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# Incentive Contracts and Optimal Green Technology Choice: A Differential Game Analysis

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**Abstract**

This study explores the use of government subsidies to encourage the production of low-carbon products in supply chains involving local governments and firms. The government can offer technical subsidies (OT), financial subsidies (OF), and combined fund-technology subsidies, categorized as fund-technology (FT) and technology-fund (TF) modes. Four game models are developed to thoroughly examine firms' decision-making processes under these subsidy modes, focusing on firm income, pollution control, and emission reduction efficiency. The findings reveal that the OT mode achieves the highest emission reduction efficiency, while the OF mode results in the best firm income. Mixed modes exhibit the highest level of pollution control, particularly under the FT mode. Consequently, the government should employ distinct subsidy modes based on specific emission reduction targets to maximize benefits. These conclusions provide valuable insights for international policymakers.

***Keywords:*** *Differential pollution game, emission reduction, green fund, green technology, pollution control*

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## 1 INTRODUCTION

Firms frequently encounter significant upfront investments when implementing energy-saving and emission reduction strategies, which increase production costs and introduce uncertainty in returns, thereby discouraging participation in such initiatives (Zheng et al., 2022; Huang et al., 2016). Consequently, government intervention is essential to promote low-carbon development among firms, directly influencing their decision-making through incentive policies (Bai et al., 2023; Ling et al., 2022). Previous studies have developed dynamic game models to formulate optimal incentive policies that balance economic development and environmental protection (Qin et al., 2021; Zhang & Yu, 2022; Yu, 2020; Chen & Nie, 2016).

However, these studies primarily focus on fiscal policies. A review of the existing literature reveals that, in addition to fiscal and tax funding policies, internationally recognized mainstream incentive mechanisms also include green technology transfer mechanisms (Rustico & Dimitrov, 2022; Hua et al., 2023; Chen et al., 2019). Green technology transfer mechanisms emphasize the long-term effects of technological innovation and knowledge sharing, focusing on the entire process of technology research and development, transfer, absorption, and application (Yan et al., 2024; Adomako & Tran, 2024). Therefore, this paper examines green technology as an incentive method, investigating its dynamic characteristics and emission reduction effectiveness. The study addresses the following questions: Which is more advantageous for promoting emission reduction and pollution control, green fund or green technology? Are firms more inclined toward green fund or green technology? Is there a critical condition that leads firms to choose one over the other?

International climate cooperation is a crucial application of our analysis. Since climate change impacts transcend borders, countries lack incentives to reduce greenhouse gas emissions unless others also take action. Thus, the international community has implemented measures to mitigate climate change, with green fund and green technology transfer mechanisms being significant. For instance, the 21st Conference of the Parties in Paris emphasized developed countries' commitment to offering $100 billion annually to developing countries before 2020 and establishing technology transfer mechanisms to promote carbon emission reductions.

To verify the effectiveness of the fund and technology transfer mechanisms, we use a differential game model to represent the dynamic interaction between local governments and polluting firms. Firms generate carbon emissions during production, which accumulate and cause environmental damage. They can adopt either green or non-green production strategies, with green strategies incurring higher costs but generating lower emissions. Therefore, local governments should provide subsidies to firms that engage in energy conservation and emission reduction. This paper considers two forms of government subsidies: green fund and green technology.

This paper presents a unique perspective compared to previous literature. Prior studies primarily examined positive incentives (carbon subsidies) and negative incentives (carbon taxes). Here, we include green technology subsidies and conduct a comprehensive comparison with green fund subsidies to understand their dynamic characteristics and scope. This analysis offers a theoretical foundation and scientific reference for policymakers involved in international climate cooperation.

This study examines an emission reduction game model involving a local government and multiple homogeneous local firms. The local government determines the value and nature of green subsidies, while firms establish their production plans based on these subsidies. The decisions made by both parties influence $CO_2$ accumulation in the atmosphere. Initially, the paper analyzes the cost structure of both parties and establishes the functional representation of green subsidies. Subsequently, using a differential game model, the study explores the dynamic characteristics of local government decision-making within four subsidy modes. This analysis elucidates the impact of enterprise production behavior on emission reduction, pollution control, and financial gains.

The primary contributions of this study are as follows:

This study conducts a comprehensive comparative analysis of the roles and impacts of green fund and green technologies in emission reduction games. Although the transfer of green fund and technologies is widely acknowledged as an effective strategy for facilitating emission reductions—a critical agenda in international climate summits—the dynamic characteristics and comparative advantages of these mechanisms remain under-explored. To address this gap, we investigate the following research questions: What are the dynamic properties of green fund and green technologies in driving emission reductions? Do they exhibit distinct advantages and limitations under specific conditions?

This study identifies the conditions under which firms prefer specific subsidies among four models. Specifically, when the production cost of normal products is low, firms tend to utilize normal technology regardless of the total subsidy amount. Only when these costs exceed a certain threshold do firms opt for green subsidies, enabling the production of environmentally friendly products. Moreover, when the coverage of green subsidies is limited, firms are more inclined to adopt green technology, whereas they prefer green fund when the coverage is extensive. To the best of our knowledge, no existing literature has explored the impact of relevant parameters on firms' selection of subsidy models as comprehensively as this study.

This study delineates the specific applicability scope for the four subsidy models. While none of these models possesses absolute superiority over the others, each can achieve optimal results within its respective scope. For instance, the OT mode demonstrates the highest emission reduction efficiency, the OF mode maximizes company benefits, and the mixed model achieves optimal pollution control.

By integrating four types of green subsidies as incentive mechanisms into differential games, this study establishes a dynamic relationship between green subsidies and emission reduction. In contrast to other relevant research that primarily examines the impact of subsidies on emission reduction or enterprise production from a static perspective, our study extends their work by adopting a dynamic approach.

The rest of this paper is organized as follows: Section 2 reviews the related literature. Section 3 identifies the game participants and analyzes their cost structures. In Section 4, differential game models are developed, incorporating four different subsidy modes, with the subsequent presentation of their respective optimal equilibrium solutions. Section 5 conducts a comparative analysis of the dynamic characteristics of the four subsidy modes. Section 6 provides a numerical study, and Section 7 concludes the paper.

## 2 THEORETICAL BACKGROUNDS

This study is closely related to the literature analyzing mitigation models with green subsidies and studies on green technology.

### 2.1. Mitigation Models with Green Subsidies

Research in this field can be broadly categorized into two types of incentive policies: positive and punitive. Positive incentive policies, such as carbon subsidies and corporate technology upgrade subsidies (e.g., Cui et al., 2020; Qin et al., 2021; Zhang & Yu, 2022), aim to foster low-carbon innovation by subsidizing corporate initiatives. For instance, He et al. (2023) developed two decentralized decision-making models—with and without subsidies—to assess their impacts on product prices, profits, and carbon emissions. Similarly, Zheng and Yu (2022) constructed a three-party evolutionary game model involving fishermen, consumers, and the government, utilizing field survey data to simulate the effects of government subsidies.

