpha^2)e_1}{(8-6c^2+c^4)k-4\alpha^2}$, $\frac{\partial\pi_{m2}^{NN^*}}{\partial p_e}>0$; otherwise, $\frac{\partial\pi_{m2}^{NN^*}}{\partial p_e}<0$.

Proof of Corollary 2-6:

The proofs of Corallary2-6 are similar to Corollary 1.

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