On the other hand, punitive incentive policies, including carbon emission taxes and emission limits (e.g., Yang & Chen, 2018; Yu, 2020; Chen & Nie, 2016; Zhou et al., 2019), regulate corporate carbon emissions through restrictive measures. For example, Zheng et al. (2023) investigated the evolutionary strategies and interaction mechanisms between new energy vehicle manufacturers and local governments under both static and dynamic carbon tax regimes. Additionally, Liu et al. (2023) analyzed the policy impacts of revenue recycling schemes based on industry-differentiated carbon taxes using a dynamic computable general equilibrium (CGE) model.

Recent studies have further compared the efficacy of positive and negative incentive policies (e.g., Yu, 2020; Xu et al., 2023; Yi et al., 2021). Notably, Yu (2020) examined the selection of carbon policies—taxes versus subsidies—under the influence of interest groups across different countries.

Existing literature primarily examines the impact of either technology subsidies or green subsidies on corporate green technology innovation, with limited comparative analysis of the effects of these two macro-level policies. Furthermore, most studies on the mechanism of government subsidy policies in promoting corporate green technology innovation remain at the empirical level, lacking sufficient theoretical modeling and derivation. Consequently, there is a pressing need to develop appropriate theoretical models to conduct more in-depth investigations into the mechanisms through which technology subsidies and green subsidies influence corporate green technology innovation.

### 2.2. Green Technology

Green technology innovation has become a critical benchmark for evaluating firms' sustainable development capacity and competitiveness (Ahmed & Streimikiene, 2021). The majority of literature on green technology subsidies focuses on two key areas: the conditions for successful green technology transfer (e.g., Li et al., 2022; Wang et al., 2021; Chen et al., 2023) and the factors leading to its failure (e.g., Liu & Liang, 2011; Saggi, 2002; Ockwell et al., 2010; Rai et al., 2014). Additionally, several studies have explored various dimensions of green technology innovation, including research and development, commercialization, and policy support (Amore & Bennedsen, 2016; Zheng et al., 2025; Lu et al., 2025). However, there is a shortage of research comparing green technology as a subsidy with alternative incentive measures. Moreover, while much of the existing literature evaluates the success or failure of technology subsidies from a macro perspective, it often overlooks how firms select the most appropriate subsidy schemes based on their development levels and the specific constraints of emission reduction policies.

## 3. METHODOLOGY

### 3.1. Game Model

This study focuses on the game relationship between local governments and local firms in the context of emission reduction activities. Local governments provide green subsidies, including green fund[1] and green technology,[2] to incentivize firms to reduce emissions and achieve local emission reduction targets. Firms then determine their production plans based on the form and value of the subsidies and their own economic interests. In this context, the control variables for the local government are the subsidy form (green fund or green technology) and the subsidy amount, while the control variable for firms is their respective production plans. Thus, the government acts as the leader in this Stackelberg game, with firms as followers.

### 3.2. Cost Structure of Firms

Consider a scenario where multiple firms operate in a specific region, producing products of identical quality and functionality but employing different technologies—normal and green technology—resulting in varying levels of carbon emissions during production. These

[1] For example, The National Energy Policy Act of 2005 Case was enacted in the United States in August 2005. The bill proposes 12.3 billion dollars in subsidies for green innovation in the oil, gas and power sectors over the next 10 years.

[2] For example, a green technology bank was established in the Yangtze River delta region to explore the mechanism for transferring technological achievements in the field of green technology in 2017. The green technology bank is a government-led platform for the transfer of low-carbon expertise. More than 100,000 green and low-carbon cross-city patents were transferred in the Yangtze River delta by 2020, and the green technology bank completed more than 4,000 green technology transfers in 2020 (Zou et al. (2023).

differences influence only carbon emissions and variable costs, without affecting the functional characteristics of the final product or consumer demand.

For example, in the cement industry, replacing air combustion technology with oxygen combustion technology improves combustion efficiency and facilitates the transportation, storage, and conversion of pure carbon dioxide generated during combustion. Although the functionality of cement produced using these technologies remains unchanged, oxygen combustion technology reduces carbon emissions during production while incurring higher unit production costs.

To streamline the discussion, we establish the following assumptions: for normal products, each unit produced generates one unit of carbon emissions, denoted as $e = q_d$. For low-carbon products, each unit produced reduces $\beta \in (0,1)$ units of emissions, denoted as $\Delta e = \beta q_c$. Consequently, the emissions associated with low-carbon products can be expressed as $e = (1-\beta) q_c$.

Given that product demand is influenced not only by price but also by the environmental attributes of the product, drawing on studies by Sengupta (2015) and Hua et al. (2023), the demand functions for normal and low-carbon products are formulated as follows:

$$p_c = 1 - Q_c + \Delta e, \tag{1}$$

$$p_d = 1 - Q_d \tag{1}$$

where $Q_d = \sum q_d$ is the sales volume of normal products; $Q_c = \sum q_c$ denotes the sales volume of low-carbon products.

Evidently, as indicated by equation (1), the demand for green products is higher under identical pricing conditions.

The unit production cost of normal products is denoted as $c_i$. Due to variations in technological capabilities and cost structures across firms, this study assumes heterogeneous production costs for identical products among different enterprises, i.e., $c_i \neq c_j$ for $i \neq j$ ,where $i, j \in [1, n]$.

Compared to normal products, low-carbon products incur additional emission reduction costs, denoted as $\alpha_I c_i$ ,where $\alpha_I \in (0,1)$ represents the industry-specific emission reduction cost coefficient. Thus, the unit production cost of low-carbon products can be expressed as $(1+\alpha_I)c_i$ .A smaller $\alpha_I$ indicates a more pronounced cost advantage of normal technology.

In a free-market environment, profit-maximizing firms prioritize normal technology. To promote low-carbon industry development, governments can implement subsidy policies to directly reduce the production costs of low-carbon products and enhance their market competitiveness. This study examines two types of subsidy mechanisms: green funding and green technology subsidies.

When the subsidy is in the form of green fund, the government's green subsidy can be designed as follows:

$$T = T_F \Delta e = T_F \beta q_c , \tag{2}$$

where $T_F$ is the unit subsidy coefficient. The subsidies primarily take the form of cost subsidies for emission reduction investments. In other words, the greater the emission reduction achieved by a firm, the higher the fund subsidy it will receive. Clearly, the subsidy formulated in equation (2) has a positive incentive effect on emission reduction.

Therefore, firm $i's$ total income $\pi_i^F$ from low-carbon products can be expressed as:

$$\pi_i^F = p_c q_c - (1+\alpha) c_i q_c + T_F \Delta e , \tag{3}$$

When the subsidy is in the form of green technology, the government's green subsidy can be designed as follows:

$$T = T_T q_c , \tag{4}$$

where $T_T$ is the unit subsidy coefficient. Technology subsidies are primarily allocated to cover the costs associated with production equipment and personnel training. Evidently, the larger the production scale of a firm, the greater the technology subsidy it requires. The technology subsidy formulated in equation (4) also exerts a positive incentive effect on enterprises.

In this case, the firm $i's$ total income $\pi_i^T$ of low-carbon product can be expressed as:

$$\pi_f^T = p_c q_c - (1+\alpha) c_i q_c + T_T q_c , \tag{5}$$

Finally, the firm $i's$ total revenue $\pi_i^N$ of the normal product can be expressed as:

$$\pi_i^N = \left(p_d - c_i\right) q_d$$

**3.3. The cost structure of local government**

Denote the cumulative amount of carbon dioxide in a region as $x(t)$, its dynamic evolution equation can be expressed as:

$$\dot{x} = e_1 + e_2 + \cdots + e_n - \delta x , \tag{6}$$

where $\delta \in (0,1)$ represents the natural absorption rate of carbon dioxide; $e_i , i \in (0, n)$ denotes the actual emissions of firm $i$. The adverse effects caused by $CO_2$ pollution can be represented by a function with $x$ as the variable[3]:

$$W = W(x) = \tau x$$

[3] The assumption that environmental costs have a linear relationship with emissions is common in the literature (see, for example, Chen and Li (2023) or Hua et al. (2023)). This assumption is adopted for ease of analysis. However, some papers adopt a quadratic function form, such as Li and Chen (2021), etc. These two assumptions have no impact on the accuracy of the results.

where $\tau \in (0,1)$ represents the pollution hazard coefficient. The government aims to balance carbon emission control with local economic development. Consequently, its payoff $\pi_g$ can be expressed as:

$$\pi_g = Q - T_i - \tau x, \tag{7}$$

where $T_i$ , $i = F, T$ represents the total amount of government subsidies.

# 4. THE OPTIMAL SOLUTION OF THE GAME MODEL

This paper primarily examines three types of subsidies: (1) green technology subsidies exclusively (OT); (2) green fund subsidies exclusively (OF); and (3) a mixed subsidy strategy combining both technology and fund subsidies. The third scenario can be further categorized into two cases: supplementing green technology on the basis of fund subsidies (FT), and supplementing green fund on the basis of technology subsidies (TF).

## 4.1. The case of OT

In this case, all firms can receive green technology subsidies from the government, which means that there are only low-carbon products available in the market, i.e., $Q_d = 0$ and $Q_c = \sum_{i=1}^{n} q_c^i$ . Combining formulas (1) and (5), the optimization objective of the firm can be expressed as:

$$\max_p \pi_f^T = \left(1 - (1-\beta)\sum_{i=1}^{n} q_c^i + T_T - (1+\alpha_I)c_i\right) q_c, \tag{8}$$

The optimal product price $q_c$ can be obtained by calculating $\frac{\partial \pi_f^T}{\partial q_c} = 0$, which means

$$q_c = \frac{1+T_T}{2(1-\beta)n} - \frac{(1+\alpha_I)c_i}{2(1-\beta)}, \tag{9}$$

Where $Q_c = \frac{1+T_T - n(1+\alpha_I)\bar{c}}{2(1-\beta)}$ with $\bar{c}$ denotes the average product price.

The above formula demonstrates the following insights:

Regarding product demand, an increase in the number of firms participating in emission reduction $n$ results in a decrease in the optimal output of each firm, consistent with the competitive relationship among them. Additionally, the optimal production volume of a firm is directly proportional to the technical subsidy coefficient $T_T$ . A larger technology subsidy scale corresponds to a higher optimal production volume for the firm.

At this stage, the actual total emissions of $n$ firms are $e = \beta Q_c$ . Consequently, the dynamic evolution equation of carbon dioxide in the region (6) can be reformulated as follows:

$$\dot{x} = (1-\beta)Q_c - \delta x = \frac{1+T_T - n(1+\alpha_I)\bar{c}}{2} - \delta x$$

The government's revenue function $\pi_g$ can be rewritten as

$$\pi_g = Q_c(1-\eta T_T) - \alpha_I x, \tag{10}$$

where $\eta$ represents the technology transfer coefficient.

Then the government's optimization problem can be expressed as the following model

$$\max_{T_T} \int_0^t [Q_c(1-\eta T_T) - \tau x] dt, \tag{11}$$

*s.t.*

$$\dot{x} = \frac{1+T_T - n(1+\alpha_I)\bar{c}}{2} - \delta x$$

To solve the above optimal model, we adopt a dynamic programming approach, and the Hamilton-Jacobi-Bellman (HJB) equation $V_T$ of the model (11) can be set as

$$rV_T(x) = \max_{T_T}\left\{[Q_c(1-\eta T_T) - \tau x] + \frac{\partial V}{\partial x}[(1-\beta)Q_c - \delta x]\right\}, \tag{12}$$

The intensity of technology subsidies is assumed to be a linear function of the accumulated local carbon emissions $x$:

$$T_T = k_T x + b_T, \tag{13}$$

To solve for the specific expression of $T_T$, we assume that equation (12) takes the following quadratic form[4]:

$$V(x) = Ax^2 + Bx + C$$

and combining with equation (12), we can obtain

$$rV = \frac{A(A\beta^2 - 2A\beta + A - 4B\delta\eta)}{2b\eta}x^2 +$$

$$\frac{A(\beta-1) - AB(\beta-1)^2 - A\eta(1-\bar{c})(1-\beta) + 2\eta(\alpha + B\delta)}{2\eta}x + \frac{(B - B\beta + \eta - \bar{c}\eta + 1)^2}{8\eta}, \tag{14}$$

The formula (14) holds for any $x$, so there is

[4] An alternative approach exists for solving the expression $T_T$. For a detailed analysis, please consult the author's previous work, Chen and Li (2023).

$$rA = \frac{A\left(A\beta^2 - 2A\beta + A - 4b\delta\eta\right)}{2b\eta}$$

$$rB = \frac{A(\beta-1) - AB(\beta-1)^2 - A\eta(1-\bar{c})(1-\beta) + 2\eta(\alpha + B\delta)}{2\eta}$$

$$rC = \frac{(B - B\beta + \eta - \bar{c}\,\eta + 1)^2}{8\eta}$$

which means

$$k_T = \frac{2(2\delta + r)}{n}, \tag{15}$$

$$b_T = \frac{B(1-\beta) - (1-\bar{c})\eta + 1}{2\eta\delta}, \tag{16}$$

Where

$$B = \frac{A(\beta-1)[\eta(1-\alpha_I\bar{c})+1] + 2\eta\tau}{2\eta(\delta + r) - A(\beta-1)^2}$$

$$A = \frac{2\eta(2\delta + r)}{(\beta-1)^2}$$

The emission reduction cost coefficient $\bar{c}$ and the pollution damage coefficient $\tau$ influence the optimal scale of green technology subsidies to some extent. However, during the initial phase of emission reduction, when the cumulative emissions $x$ are substantial, the impact of these factors on the optimal technology subsidy scale is minimal. By substituting the subsidy expression (13) with (15) (16) into expressions (8) and (10), we can derive the optimal strategies, including corporate income, government income, and total emission reduction, respectively. The results are omitted here and in the following subsections.

### 4.2. The case of OF

Given that the coverage of an equivalent amount of green fund is smaller than that of green technology, only a subset of firms can obtain green fund. The firms that receive green fund are labeled as $1,2,3\ldots m$, while the remaining firms, which do not receive green subsidies from the government, are labeled as $m+1, m+2, \ldots, n$. Firms that receive subsidies produce low-carbon products, with a total output of $Q_c$, whereas firms that do not receive subsidies produce normal products, with a total output of $Q_d$.

The benefits of low-carbon products can be expressed as:

$$\pi_i^F = [1 - (1-\beta)Q_c + \beta T_F - (1+\alpha_I)c_i]q_c, i = 1,2,\ldots,m, \tag{16}$$

The income of normal products can be expressed as:

$$\pi_i^N = [1 - Q_d - c_i]q_d, i = m+1, m+2, \ldots, n, \tag{17}$$

Two products optimal sales $q_c^*$ and $q_d^*$ is[5]

$$q_c^* = \frac{1+\beta T_F}{2m(1-\beta)} - \frac{(1+\alpha_I)c_i}{2(1-\beta)}, \tag{18}$$

$$q_d^* = \frac{1}{2(n-m)} - \frac{c_i}{2}, \tag{18}$$

At this stage, the actual emissions of $m$ low-carbon products are $e=(1-\beta)Q_c$, and the actual emissions of normal products are $e=Q_d$.

Consequently, the dynamic evolution equation of carbon dioxide in the region can be reformulated as

$$\dot{x} = (1-\beta)Q_c + Q_d - \delta x$$

Following a similar approach to the previous subsection, the optimal subsidy coefficient of the local government, $T_F$, in feedback form, is given by:

$$T_F = \frac{2(2\delta+r)}{m\beta}x + \frac{B(1-\beta)+\bar{c}(1+\alpha_I)+1}{4\beta}$$

where $x$ represents the regional accumulation of carbon dioxide[6].

### 4.3. The case of FT

In this section, we analyze the FT model, where certain firms receive green fund, labeled as $1,2,3,\ldots,m$. The remaining firms, labeled as $m+1, m+2,\ldots,n$, adopt green technology. In this scenario, the market consists exclusively of low-carbon products.

The supply and demand relationship can be expressed as follows:

$$p = 1-(1-\beta)(Q_T+Q_F), \tag{20}$$

where $Q_T = \sum q_T$ represents the total output of firms receiving technology subsidies; and $Q_F = \sum q_F$ denotes the total output of firms receiving fund subsidies.

The benefits of firms receiving green fund can be expressed as:

$$\pi_f^F = [1-(1-\beta)(Q_T+Q_F)+\beta T_F - (1+\alpha_I)c_i]q_F, i=1,2,\ldots,m, \tag{21}$$

[5] It can be made of the first order optimal condition $\frac{\partial \pi_i^F}{\partial q_c}=0$ and $\frac{\partial \pi_i^N}{\partial q_d}=0$.

[6] Where

$$B = -\frac{2A\beta - 8A + 2A\bar{c} + 6\tau + 2A\beta - 4A\beta\bar{c} + 5A\bar{c}\alpha + 2A\bar{c}\beta\alpha}{6(\delta+r) - A(\beta-1)^2} \quad A = \frac{6(2\delta+r)}{(\beta-1)^2}$$

The benefits of firms receiving technology subsidies can be expressed as:

$$\pi_f^T = [1-(1-\beta)(Q_T + Q_F) + T_T - (1+\alpha_I)c_i]q_T, i = m+1, m+2, \ldots, n, \tag{22}$$

Following a similar approach to the previous two subsections, the optimal outputs $q_F^*$ and $q_T^*$ for the two types of firms are:

$$Q_F^* = mq_F = \frac{1-m(1+\alpha_I)\bar{c} + 2\beta T_F - T_T}{3(1-\beta)}, \tag{23}$$

$$Q_T^* = (n-m)q_T = \frac{1-(n-m)(1+\alpha_I)\bar{c} + 2T_T - \beta T_F}{3(1-\beta)}, \tag{23}$$

Then, we have the optimal subsidy coefficient of local government, $T_T^{FT}$ and $T_F^{FT}$ are, in the feedback form[7] ,

$$T_F^{FT} = \frac{(2\delta + r)(5\eta+1)}{2\beta(1-\beta)(1+\eta)}x + \frac{(1+5\eta)[B(1-\beta)+1] - \eta(1-\bar{c})(\eta+5)}{\beta(\eta^2 - 14\eta + 1)}, \tag{25}$$

$$T_T^{FT} = \frac{(2\delta + r)(\eta+5)}{2(1-\beta)(1+\eta)}x + \frac{(5+\eta)[B(1-\beta)+1] - (1-\bar{c})(5\eta+1)}{(\eta^2 - 14\eta + 1)}, \tag{25}$$

where $x$ represents the regional accumulation of carbon dioxide.

### 4.4. The case of TF

In this scenario, firms that solely adopt technology are labeled as $m+1, m+2, \ldots, n$ , while firms that receive both types of subsidies are labeled as $1,2,3,\ldots,m$ . The supply and demand relationship can be expressed as follows:

$$p = 1-(1-\beta)(Q_T + Q_{TF}), \tag{26}$$

where $Q_T = \sum_{n-m} q^T$ represents the total output of firms that accept the technology subsidies; $Q_{TF} = \sum_m q^{TF}$ denotes the total output of low-carbon firms receiving both types of subsidies.

The benefits of low-carbon firms receiving both types of subsidies can be expressed as:

$$\pi_f^{TF} = [1-(1-\beta)(Q_T + Q_{TF}) + T_T + \beta T_F - c_i]q_{TF}, i = 1,2,\ldots,m$$

$$\pi_f^T = [1-(1-\beta)(Q_T + Q_{TF}) + T_T - c_i]q_T, i = m+1, m+2, \ldots, n$$

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[7] Where $B = \dfrac{2A(1-\beta)(1-\bar{c})(6\eta - \eta^2 - 2) + 4A(1-\beta)(1+\eta) - 14\eta - 12A\bar{c}\eta}{6(1+\alpha)(\eta^2 - 14\eta + 1)}$

$A = \dfrac{(2\delta + r)(\eta^2 - 14\eta + 1)}{4(\beta - 1)(1+\eta)}$

The optimal output $q_{TF}^{*}$ and $q_{T}^{*}$ for the two types of firms satisfy the following conditions:

$$Q_{TF}^{*} = \frac{1 - m(1+\alpha_I)\bar{c} + 2\beta T_F + T_T}{3(1-\beta)}, \tag{27}$$

$$Q_{T}^{*} = \frac{1 - (n-m)(1+\alpha_I)\bar{c} - \beta T_F + T_T}{3(1-\beta)}, \tag{28}$$

Then, we have the optimal subsidy coefficient of local government, $T_T^{TF}$ and $T_F^{TF}$ are, in the feedback form[8] ,

$$T_F^{TF} = \frac{(2\delta + r)(1-\eta)}{2\beta(1-\beta)}x + \frac{(2\eta - 2)[B(1-\beta) + \eta(1-\bar{c}) + 1]}{\beta(\eta^2 - 14\eta + 1)}, \tag{29}$$

$$T_T^{TF} = \frac{(2\delta + r)(7-\eta)}{4(1-\beta)}x + \frac{(7-\eta)[B(1-\beta) + 1] + (1-\bar{c})(1-7\eta)}{(\eta^2 - 14\eta + 1)}, \tag{29}$$

where $x$ represents the regional accumulation of carbon dioxide.

By combining equations (27), (28), and (29), the following results can be derived:

(1)Regarding product demand, the optimal production quantity $Q_{TF}^{*}$ of firms is influenced by both the fund subsidy coefficient $T_F$ and the technology subsidy coefficient $T_T$ ,with the impact of the fund subsidy coefficient $T_F$ being significantly greater than that of the technology subsidy coefficient $T_T$ .

(2)Extending the analysis to the international level, the technology transfer coefficient $\eta$ may decrease due to higher barriers in international technology transfer, such as policy differences and intellectual property protection. However, if mechanisms such as international green technology research, collaboration, and sharing are implemented to reduce technology transfer barriers (Aisbett et al., 2023), the technology transfer coefficient $\eta$ could increase significantly. Through the synergistic effect of technology transfer and financial subsidies, it is possible to effectively enhance the carbon dioxide absorption rate $\delta$ and reduce the carbon emission coefficient $\beta$ in developing countries. Furthermore, this can promote economic growth in developed countries through technology exports and trade expansion, thereby lowering global carbon emission intensity. These findings are consistent with the results of Gu and Wang (2018).

**Remark.** If the model is to be extended to a transnational context, we introduce key parameters like the international technology transfer barrier coefficient and heterogeneity grouping, and establish a hierarchical game framework. The coefficient quantifies obstacles in cross-border technology transfer, including policy differences and technical standards compatibility, while distinguishes between developed and developing countries, reflecting differences in technological capabilities and emission reduction costs. This extension better

[8] Where

$$B = \frac{2A(1-\beta)(1-\bar{c})(6\eta - \eta^2 - 2) + 4A(1-\beta)(1+\eta) - 14\eta - 12A\bar{c}\eta}{6(1+\alpha)(\eta^2 - 14\eta + 1)} \quad A = \frac{(2\delta + r)(\eta^2 - 14\eta + 1)}{4(\beta - 1)(1+\eta)}$$

captures the complexities of international cooperation and competition in green technology adoption.

## 5. MAIN RESULTS

This section provides a comprehensive analysis and comparison of the equilibrium characteristics in the four scenarios, as well as the preferences of the game participants toward the four subsidy modes.

First, we examine the government's preferences. In the case of fund transfer, the emissions of low-carbon firms should be lower than those of general firms under identical conditions, i.e., $(1-\beta)Q_c < Q_d < Q_c$. This discrepancy underscores the advantages of low-carbon products.

Based on this, we propose the following theorem to describe and summarize the government's strategy for green fund subsidies:

**Theorem 1:** The government should ensure that the coverage of green fund meets the following requirements to encourage firms to actively engage in green and low-carbon production and to control local carbon emissions:

$$\frac{\beta T_F + n\bar{c}}{(2+\alpha)\bar{c}} < m < \frac{\beta(1+T_F)+(1-\beta)n\bar{c}}{(2+\alpha-\beta)\bar{c}}$$

Furthermore, the government will select the funding model based on the efficiency of emission reduction.

**Theorem 2:** When the funding value is the same,

(1) If the following condition is met, government tends to provide green technology rather than green fund:

$$0 < \eta < \beta$$

(2) If the following condition is met, the government tends to provide the TF strategy instead of the FT strategy:

$$0 < \eta < \frac{\beta\left(EQ_F^1 - Q_F^2\right)}{Q_T^2 + Q_F^2 - EQ_T^1}$$

where $E = \dfrac{Q_F^2 + Q_T^2}{Q_F^1 + Q_T^1}$.

(3) The government aiming for optimal emission reduction efficiency will not choose the hybrid strategies since their emission reduction efficiency is always lower than that of the single subsidy model.

**Proof. Please see Appendix A.**

Theorem 2 illustrates the impact of the technology transfer coefficient $\eta$ on government subsidy policies. When the technology transfer coefficient is small, the emission reduction efficiency is higher under technology subsidies compared to fund subsidies. To maximize emission reduction efficiency, the optimal subsidy mode is the technology subsidy. As the technology transfer coefficient increases, the advantage of technology subsidies over fund subsidies gradually diminishes. When the technology transfer coefficient reaches a certain threshold, the emission reduction efficiency under technology subsidies becomes lower than that under fund subsidies. At this point, the government is more inclined to provide fund subsidies.

On the other hand, theorem 2 demonstrates that, in all cases, the emission reduction efficiency under the mixed subsidy model is lower than that under the single subsidy model. Therefore, from the perspective of emission reduction efficiency, the government would not choose the mixed subsidy model. However, considering other factors, the mixed subsidy model can effectively reduce product prices, increase the income from low-carbon products, and reduce emissions. Thus, during the early stages of emission reduction, the government may adopt a mixed subsidy model to enhance the competitiveness of low-carbon products, thereby promoting their adoption.

For firms, the income from low-carbon products must be greater than that from normal products; otherwise, firms will not choose to produce low-carbon products. Based on this, we derive the following theorem.

**Theorem 3:** (1) For a competitive industry comprising $n$ heterogeneous firms, there exists a critical low-carbon cost coefficient:

$$\alpha_I^* = \frac{1+\beta T_F - (1-\beta)(1-(n-m)\bar{c})}{m\bar{c}} - 1$$

such that if and only if the industry's incremental green transition cost coefficient satisfies $0 < \alpha_I < \alpha_I^*$, the industry as a whole exhibits a positive net benefit effect from green transition.

(2) When the industry satisfies the condition $0 < \alpha_I < \alpha_I^*$, individual firms adhere to the cost-threshold principle in adopting green transition strategies. The incentive compatibility condition for a firm's participation in green transition holds if and only if its unit environmental cost $c_i$ is below the industry-average cost $\bar{c}$, i.e., $c_i < \bar{c}$.

Theorem 3 posits that when $0 < \alpha_I < \alpha_I^*$, the revenue from low-carbon products surpasses that of normal products, prompting the industry to favor low-carbon production strategies. However, when $\alpha_I > \alpha_I^*$, normal products regain dominance due to their pronounced cost advantage. Thus, although the reduction in carbon emissions may enhance market demand and improve the profitability of low-carbon products, the industry as a whole may still be reluctant to adopt low-carbon production strategies. This reluctance is primarily driven by the significant cost advantage of normal products, coupled with the high costs associated with carbon reduction, which often result in lower profitability compared to normal products. However, as subsidies increase, products manufactured using low-carbon technologies become more cost-effective. The offsetting of production costs gradually enhances their competitive advantage, encouraging firms to opt for low-carbon products that reduce emissions. This demonstrates that well-calibrated subsidy policies can influence manufacturers to adopt low-carbon technologies, ultimately achieving the policy objective of reducing carbon emissions. On the other hand, when the industry meets the conditions for green transformation, firms with cost advantages are more inclined to access green funding. Specifically, firms with production costs below the industry average are more willing to pursue green transformation, highlighting the role of cost efficiency in driving sustainable practices.

In the following section, we will discuss the scope of application for green fund and green technology, as well as the conditions that influence firms' preference for either option. To facilitate a thorough comparison of the benefits and drawbacks between green fund and green technology, we will make the assumption that the green fund and green technology obtained by firms are equivalent, denoted as $T_F = T_T = T$.

**Theorem 4:** Under equal funding considerations, firms are inclined to select green technology over green fund only when the following condition is satisfied:

$$n - m < \frac{(1-\beta)T}{(1+\alpha_I)\bar{c}}$$

Theorem 4 posits that the benefits of low-carbon products vary across different subsidy models, depending on the scale of subsidies, the costs of low-carbon production, the intensity of market competition, and consumer preferences for green products. Consequently, firms must evaluate the relative magnitudes of these factors to determine the most appropriate subsidy model during the low-carbon transition. This phenomenon can be attributed to the heightened competition among low-carbon products as subsidy coverage expands, coupled with the increasing consumer preference for environmentally friendly products. As a result, the optimal sales volume for each firm decreases, leading to a reduction in revenue from low-carbon products. Specifically, due to their inherent characteristics, technology subsidies naturally offer broader coverage compared to financial subsidies. Consequently, as the scale of technology subsidies increases, the income of firms engaged in low-carbon product production declines at a faster rate. Furthermore, intensified market competition and shifting consumer preferences for green products also influence firms' decision-making processes. Therefore, firms aiming to maximize their own interests are more likely to opt for financial subsidies when $n - m < \frac{(1-\beta)T}{(1+\alpha_I)\bar{c}}$.

## 6. DISCUSSION

Numerical simulations are employed to further elucidate the evolutionary trajectories of multiple agents in an empirical setting and the impact of relevant parameter values on stable strategies. In this process, MATLAB is utilized to simulate the evolutionary dynamics of the Chinese cement industry. Based on data provided by Guo (2025), the price of cement in China has fluctuated between 310 and 650 yuan per ton over the past three years. Accordingly, the production cost of traditional cement is set at approximately 350 yuan per ton, while the production cost of cement utilizing green technologies is set at 500 yuan per ton. In terms of carbon emissions, the $CO_2$ emission intensity of normal cement production is 0.85 tons per ton of cement. Recent studies (e.g., Scrivener et al., 2018) indicate that improvements in green technologies can enhance the carbon reduction efficiency per unit product by approximately 25%, thereby reducing the carbon emissions of green cement products to 0.65 tons of $CO_2$ per ton of cement. Furthermore, additional parameters are normalized as benchmark values based on prior research (e.g., Chen & Li, 2023; Huang et al., 2016), with the parameter settings as follows:

Tab. 1 – The basic parameters. Source: Guo (2025), Chen & Li (2023), Huang et al. (2016), etc.

| $r$ | $\alpha$ | $\beta$ | $\bar{c}$ | $\delta$ | $\eta$ | $\tau$ |
|---|---|---|---|---|---|---|
| 0.01 | 0.42 | 0.76 | 0.35 | 0.05 | 0.4 | 1.2 |

According to the bulletin published by the World Meteorological Organization, the global average surface carbon dioxide concentration has reached 450.0 ppm. Therefore, we assume the initial carbon dioxide accumulation to be 450 ppm.

First, we provide the dynamic trajectories of carbon dioxide accumulation, optimal firm emission reduction, and government subsidies under four subsidy models based on subsections 3.1 to 3.4.

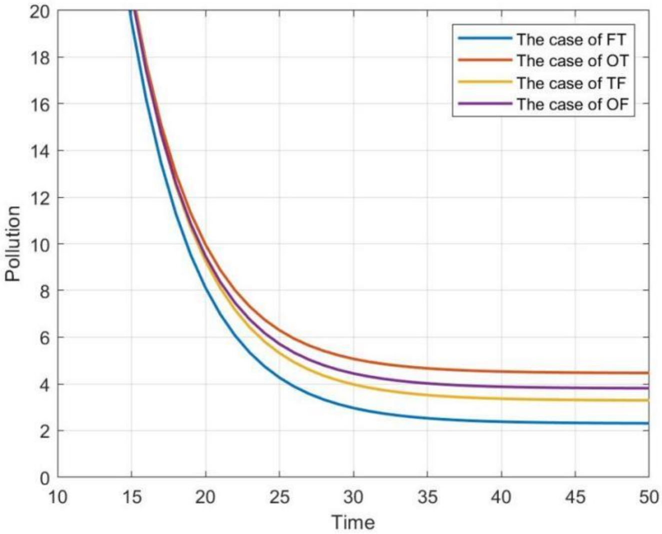


Fig. 1 – Pollution trajectories under four different subsidy modes. Source: own research

Figure 1 illustrates the gradual reduction in regional $CO_2$ accumulation over time as firms adopt low-carbon technologies, eventually stabilizing at a lower level. Notably, the mixed subsidy modes (TF and FT) demonstrate a significant decrease in $CO_2$ accumulation, whereas the single subsidy modes (OT and OF) exhibit a more modest reduction. Consequently, in terms of pollution control, the mixed subsidy model outperforms the single subsidy model. Furthermore, the FT model yields the most effective carbon reduction.

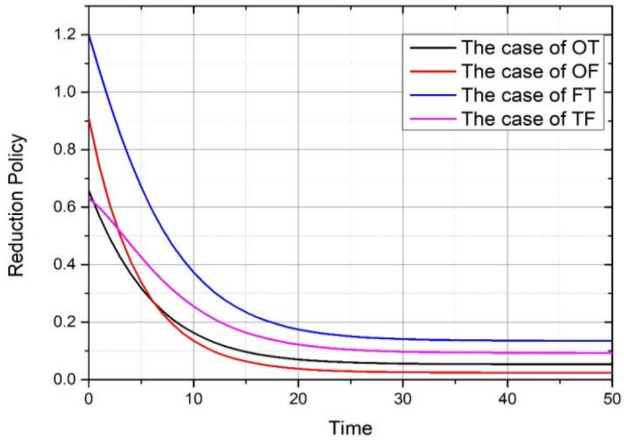

Fig. 2 – Emission reductions under four different subsidy modes. Source: own research

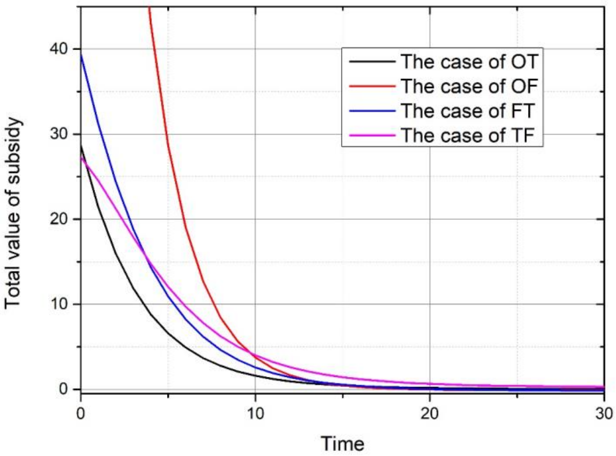


Fig. 3 – Aggregate subsidies across four different subsidy modes. Source: own research

Figures 2 and 3 depict the dynamic trajectories of corporate emission reduction and total government subsidies for the four subsidy models. Subsidies, acting as a feedback mechanism for carbon dioxide accumulation, decrease gradually as pollution and carbon dioxide emissions are reduced, leading to corresponding declines in both corporate emission reductions and total government subsidies. This suggests that during the initial phase of emission reduction, both the government and firms face significant pressure to reduce emissions. Over time, as carbon emissions are brought under control, this pressure gradually diminishes. It should be noted that during the initial phase of emission reduction in the OF model, the government experiences the highest financial pressure due to the provision of financial subsidies, significantly exceeding that of the other three models. In contrast, technology subsidies (OT) impose the least financial pressure. Therefore, from the government's perspective, the OT model is the most favorable option. However, if technological subsidies are interrupted, firms may revert to high-carbon production due to their inability to afford the costs of technological upgrades, resulting in a rebound in carbon dioxide accumulation.

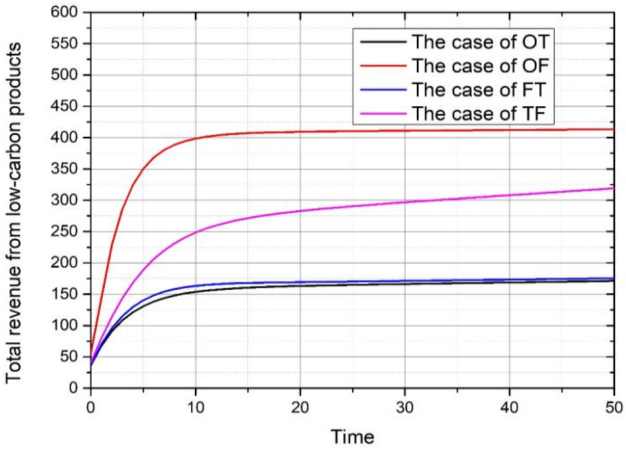


Fig. 4 – Overall profitability of low-carbon products across four different subsidy modes. Source: own research

Figure 4 illustrates the dynamic characteristics of total revenue generated by firms producing low-carbon products over time under the four subsidy models. The revenue from low-carbon products in all four subsidy models shows rapid initial growth, followed by relative stability. When analyzed alongside figure 1, it is evident that the period of increasing revenue from low-carbon products coincides with the period of declining carbon dioxide accumulation. Consequently, as carbon dioxide accumulation stabilizes at a lower level, the revenue from low-carbon products also stabilizes. This suggests that during the initial stage of emission reduction, low-carbon products exhibit strong competitiveness, which gradually diminishes as carbon emissions and pollution are controlled and mitigated. Additionally, figure 4 reveals that the revenue from low-carbon products under the fund subsidy model (OF) is the highest, followed by the TF and FT models, while the technology subsidy model yields the lowest revenue. Therefore, the OF model can maximize short-term profits for businesses, but in the long run, it may undermine their incentive for technological innovation (e.g., Rustico, 2022).

The relationship between emission reduction efficiency and the technology transfer coefficient $\eta$ under four subsidy modes at $T = 2$ is illustrated in figure 5. A three-dimensional graph illustrating the relationship among emission reduction efficiency, technology transfer coefficient $\eta$, and subsidy $T$ is provided.

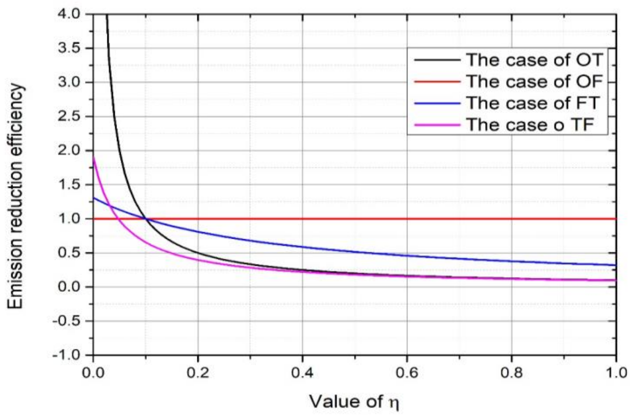


Fig. 5 – Efficiency of emission reduction under four different subsidy modes.
Source: own research

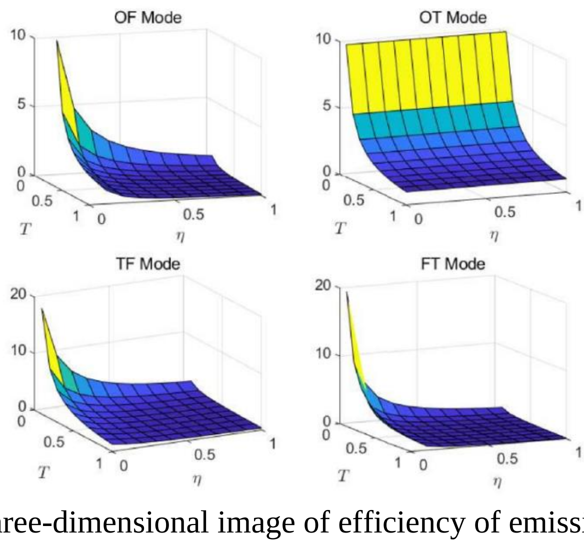


Fig. 6 – The three-dimensional image of efficiency of emission reduction.
Source: own research

From figure 5, it is evident that when the technology transfer coefficient $\eta$ is small, the highest emission reduction efficiency is achieved through technology transfer (OT), followed by TF and FT. Conversely, the least efficient emission reduction is attained through fund transfer (OF). As $\eta$ increases, the advantage of technology transfer diminishes, leading to a rapid decrease in emission reduction efficiency for the first three cases. Eventually, their efficiency becomes lower than that of green capital.

According to figure 6, when subsidies are relatively small (i.e., $T \in (0,1)$), the FT and TF modes exhibit similar levels of maximum emission reduction efficiency. Likewise, the OT and OF modes demonstrate comparable levels of maximum emission reduction efficiency, with the former surpassing the latter. Combining this with figure 5, we can conclude that in the advanced stage of emission reduction, with the preliminary control of carbon dioxide, employing a hybrid subsidy mode not only enhances the effects of pollution control but also concurrently achieves optimal emission reduction efficiency.

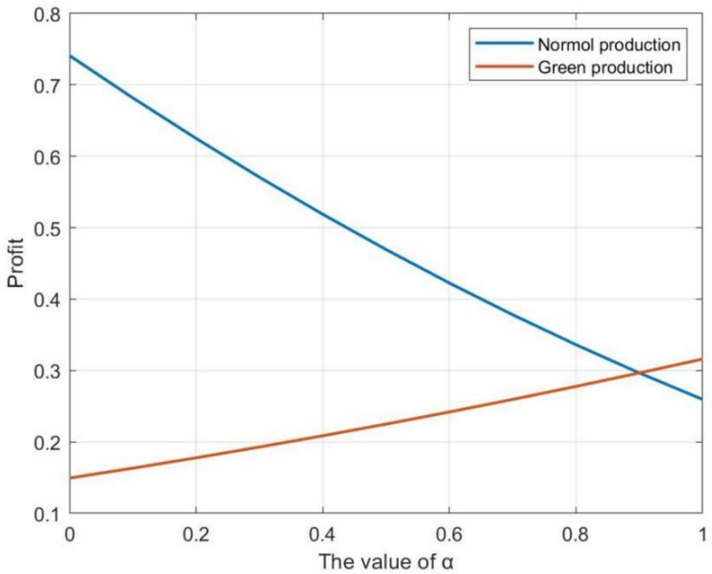


Fig. 7 – The influence of $\alpha_I$ on product returns. Source: own research

Figure 7 illustrates the influence of $\alpha_I$ on the income of normal products and low-carbon products. As $\alpha_I$ decreases, the cost advantage of normal products becomes more apparent, resulting in greater product income. As $\alpha_I$ increases, the competitive advantage of normal products gradually diminishes, while the income of low-carbon products begins to rise. By combining figure 7 and proposition 2, it can be deduced that when $\alpha_I < 0.9$, the income from low-carbon products surpasses that of normal products. Consequently, firms exhibit a greater preference for low-carbon alternatives.

## 7. CONCLUSION

This study focuses on local governments and homogeneous firms as the research subjects. It examines four subsidy models—OT, OF, FT, and TF—and constructs four differential game models with the government as the leader and firms as the followers. We investigate the optimal decision-making of both the government and firms across these four subsidy models, further analyzing and comparing the dynamic characteristics of firm profits, pollution control levels, and emission reduction efficiency within each model.

The findings reveal the following: (1) From the government's perspective, the OT model is the most advantageous due to its high emission reduction efficiency, particularly when the technology transfer coefficient is small. Additionally, it imposes minimal fiscal pressure on the government. (2) From the firms' perspective, the OF model is the optimal choice. First, from a holistic viewpoint, the total income generated by low-carbon products is significantly higher compared to the other three subsidy models. Second, the financial subsidy coverage in the OF model is relatively smaller, leading to reduced competition among low-carbon firms and higher individual incomes. (3) All four subsidy models contribute to a significant increase in total local emission reductions and effectively reduce and stabilize local carbon dioxide accumulation at a consistently low level over time. (4) Each subsidy model effectively lowers product prices and enhances the overall revenue generated by low-carbon products, thereby supporting the development of the low-carbon market.

The managerial implications derived from this study are as follows: (1) The government should set phased emission reduction targets and provide corresponding subsidy models aligned with specific reduction goals. For example, in the short term, subsidies (such as OF or OT) can be offered to encourage businesses to engage in low-carbon production and produce the most efficient low-carbon products. In areas with tight fiscal resources, technical subsidies (OT) could be prioritized to reduce long-term expenses. In regions with weak technological foundations, financial subsidies (OF) can be used to nurture the low-carbon market, gradually transitioning to technology-driven approaches. On the other hand, if the long-term goal is to achieve optimal pollution control, the FT model could replace the OF subsidy model to achieve the desired environmental benefits. (2) When selecting subsidy models, governments must carefully balance fiscal constraints and environmental benefits. For example, while the OT model enhances firms' emission reduction efficiency, it may also constrain their profitability. To mitigate potential financial losses, governments can provide tax incentives as compensation. On the other hand, although the OF model increases corporate profits, it places a significant burden on public finances. Therefore, it is essential to strictly regulate the scope of subsidy coverage to ensure fiscal sustainability. (3) International climate agreements should design a phased dynamic subsidy mechanism that deeply integrates green funding and technology transfer, constructing a differentiated policy toolkit: leveraging the U.N. Green Climate Fund (GCF) to embed the OF model (green funding) for targeted support in high-emission sectors of developing countries, while simultaneously establishing a patent-sharing platform through the Technology Executive Committee (TEC) to reduce technology transfer barriers under the OT model (technology subsidies). For North-South cooperation projects, the TF hybrid model (funding + technology) can be applied to incentivize developed countries to export green technologies and allow developing countries to offset part of the funding costs with emission reduction outcomes, creating a "technology-for-emission-reduction" bidirectional incentive mechanism. This approach requires a dynamic monitoring system to ensure subsidy continuity and quantify emission reduction effectiveness, avoiding policy gaps that could lead to high-carbon rebound, thereby achieving global emission reduction goals and North-South mutual benefits through funding-technology synergy.

This study provides a preliminary theoretical framework for low-carbon production and the design of incentive policies, yet several limitations remain. First, the research primarily focuses on positive incentive policies, such as green fund and technology subsidies, without exploring their combined effects with punitive measures, such as carbon taxes, on firms' production decisions. Second, the complexities of real-world market dynamics, including regulatory uncertainties, market competition, and consumer preferences, which may significantly influence firm behavior, are not fully captured in the model. Additionally, the study does not account for cross-border policy differences, such as technology transfer barriers, or global carbon leakage effects, both of which hold critical importance in international climate cooperation. Future research could enhance the theoretical framework by integrating these real-world complexities and transnational contexts, thereby offering policymakers more globally informed decision-making support.


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## Appendix A

Proof. Based on the preceding discussion, efficiency in reducing emissions under the context of OT mode can be expressed as

$$\Lambda^{T}=\frac{\beta Q_2}{\eta Q_2 T}=\frac{\beta}{\eta T}$$

Similarly, the efficiency in reducing emissions of OF modes can be expressed as

$$\Lambda^{F}=\frac{\beta Q_2}{\eta Q_2 T}=\frac{1}{T}$$

The efficiency in reducing emissions of FT modes can be expressed as

$$\Lambda^{FT}=\frac{\beta\left(Q_T^1+Q_F^1\right)}{\left[\beta Q_F^1+\eta Q_T^1\right]T}$$

The efficiency in reducing emissions of TF modes can be expressed as

$$\Lambda^{TF}=\frac{\beta\left(Q_T^2+Q_F^2\right)}{\left[(\beta+\eta)Q_F^2+\eta Q_T^2\right]T}$$

From the fact that $\Lambda^{T}>\Lambda^{F}$, we deduce that $\eta<\beta$.

By observing that $\Lambda^{TF}>\Lambda^{FT}$, it can be concluded that $\eta<\frac{\beta\left(EQ_F^1-Q_F^2\right)}{Q_T^2+Q_F^2-EQ_T^1}$ ,where $E=\frac{Q_F^2+Q_T^2}{Q_F^1+Q_T^1}$.

Thus, given this information, if we assume that $\Lambda^{FT}>\Lambda^{T}$, it follows that $\eta>\beta$.

Similarly, if we assume that $\Lambda^{FT}>\Lambda^{T}$, we can deduce that $\beta<0$. However, this finding contradicts the previous result. Thus, the efficiency in reducing emissions of implementing the mixed subsidy approach is consistently lower compared to the technical subsidy approach.

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